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Reimagining Forest Futures: Ecology-Driven Innovations for Sustainable Ecosystems, Biodiversity Conservation, and Community Resilience

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Editorial: Reimagining Forest Futures Through Ecology-Driven Innovation

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Introduction: The Crisis and the Imperative for Transformation

Forests represent humanity's most vital natural infrastructure, yet they face unprecedented crises from multiple converging threats. These complex terrestrial ecosystems provide essential ecosystem services that sustain both ecological systems and human societies (Aminah, 2025). The urgency of our moment demands nothing less than a profound paradigm shift away from conventional, utilitarian approaches to ecology-driven forest management that integrates scientific knowledge, technological innovation, and community-based stewardship.

The collection of 50 manuscripts compiled for this special issue on "**Reimagining Forest Futures: Ecology-Driven Innovations for Sustainable Ecosystems, Biodiversity Conservation, and Community Resilience**" exemplifies the scholarly rigor and multidisciplinary commitment necessary to address the converging challenges confronting the world's forest ecosystems. Beyond their conventional roles as sources of timber and carbon sinks, forests are increasingly recognized as dynamic, interconnected systems that underpin global ecological stability, harbour irreplaceable biodiversity, and provide essential ecosystem services that sustain human societies. However, these vital ecosystems face an unprecedented convergence of stressors. Climate change acts as a devastating amplifier of existing forest threats, intensifying the impacts of deforestation, particularly the destruction of tropical rainforests, which represents a significant driver of anthropogenic climate change itself (Abera et al., 2024). The resulting cascade of increasingly severe extreme events, including catastrophic wildfires, devastating floods, and prolonged droughts, damage forest ecosystems in ways that are sometimes irreversible, compromising their capacity for recovery and resilience (Potapov et al., 2025). Habitat fragmentation, unsustainable resource exploitation, and the relentless escalation of human activities have created a situation in which forests worldwide are under siege (Eke et al., 2025).

Moving Beyond Incremental Approaches: The Science of Ecological Management

Modern forest management must transcend the limited worldview that treats forests primarily as commodity sources and embraces a holistic understanding of forest ecological complexity grounded in the integrative principles of ecosystem ecology, landscape ecology, and conservation biology working in concert. Sustainable forest management (SFM) has emerged as an essential pillar of contemporary forest management; however, its implementation demands far more than procedural compliance. True SFM requires integrating local and traditional ecological knowledge accumulated through generations of careful observation and adaptive management, with cutting-edge scientific advancements and technological innovations (Hongal and Kshirsagar 2024). This integrative approach must recognize that forest ecosystems exist not in isolation but as components of complex socio-ecological systems where human communities, forest structures, biodiversity, and biogeochemical cycles are inextricably linked.

The paradigm shift required extends to recognizing forest disturbance dynamics not as anomalies to be prevented, but as natural processes that, when appropriately managed, can enhance ecosystem resilience (Adamopoulos et al., 2025). Research has demonstrated that moderate ecological disturbances, such as controlled burns and natural succession, can enhance species richness and functional diversity (Aminah 2025), whereas habitat fragmentation emerges as a major barrier to gene flow and species dispersal, which must be actively addressed through restoration efforts and landscape connectivity (Haddad et al., 2015). The framework for ecosystem management must balance human intervention with natural processes, moving beyond the false dichotomy of "preservation versus use" toward multifunctional landscapes that provide multiple ecosystem services (Velayudhan and Jaeger 2025).

Biodiversity Conservation in a Changing World

Biodiversity conservation has emerged as both a moral imperative and a practical necessity for maintaining functional forest ecosystems. The planet's forests harbor a

disproportionate share of global biodiversity, making their conservation a global responsibility of paramount importance (Pereira et al., 2024). However, biodiversity conservation cannot be achieved using fortress conservation approaches that exclude human participation. Instead, it must be conceived as an integrative endeavor that recognizes forests as dynamic systems shaped by human and ecological processes that operate across multiple spatial and temporal scales (Khawand 2025). The research presented in this special issue reveals the sophistication required for effective conservation of biodiversity. Studies documenting species diversity patterns across elevational gradients, examining ecological dominance and distribution patterns, and assessing species composition in varied forest contexts provide essential information on how biodiversity is organized and how it responds to environmental changes and management interventions.

Landscape ecology and connectivity have emerged as crucial frameworks for understanding how biodiversity persists across fragmented forest landscapes (Mori et al., 2016). When habitats become fragmented through agricultural expansion, infrastructure development, and other land-use changes, species populations become isolated, reducing genetic diversity and limiting their capacity for adaptation and recovery. Connectivity conservation-maintaining or restoring pathways that allow species movement across fragmented landscapes— is essential for long-term biodiversity persistence. Research demonstrates that functional diversity, the range of ecological roles and processes that different species perform, is critical, as species loss affects ecosystem functioning through the disruption of these essential processes (Hooper et al., 2005). Climate-resilient biodiversity conservation requires forward-thinking approaches that consider not only current environmental conditions but also projected future conditions, select conservation strategies that enhance adaptive capacity, and maintain options for ecosystem reorganization as climate shifts (Bellard et al., 2012).

Agroforestry: Reconciling Production and Conservation

Agroforestry systems present a particularly promising avenue for reconciling the apparent tension between agricultural production and conservation. Rather than viewing these as inherently conflicting goals, agroforestry demonstrates how production landscapes can simultaneously provide biodiversity habitats, maintain ecosystem services, support carbon sequestration, and generate income for rural communities (Sari 2025). The exceptional diversity in agroforestry research in this special issue reflects the recognition that these systems merit serious scientific attention and policy support. Agroforestry enhances carbon stocks, improves soil quality, and fosters biodiversity, offering clear advantages over monoculture systems (VijayKumar et al., 2024). These systems strengthen smallholder resilience by diversifying income sources and improving nutritional security (Sudomo et al., 2023).

The integration of non-timber forest products (NTFPs) into agroforestry systems deserves particular emphasis, as these products have historically provided essential income for rural populations and are undervalued in conventional forestry economics (Amenu et al., 2025). Medicinal and aromatic plants, resins, gums, bamboos, and other diverse forest products generate substantial employment and income for rural communities, yet their potential within agroforestry systems remains substantially under-developed in many regions. Research demonstrating the multifarious ecosystem services provided by agroforestry, including provisioning, regulating, and cultural services, provides crucial evidence for their integration into broader sustainable development frameworks (Subramanian et al., 2024). Agrobiodiversity, the maintenance of crop and tree genetic diversity within production systems, has emerged as another critical dimension of sustainable agroforestry with implications for food security, adaptive capacity, and ecosystem resilience (Tazebew et al., 2025).

Technology and Innovation as Enablers

The innovative technological approaches examined in this special issue offer powerful tools for advancing forest management and conservation. However, technology must always serve ecological and social goals rather than driving them. Remote sensing, Geographic Information Systems (GIS), and related geospatial technologies enable forest monitoring at scales and temporal frequencies that are impossible through traditional field methods (Ali et al., 2025). These tools provide crucial information about forest cover dynamics, land use changes, vegetation patterns, and ecosystem properties across landscapes. Artificial intelligence and machine learning applications show particular promise for processing massive quantities of data generated by modern monitoring systems and extracting patterns and insights that inform management decisions (Ali et al., 2025). Drones and unmanned aerial vehicles (UAVs) have revolutionized forest inventory and mapping capabilities, providing detailed spatial information regarding forest structure and composition.

Technological innovation should be coupled with ecological wisdom and social awareness. Biotechnology for forest improvement, sustainable harvesting technologies, and genetic analysis tools can advance conservation and restoration objectives when applied carefully (Sato and

Yoshimura 2023). Studies examining seed germination techniques, plant growth regulator effects, and biofertilizer influence on seedling performance have provided practical information for nursery management and restoration implementation. Analysis of wood properties and timber characteristics ensures that forest products are efficiently and sustainably utilized. Dendrochronological research linking growth rings to climate patterns provides crucial information about forest responses to environmental variation, providing projections of future responses to climate change (Lapola et al., 2018).

Community Engagement and Governance

Effective forest management ultimately depends on governance systems and community engagement approaches that empower local stakeholders, while maintaining ecological integrity. Community-based forest management (CBFM) represents a shift away from centralized, top-down management of approaches that recognize community rights, knowledge, and management capacities (Bamidele 2025). Forest tenure security, ensuring that communities have secure rights to forest resources and can benefit from conservation investments, provides crucial incentives for long-term management. Payment for ecosystem services (PES) schemes offer mechanisms to compensate communities for providing ecosystem services valued by external beneficiaries, thereby creating economic incentives for conservation (Ojelel et al., 2024). These mechanisms require careful design to avoid creating perverse incentives or undermining communities' sense of stewardship responsibility (Sele and Mukundi 2024).

The cultural and health dimensions of forests have emerged as essential but often overlooked aspects of forest value. Research documenting the traditional plant-based health practices of tribal peoples, exploring cultural ecosystem services, and examining how forests contribute to community well-being broadens the concept of forest benefits beyond ecological and economic metrics (Nugroho et al., 2022). Urban green spaces, documented through models such as the i-Tree Eco framework, demonstrate that forests and forest-like systems provide crucial benefits in populated areas, improve air quality, moderate urban heat, support mental health, and connect urban populations to ecological systems (Wang et al., 2024).

Addressing Systemic Challenges

Despite substantial progress in understanding forest ecology and developing innovative management approaches, significant barriers to its implementation persist. Policy fragmentation remains a critical challenge because of the limited financial access for smallholders to implement sustainable practices (VijayKumar et al., 2024). The integration of multiple ecosystem services in forest management reveals complex trade-offs, requiring sophisticated decision support systems that account for the multifunctionality of forests while maintaining ecological integrity (Knoke et al., 2020). Research addressing these challenges through adaptive management approaches demonstrates that flexible, responsive management frameworks can enhance real-time decision-making abilities and long-term ecosystem resilience (Khawand 2025).

Charting the Path Forward

The manuscripts comprising this special issue collectively demonstrate that reimagining forest futures requires moving beyond incremental improvements toward transformative approaches grounded in ecological science, technological innovation, social justice, and cultural wisdom. Forests are not static reserves to be preserved in suspended animation but dynamic systems that can be managed to provide multiple benefits when stewardship integrates ecological knowledge with community engagement and technological capability. The research presented here provides evidence-based foundations for such approaches, while simultaneously revealing gaps in our understanding and opportunities for future investigation (Pereira et al., 2024).

As we confront an uncertain future shaped by climate change, ongoing habitat loss, and ecological disruption, forests have emerged as crucial allies in global efforts to maintain planetary habitability and human wellbeing (Rajasugunasekar et al., 2023). The transformations documented and proposed in this special issue offer pathways toward forest futures that are simultaneously ecologically resilient, economically viable, culturally valued, and socially equitable. The Indian Ecological Society's commitment to fostering such transformation, reflected in this special issue, provides hope that the sophisticated integration of science, innovation, and community wisdom can indeed reshape how humanity relates to and depends on these irreplaceable ecosystems (Raman et al., 2024). The future of forests—and of human societies dependent upon them—depends on our collective commitment to implementing the innovative, ecology-driven approaches exemplified in the research compiled here.

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Vegetational Diversity in Submerged Hydro-Electric Project in the Eastern Himalaya

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***Abstract*:** The study was conducted to assess the vegetation diversity and forest structure in and around the Dumbur Hydroelectric Project in the Lower Eastern Himalayan Region of Tripura, India. A nested quadrat design was used with slight modifications to assess plant diversity. A total of 221 plant species were recorded, of which, 112 were herb species (53 families), followed by 45 shrub species (20 families), and 64 tree species (26 families). The Simpson index (1–D = 0.83) and Shannon diversity (H = 2.15) reflect moderate taxonomic diversity, while the evenness (E^H = 0.64) suggests that some shrub species are far more abundant than others. The diversity analysis showed a clear stratified pattern of species distribution and revealed gradient of decreasing diversity from herbs to shrubs to trees. This structure reflects ecological conditions that favour herbaceous species richness and suggests varying levels of disturbance, succession, or competitive interactions across vegetation strata in the study area. The vegetation of the study area is vital for sustaining the livelihoods of the local people, as most of the surrounding communities are forest-dwelling communities. This study calls for an urgent conservation initiative to conserve biological diversity, while ensuring food security, livelihood, and sustainable development.

***Keywords*:** Bioresource, Indian Himalayan Region, Plant diversity, Socio-ecological landscape, Sustainable resource use

Globally, more than 1.6 billion people depend on forests for subsistence, livelihood, employment, and income generation (UNDESA-UNFFS 2021). It plays an essential role in soil conservation, mitigation of the impact of climate change, and control of water runoff, food security, and job opportunities in tropical areas (FAO 2006). The National Forest Policy (NFP) of 1988 foresees a target of achieving 33 per cent forest cover with respect to forest and tree cover. The total forest cover of India, as per the current assessment, is 7,15,342.61 $km^{2.}$ that is, 21.76 per cent of the total geographical area of the country, of which Tripura constitutes 7,584.77 km^2 of forest land, that is, 72.33 per cent of the total geographical area of the state (FSI 2023). However, the global biodiversity crisis has given rise to growing concerns for which conservation and sustainable use of biodiversity and natural resources is the only key to sustainable development (Johnson et al., 2024). The assessment of species diversity is crucial for checking ecosystem health, as it influences key ecological processes (Naidu and Kumar 2016). The Himalayan region is a rich biodiversity area that boasts about 8000 angiosperms, 44 gymnosperms, and 60 pteridophytes (Singh and Hajra 1996, Thakur et al., 2005) and the state of Tripura is endowed with rich biodiversity with 1463 species of angiosperms and 13 species of gymnosperms (Naithani 2020).

The Dumbur Reservoir is an artificial lake created in 1976 by the creation of the 15 MW hydroelectric project at Dumbur, which falls on the river Gomati in the Indian Lower Eastern Himalayan Region, Tripura. The HEP had a submerged area of approximately 40 sq. km. The land lies within the Gumti wildlife sanctuary. This has led to about 27000 indigenous farmers being displaced and relocated towards the biodiversity-rich natural forest hill slopes, leading them to over-dependency on forest resources due to the absence of sustainable livelihood options. Hence, they ultimately become a threat to local biodiversity, however, no assessment of the available biodiversity, especially regarding vegetation diversity. The ethnic communities residing in these landscapes were mostly Reang, Tripura, Chakma, Jamatia, Molsom, and Bengalis. They collect resources from forests for food, fodder, and livelihoods, in addition to practising jhum/shifting cultivation. Limited livelihood options, sometimes, drive them to adopt monoculture-based commercial plantations by converting natural forests into areca nut or rubber plantations. This type of land use conversion may soon create serious issues. Owing to their dependence on forests and deforestation, some minor fruits, tuberous crops, and important bamboo species are threatened by conservation. It is widely accepted that indigenous peoples and local communities are custodians of a vast share of the world's genetic resources. Their traditional knowledge and practices have proven to be impertinent to biodiversity conservation and sustainable use (UNDP 2011). Thus, engaging the community in identifying important plant diversities enhances awareness and conservation efforts. The impact of HEPs on terrestrial biodiversity can be understood by studying the richness of local species and bioclimatic conditions. This study was

conducted to obtain a detailed understanding of the vegetation structure and its importance for HEP-affected people. This will also provide baseline information on the availability of different plant species and help natural resource managers to generate management plans for the area.

MATERIAL AND METHODS

Standard methods were adopted in this study and are discussed in detail in the following sections (Fig. 1).

Description of the study site: Tripura is the second-smallest state in northeast India and the third-smallest in the country, with a geographical area of 10,491 km^2. It belongs to the biogeographic zone of 9B. The study area lies between 23°22' to 23°42' N and 91°43′ to 91°58' E, and is the watershed area of the Dumbur reservoir falling under two administrative districts of Tripura *viz.,* Dhalai and Gomati. The basin areas obtained after delineation with GIS dataset and census data is estimated at 550.70 sq. km (Selvan and Dasgupta 2018). The elevation ranges between 40 to 300m above the mean sea level. The climate of this area is generally moist and humid. The minimum and maximum temperatures of the area are between 4 and 33°C during the winter. In summer, the temperature ranges from 21 to 38°C. The average annual rainfall varies between 1922 and 2855 mm and increases from southwest to northeast monsoon. This study was conducted in the adjoining forest landscapes of the Dumbur Reservoir, which falls under the Gumti Wildlife Sanctuary, Tripura.

Sampling procedure: Eleven line transects of 500 m each were laid around the reservoir in such a way that the starting point of the transect started from the nearby waterbody area and it moved towards a higher altitude towards the natural forests (Table 1). The vegetation was studied using a random sampling method to obtain the most representative vegetation composition. The fieldwork was conducted using the nested quadrat design (Peet et al., 1998, Barnett et al., 2019) with slight modifications by removing the centre

Fig. 1. Scheme of work

Table 1. Location details of study area

Transact name	Site/ Locality	Start point		End point	
		Latitude	Longitude	Latitude	Longitude
T1	Monadhan Para	23°33'18.32°N	91°49'42.73°E	23°34'°4.65°N	91°50'27.98°E
T2	Rupadhan Para	23°33'35.79°N	91°49'44.97°E	23°35'06.97°N	91°49'57.17°E
T3	Jagaram Para	23°29'54.08°N	91°51'38.13°E	23°29'51.51°N	91°51'43.73°E
T4	Nakku-Indrajoy Para	23°30'°6.84°N	91°48'31.38°E	23°32'18.95°N	91°48'°3.37°E
T5	Bhakta Para	23°31'40.23°N	91°50'53.56°E	23°33'04.05°N	91°51'48.96°E
T6	Chaplingchara	23°24'°3.67°N	91°50'09.08°E	23°24'03.78°N	91°49'46.03°E
T7	Mandirghat	23°25'17.75°N	91°49'07.15°E	23°25'17.09°N	91°49'15.74°E
T8	Gudhamjoy Para	23°25'35.38°N	91°52'21.34°E	23°25'26.73°N	91°52'42.59°E
T9	Bijoy Para	23°30'39.36°N	91° 52'57.05°E	23°31'15.24°N	91°53'16.78°E
T10	Mandul kami	23°34'04.91°N	91°48'10.41°E	23°35'33.75°N	91°46'38.32°E
T11	Mitrahum Para	23°34'24.18°N	91°51'09.92°E	23°35'02.25°N	91°51'09.76°E

quadrat to make the fieldwork more manageable. Total forty-four (44) quadrats of size 20 x 20 m were laid along the 11 transect lines, each transect having four quadrats (Fig. 2). Quadrats were laid alternatively along the transect lines, that is, two quadrats on the left and two quadrats on the right of the transect line. These sampled quadrates were used for necessary measurements of the tree samples. In each 20 × 20 m quadrat, two quadrats of size 5 × 5 m at the opposite corners for shrub species, and four quadrats of size 1 × 1 m were laid out for herb species. The total 44 quadrats for trees, 88 quadrats for shrub species, and 176 quadrats for herb species were laid.

Assessment of the vegetational diversity: Vegetation composition was evaluated by analyzing the frequency, density, abundance, importance value index (IVI), and A/F value (Mishra 1968, Tripathi 2004). Species were identified using the Flora of the State Tripura, Flora of Assam, and other secondary literatures (Kanjilal et al., 1938, Deb 1981, 1983).

Data analysis and compilation: Based on the number of species and individuals recorded in different quadrats, vegetation data were analyzed quantitatively for estimating relative frequency, relative density, relative abundance, and their sum as the IVI (Curtis and McIntosh 1950, Naidu and Kumar 2016). The Simpson index, Shannon-Weiner index, Margalef index, and evenness index were determined following standard methodology (Simpson 1949, Shannon and Weiner 1963, Pielou 1966, Margalef 1968). Diversity indices were analyzed using the Past 4.09 software. Microsoft Office Excel software was used to compile and calculate the collected data using the aforementioned equations.

RESULTS AND DISCUSSION

Composition and structure of vegetation: The present study recorded 221 species, of which, 112 species were herbs, 45 were shrubs, and 64 were tree species belonging to 76 families. The highest number of species was 22 in the family Fabaceae, followed by 13 species each in Asteraceae and Euphorbiaceae, and 11 species in Poaceae (Table 2). The total number of 7328 individuals was reported in the current study, of which 4665 were herbs, 2193 were shrubs, and 470 were trees. The highest number of individuals was 1580 in the family Poaceae, followed by Asteraceae and Fabaceae. Of the total vegetation, the percentage of species in herb lifeform was the highest (51%), followed by trees (29%), and shrubs (20%). Similarly, the percentage of individuals was found to be highest in herb (64%), followed by shrub (30%), and tree lifeforms (6%).

Herb vegetation: A total of 4665 individuals from 112 herb species belonging to 53 families were identified. The Asteraceae family showed the highest number of species (10), followed by Zingiberaceae and Poaceae (Table 2). Poaceae showed the highest number of individuals (1253), followed by Fabaceae and Asteraceae. The highest frequency (50) was in *Cyrtococcum oxyphyllum*, followed by *Imperata cylindrica*, and *Mimosa pudica*. The density was

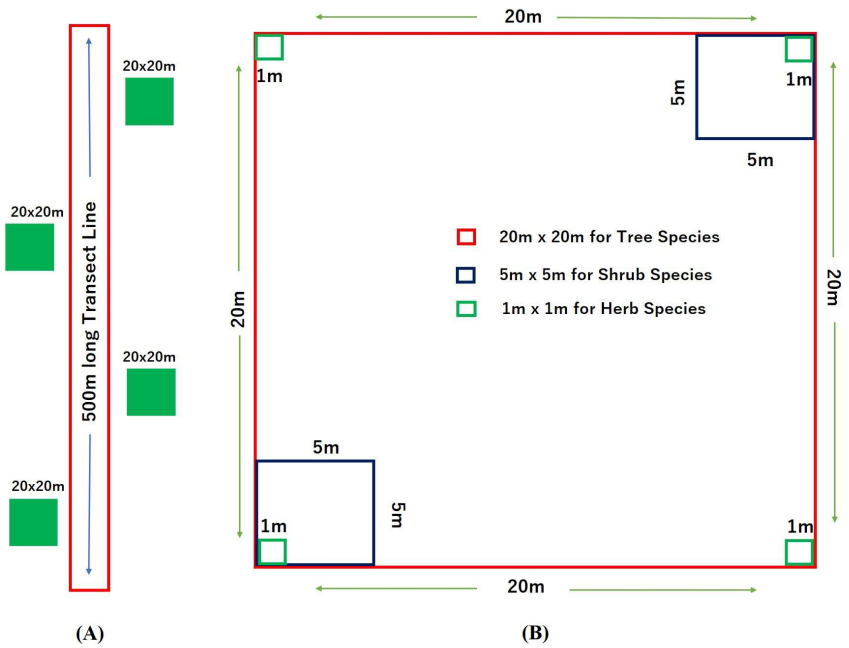

Fig. 2. Layout map of sampling: (A) 500m Line Transect (B) 20 x 20 m Quadrat with different components

Table 2. Family wise species and numbers in each habit (life form)

Family	Herb		Shrub		Tree	
	Species	Individual	Species	Individual	Species	Individual
Acanthaceae	01	42	-	-	-	-
Adiantaceae	01	04	-	-	-	-
Alangiaceae	-	-	-	-	01	01
Amaranthaceae	03	33	-	-	-	-
Anacardiaceae	-	-	-	-	02	9
Apiaceae	02	220	-	-	-	-
Apocynacae	01	8	02	20	02	15
Araceae	03	55	-	-	-	-
Araliaceae	-	-	-	-	01	01
Asteraceae	10	279	03	541	-	-
Athyriaceae	01	48	-	-	-	-
Bignoniaceae	-	-	-	-	03	27
Bombacaceae	-	-	-	-	01	02
Boraginaceae	01	9	-	-	-	-
Bromeliaceae	01	15	-	-	-	-
Buddlejaceae	01	05	-	-	-	-
Burseraceae	-	-	-	-	02	05
Cannabaceae	-	-	-	-	01	12
Cariaceae	-	-	-	-	01	2
Combretaceae	-	-	01	03	01	6
Commelinaceae	02	53	-	-	-	-
Convolvulaceae	06	97	-	-	-	-
Costaceae	01	39	-	-	-	-
Crassulaceae	01	5	-	-	-	-
Cucurbitaceae	02	33	-	-	-	-
Cyperaceae	03	85	-	-	--	-
Dilleniaceae	-	-	-	-	02	8
Dioscoreaceae	05	276	-	-	-	-
Dryopteridaceae	02	28	-	-	-	-
Euphorbiaceae	02	35	03	34	08	68
Fabaceae	05	386	09	131	08	53
Gleicheniaceae	01	33	-	-	-	-
Hypoxidaceae	03	158	-	-	-	-
Lamiaceae	01	97	05	302	02	58
Lecythidaceae	-	-	-	-	01	01
Leeaceae	-	-	01	01	-	-
Linderniaceae	01	98	-	-	-	-
Loranthaceae	-	-	01	02	-	-
Lycopodiaceae	01	3	-	-	-	-
Lygodiaceae	02	88	-	-	-	-
Lythraceae	01	8	-	-	02	60
Malvaceae	02	112	02	250	04	32

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Table 2. Family wise species and numbers in each habit (life form)

Family	Herb		Shrub		Tree	
	Species	Individual	Species	Individual	Species	Individual
Marantaceae	01	13	-	-	-	-
Melastomaceae	-	-	02	119	-	-
Meliaceae	-	-	-	-	01	09
Menispermaceae	02	64	-	-	-	-
Moraceae	-	-	-	-	10	36
Musaceae	02	38	-	-	-	-
Myrsinaceae	-	-	01	05	-	-
Myrtaceae	-	-	-	-	03	12
Nyctaginaceae	01	12	-	-	-	-
Onagraceae	02	34	-	-	-	-
Orchidaceae	02	16	-	-	-	-
Oxalidacece	01	46	-	-	-	-
Palmae	-	-	02	06	-	-
Papaveraceae	01	2	-	-	-	-
Passifloraceae	01	25	-	-	-	-
Phyllanthaceae	-	-	-	-	01	2
Piperaceae	01	30	-	-	-	-
Plantaginaceae	01	33	-	-	-	-
Poaceae	07	1253	04	327	-	-
Polygonaceae	03	61	-	-	-	-
Polypodiaceae	01	5	-	-	-	-
Rhamnaceae		-	01	08	01	04
Rubiaceae	02	229	02	21	01	15
Rutaceae		-	02	25	02	2
Scrophulariaceae	01	160	-	-	-	-
Solanaceae	02	73	01	96	-	-
Stemonaceae	01	03	-	-	-	-
Sterculiaceae	-	-	01	21	-	-
Thelypteridaceae	01	03	-	-	-	-
Tiliaceae	-	-	-	-	01	02
Urticaceae	01	12	01	11	-	
Verbenaceae	01	57	01	270	02	28
Vitaceae	02	23	-	-	-	-
Vittariaceae	01	03	-	-	-	-
Zingiberaceae	08	118	-	-	-	-
Total	112	4665	45	2193	64	470

highest in *I. cylindrica* (11.20), followed by *C. oxyphyllum* and *Spermacoce latifolia*, while abundance was highest in *Centella asiatica* (44.25), followed by *Stachytarpheta australis* and *I. cylindrica.* The highest IVI was 17.24 in *I. cylindrica,* followed by *C. oxyphyllum Centella asiatica* (Table 3).

Shrub vegetation: A total of 45 shrub species, consisting of 2193 individuals belonging to 20 families, were reported in this study. The Fabaceae family showed the highest number of species (9), followed by Lamiaceae and Poaceae (Table 2). The family Asteraceae had the highest number of individuals (541), followed by Poaceae and Lamiaceae. The

Table 3. Diversity indices of herb species

Species name	Family	F	RF	D	RD	A	RA	IVI	A/F
Achyranthes aspera L.	Amaranthaceae	9.09	0.77	0.43	0.41	4.75	0.55	1.72	0.52
Acmella oleracea (L.) R.K. Jansen	Asteraceae	2.27	0.19	0.16	0.15	7.00	0.80	1.15	3.08
Adiantum caudatum L.	Adiantaceae	2.27	0.19	0.09	0.09	4.00	0.46	0.74	1.76
Ageratum conyzoides L.	Asteraceae	22.73	1.92	1.52	1.44	6.70	0.77	4.13	0.29
Alocasia indica (Lour.) Spach	Araceae	2.27	0.19	0.05	0.04	2.00	0.23	0.46	0.88
Alpinia allughas (Retz.) Roscoe	Zingiberaceae	4.55	0.38	0.45	0.43	10.00	1.15	1.96	2.20
Alpinia malaccensis (Burm.f.) Roscoe.	Zingiberaceae	13.64	1.15	1.02	0.96	7.50	0.86	2.98	0.55
Amaranthus spinosus L.	Amaranthaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Ammannia baccifera L.	Lythraceae	2.27	0.19	0.18	0.17	8.00	0.92	1.28	3.52
Amorphophallus bulbifer (Roxb.) Blume	Araceae	22.73	1.92	0.95	0.90	4.20	0.48	3.31	0.18
Ananas comosus (L.) Merr.	Bromeliaceae	4.55	0.38	0.34	0.32	7.50	0.86	1.57	1.65
Argemone mexicana L.	Papaveraceae	2.27	0.19	0.05	0.04	2.00	0.23	0.46	0.88
Arundo donax L.	Poaceae	6.82	0.58	0.11	0.11	1.67	0.19	0.88	0.24
Axonopus compressus (Sw.) P.Beauv.	Poaceae	13.64	1.15	2.70	2.55	19.83	2.28	5.98	1.45
Blumea lanceolaria (Roxb.) Druce	Asteraceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Boehmeria nivea (L.) Gaudich.	Urticaceae	6.82	0.58	0.27	0.26	4.00	0.46	1.29	0.59
Boerhavia diffusa L.	Nyctaginaceae	4.55	0.38	0.27	0.26	6.00	0.69	1.33	1.32
Buddleja asiatica Lour.	Buddlejaceae	4.55	0.38	0.11	0.11	2.50	0.29	0.78	0.55
Cayratia trifolia (L.) Domin	Vitaceae	2.27	0.19	0.18	0.17	8.00	0.92	1.28	3.52
Centella asiatica (L.) Urb.	Apiaceae	9.09	0.77	4.02	3.79	44.25	5.08	9.64	4.87
Chenopodium album L.	Amaranthaceae	2.27	0.19	0.25	0.24	11.00	1.26	1.69	4.84
Coccinia grandis (L.) Voigt	Cucurbitaceae	13.64	1.15	0.57	0.54	4.17	0.48	2.17	0.31
Colocasia esculenta (L.) Schott.	Araceae	2.27	0.19	0.25	0.24	11.00	1.26	1.69	4.84
Commelina paludosa Blume	Commelinaceae	6.82	0.58	0.75	0.71	11.00	1.26	2.55	1.61
Costus speciosus (J.König) Sm.	Costaceae	20.45	1.73	0.89	0.84	4.33	0.50	3.06	0.21
Curculigo latifolia Dryand. ex W.T.Aiton	Hypoxidaceae	13.64	1.15	1.45	1.37	10.67	1.22	3.75	0.78
Curculigo orchioides Gaertn.	Hypoxidaceae	20.45	1.73	2.00	1.89	9.78	1.12	4.74	0.48
Curculigo recurvata Dryand.	Hypoxidaceae	2.27	0.19	0.14	0.13	6.00	0.69	1.01	2.64
Curcuma longa L.	Zingiberaceae	2.27	0.19	0.30	0.28	13.00	1.49	1.96	5.72
Curcuma zedoaria (Christm.) Roscoe	Zingiberaceae	2.27	0.19	0.09	0.09	4.00	0.46	0.74	1.76
Cuscuta reflexa Roxb.	Convolvulaceae	2.27	0.19	0.02	0.02	1.00	0.11	0.33	0.44
Cyclea barbata Miers.	Menispermaceae	11.36	0.96	0.66	0.62	5.80	0.67	2.25	0.51
Cyclosorus unitus (L.) Ching	Thelypteridaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Cymbidium aloifolium (L.) Sw.	Orchidaceae	6.82	0.58	0.18	0.17	2.67	0.31	1.05	0.39
Cynodon dactylon (L.) Pers.	Poaceae	13.64	1.15	2.52	2.38	18.50	2.12	5.66	1.36
Cyperus pilosus Vahl.	Cyperaceae	6.82	0.58	0.75	0.71	11.00	1.26	2.55	1.61
Cyrtococcum oxyphyllum (Steud.) Stapf	Poaceae	50.00	4.23	9.02	8.51	18.05	2.07	14.81	0.36
Dendrobium transparens Wall. ex Lindl.	Orchidaceae	6.82	0.58	0.18	0.17	2.67	0.31	1.05	0.39
Dicranopteris linearis (Burm.f.) Underw.	Gleicheniaceae	15.91	1.35	0.75	0.71	4.71	0.54	2.59	0.30
Dioscorea bulbifera L.	Dioscoreaceae	2.27	0.19	0.09	0.09	4.00	0.46	0.74	1.76
Dioscorea deltoidei Wall. ex Grisep.	Dioscoreaceae	15.91	1.35	0.64	0.60	4.00	0.46	2.41	0.25
Dioscorea glabra Roxb.	Dioscoreaceae	18.18	1.54	0.91	0.86	5.00	0.57	2.97	0.28
Dioscorea hamiltonii Hook. f.	Dioscoreaceae	20.45	1.73	2.25	2.12	11.00	1.26	5.12	0.54
Dioscorea villosa L.	Dioscoreaceae	27.27	2.31	2.39	2.25	8.75	1.00	5.56	0.32
Diplazium esculentum (Retz.) Sw.	Athyriaceae	13.64	1.15	1.09	1.03	8.00	0.92	3.10	0.59
Drynaria quercifolia (L.) J. Sm.	Polypodiaceae	4.55	0.38	0.11	0.11	2.50	0.29	0.78	0.55
Dryopteris affinis Fraser-Jenk.	Dryopteridaceae	2.27	0.19	0.09	0.09	4.00	0.46	0.74	1.76
Etlingera linguiformis (Roxb.) R.M.Sm.	Zingiberaceae	4.55	0.38	0.20	0.19	4.50	0.52	1.09	0.99
Euphorbia hirta L.	Euphorbiaceae	4.55	0.38	0.55	0.51	12.00	1.38	2.28	2.64
Evolvulus nummularius L.	Convolvulaceae	6.82	0.58	0.86	0.81	12.67	1.45	2.85	1.86
Fimbristylis aestivalis Vahl.	Cyperaceae	6.82	0.58	0.64	0.60	9.33	1.07	2.25	1.37
Floscopa scandens Lour.	Commelinaceae	6.82	0.58	0.45	0.43	6.67	0.77	1.77	0.98
Globba racemose sm.	Zingiberaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Heliotropium indicum L.	Boraginaceae	4.55	0.38	0.20	0.19	4.50	0.52	1.09	0.99
Hydrocotyle sibthorpioides Lam.	Apiaceae	4.55	0.38	0.98	0.92	21.50	2.47	3.77	4.73
Hypolytrum nemorum (Vahl.) Spreng	Cyperaceae	9.09	0.77	0.55	0.51	6.00	0.69	1.97	0.66
Imperata cylindrica (L.) Raeusch.	Poaceae	45.45	3.85	11.20	10.57	24.65	2.83	17.24	0.54

Cont...

Table 3. Diversity indices of herb species

Species name	Family	F	RF	D	RD	A	RA	IVI	A/F
Ipomoea carnea Jacq.	Convolvulaceae	4.55	0.38	0.43	0.41	9.50	1.09	1.88	2.09
Ipomoea heterotricha Didr.	Convolvulaceae	2.27	0.19	0.16	0.15	7.00	0.80	1.15	3.08
Kalanchoe pinnata (Lam.) Pers.	Crassulaceae	2.27	0.19	0.11	0.11	5.00	0.57	0.87	2.20
Lepistemon binectariferum (Wall.) Kuntze	Convolvulaceae	15.91	1.35	0.57	0.54	3.57	0.41	2.29	0.22
Lindernia antipoda (L.) Alston.	Linderniaceae	18.18	1.54	2.23	2.10	12.25	1.41	5.05	0.67
Ludwigia perennis L.	Onagraceae	4.55	0.38	0.23	0.21	5.00	0.57	1.17	1.10
Ludwigia prostrata Roxb.	Onagraceae	4.55	0.38	0.55	0.51	12.00	1.38	2.28	2.64
Lycopodium cernuum L.	Lycopodiaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Lygodium flexuosum (L.) Sw.	Lygodiaceae	29.55	2.50	1.93	1.82	6.54	0.75	5.07	0.22
Lygodium scandens (L.) Sw.	Lygodiaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Melochia corchorifolia L.	Malvaceae	9.09	0.77	0.66	0.62	7.25	0.83	2.22	0.80
Merremia vitifolia (Burm.f.) Hallier f.	Convolvulaceae	4.55	0.38	0.16	0.15	3.50	0.40	0.94	0.77
Mesosphaerum suaveolens (L.) Kruntze	Lamiaceae	18.18	1.54	2.20	2.08	12.13	1.39	5.01	0.67
Mikania scandens (L.) Willd	Asteraceae	31.82	2.69	2.36	2.23	7.43	0.85	5.77	0.23
Mimosa pudica L.	Fabaceae	40.91	3.46	3.48	3.28	8.50	0.98	7.72	0.21
Mucuna bracteata L.	Fabaceae	6.82	0.58	0.23	0.21	3.33	0.38	1.17	0.49
Musa balbisiana Colla	Musaceae	11.36	0.96	0.43	0.41	3.80	0.44	1.81	0.33
Musa x paradIsiaca L.	Musaceae	9.09	0.77	0.43	0.41	4.75	0.55	1.72	0.52
Mussaenda erosa Champ. ex Benth.	Rubiaceae	15.91	1.35	0.64	0.60	4.00	0.46	2.41	0.25
Nelsonia canescens (Lam.) Spreng.	Scrophulariaceae	31.82	2.69	3.64	3.43	11.43	1.31	7.43	0.36
Oxalis corniculata L.	Oxalidacece	9.09	0.77	1.05	0.99	11.50	1.32	3.08	1.27
Parthenium hysterophorus L.	Asteraceae	9.09	0.77	0.57	0.54	6.25	0.72	2.02	0.69
Paspalum conjugatum P.J. Bergius	Poaceae	11.36	0.96	1.91	1.80	16.80	1.93	4.69	1.48
Passiflora foetida L.	Passifloraceae	18.18	1.54	0.57	0.54	3.13	0.36	2.43	0.17
Peperomia pellucida (L.) Kunth	Piperaceae	4.55	0.38	0.68	0.64	15.00	1.72	2.75	3.30
Phrynium pubinerve Blume	Marantaceae	4.55	0.38	0.30	0.28	6.50	0.75	1.41	1.43
Phyllanthus urinaria L.	Euphorbiaceae	4.55	0.38	0.25	0.24	5.50	0.63	1.25	1.21
Physalis minima L.	Solanaceae	15.91	1.35	1.07	1.01	6.71	0.77	3.12	0.42
Polygonum hydropiper L.	Polygonaceae	4.55	0.38	1.02	0.96	22.50	2.58	3.93	4.95
Polystichum acrostichoides (Michx.) Schott.	Dryopteridaceae	11.36	0.96	0.55	0.51	4.80	0.55	2.03	0.42
Pueraria phaseoloides (Roxb.) Benth.	Fabaceae	9.09	0.77	0.32	0.30	3.50	0.40	1.47	0.39
Pueraria tuberosa (Willd.) DC.	Fabaceae	25.00	2.12	1.32	1.24	5.27	0.61	3.96	0.21
Rauwolfia serpentina (L.) Benth.	Apocynacae	6.82	0.58	0.18	0.17	2.67	0.31	1.05	0.39
Rumex maritimus L.	Polygonaceae	4.55	0.38	0.30	0.28	6.50	0.75	1.41	1.43
Rumex nepalensis Spreng.	Polygonaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Scoparia dulcis L.	Plantaginaceae	13.64	1.15	0.75	0.71	5.50	0.63	2.49	0.40
Senna tora (L.) Roxb.	Fabaceae	18.18	1.54	3.43	3.24	18.88	2.17	6.94	1.04
Sida acuta Burm.f.	Malvaceae	25.00	2.12	1.89	1.78	7.55	0.87	4.76	0.30
Solanum nigrum L.	Solanaceae	11.36	0.96	0.59	0.56	5.20	0.60	2.12	0.46
Spermacoce latifolia Aubl.	Rubiaceae	27.27	2.31	4.57	4.31	16.75	1.92	8.54	0.61
Spilanthes acmella L.	Asteraceae	2.27	0.19	0.27	0.26	12.00	1.38	1.83	5.28
Spilanthes paniculata Wall. ex DC	Asteraceae	2.27	0.19	0.18	0.17	8.00	0.92	1.28	3.52
Spilanthes radicans Schrad. ex DC	Asteraceae	4.55	0.38	0.41	0.39	9.00	1.03	1.80	1.98
Stachytarpheta australis Moldenke	Verbenaceae	4.55	0.38	1.30	1.22	28.50	3.27	4.88	6.27
Stemona tuberosa Lour.	Stemonaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Synedrella nodiflora (L.) Gaertn	Asteraceae	4.55	0.38	0.55	0.51	12.00	1.38	2.28	2.64
Tetrastigma harmandii Planch	Vitaceae	11.36	0.96	0.34	0.32	3.00	0.34	1.63	0.26
Thladiantha calcarata (Wall.) C.B. Clarke	Cucurbitaceae	6.82	0.58	0.18	0.17	2.67	0.31	1.05	0.39
Thunbergia grandiflora Roxb.	Acanthaceae	25.00	2.12	0.95	0.90	3.82	0.44	3.45	0.15
Thysanolaena latifolia (Roxb. ex Hornem.) Honda	Poaceae	27.27	2.31	1.00	0.94	3.67	0.42	3.67	0.13
Tinospora cordifolia (Willd.) Miers	Menispermaceae	20.45	1.73	0.80	0.75	3.89	0.45	2.93	0.19
Vittaria elongata Sw.	Vittariaceae	2.27	0.19	0.07	0.06	3.00	0.34	0.60	1.32
Xanthium strumarium L.	Asteraceae	6.82	0.58	0.25	0.24	3.67	0.42	1.23	0.54
Zingiber chrysanthum Roscoe	Zingiberaceae	13.64	1.15	0.43	0.41	3.17	0.36	1.92	0.23
Zingiber rubens Roxb.	Zingiberaceae	2.27	0.19	0.11	0.11	5.00	0.57	0.87	2.20
Total		1181.82	100	106.02	100	871.15	100	300.00	150.52

F=Frequency, RF=Relative frequency, D=Density, RD=Relative Density, A=Abundance, RA=Relative Abundance, IVI=Important Value Index, A/F= Abundance to Frequency ratio

highest frequency (77.27) was for *Chromolaena odorata* followed by *Clerodendrum viscosum* and *Lantana camara*. Density was also the highest (11.77) in *C. odorata* followed by *L. camara* and *Melocanna bacifera.* Abundance was the highest in *Bambusa polymorpha* (21.50), followed by *M. bacifera*, and *C. odorata.* The highest IVI value (42.48) was in *C. odorata* followed by *L. camara* and *C. viscosum* (Table 4).

Tree vegetation: A total of 64 tree species comprising 470 individuals belonging to 26 families were identified in this study. The Moraceae family showed the highest number of species (10), followed by the Euphorbiaceae and Fabaceae families. The family Euphorbiaceae recorded the highest number of individuals (68), followed by Lythraceae and Lamiaceae (Table 2). Similar kinds of result was found by . The highest frequency was in *Lagerstroemia parviflora* (40.91), followed by *Albizia procera*. The density was highest in *L. parviflora* (1.34), followed by *Tectona grandis* and *Hevea brasiliensis*. The highest abundance was in *H. brasiliensis* (36), followed by *T. grandis* and *Pterospermum acerifolium*. The reason for the distinct abundance of *H. brasiliensis* is that it is a monocultured tree. The value of IVI was highest in *L. parviflora* (21.90), followed by *Ficus auriculata* and *A. procera* (Table 5). IVI is an index that represents the social standing of a species in a community and can be understood as the pattern of affiliation of the dominant species of that specific community (Sharma et al., 2023). Greater IVI values indicate a broad ecological amplitude, adaptability, and strong regeneration capability.

Distribution pattern: The ratio of abundance to frequency (A/F) or distribution pattern in herbs was highest in *Stachytarpheta australis* (6.27), followed by *Curcuma longa*, *Spilanthes acmella* and lowest in *Thysanolaena latifolia* (0.13). Among the shrubs, the A/F value was highest in *Bambusa polymorpha* (4.73), followed by *Parthenium hysterophorus* and *Sesbania cannabina*), whereas *Ziziphus oenoplia* (0.10) recorded the lowest A/F value. Among the tree species, the A/F value was highest in *H. brasiliensis* (15.84) and lowest in *Albizia procera,* (0.06). The distribution pattern for herbs, shrubs, and trees in all the 11 transects studied (Table 3, 4 & 5 respectively) was a contagious distribution, that is, A/F value (more than 0.05) ranging from 0.15 (*Thunbergia grandiflora*) to 6.27 (*S. australis*) in herbs, 0.10 (*Ziziphus oenoplia*) to 4.73 (*Bambusa polymorpha*) in shrubs and 0.06 (*A. procera*) to 15.84 (*H. brasiliensis*) in trees.

Plant diversity parameters and diversity indices: The highest mean frequency in all life forms was fin shrubs *i.e.,* 13.94, followed by herbs and tree species). Similarly mean density was highest among shrubs (1.11), followed by herbs and tree species. Both mean abundance and mean A/F value were the highest among herbs (7.78 and 1.34, respectively), followed by shrubs and trees. Mean IVI was highest among shrubs (6.67), followed by trees and herbs (Table 6). The diversity analysis of herbs, shrubs, and trees across all transects shows a clear stratified pattern of species distribution. The herb layer exhibited the highest species richness, with an average of 30.82 species and approximately 415 individuals, indicating a highly diverse and stable ground-layer community. Low dominance (D = 0.08), coupled with high Simpson diversity (1–D = 0.92) and a relatively high Shannon index (H = 2.95), suggests that no single species dominates the herbaceous vegetation. The evenness value (E^H = 0.68) further reflects a fairly balanced distribution of individuals among species, while the high Margalef index (4.99) points to significant contributions of species richness across the transects. These results together indicate that the herb layer is the most ecologically balanced and species-rich stratum in the study area, likely benefiting from favourable microhabitat conditions and reduced competitive exclusion. In contrast, the shrub layer showed moderate levels of diversity, with an average of 16 species and about 199 individuals. Dominance was slightly higher (D = 0.17) than in the herb layer, indicating that a few species occur more frequently. The Simpson index (1–D = 0.83) and Shannon diversity (H = 2.15) reflect moderate taxonomic diversity, while the evenness (E^H = 0.64) suggests that some shrub species are far more abundant than others. The Margalef index of 2.83 confirms that shrub richness is present but not as strong as in herbs. Overall, the shrub community appears to be in a transitional state, likely influenced by canopy cover, succession, or human disturbance, resulting in a moderately diverse but uneven distribution of species. The tree layer recorded the lowest diversity among the three strata, with an average species richness of 13.73 and roughly 43 individuals. Dominance was comparatively higher (D = 0.19), indicating that only a few canopy species are ecologically influential. Diversity values, including Simpson's index (1–D = 0.81) and Shannon H (2.12), show that the tree layer is less diverse than the lower vegetation strata. Although the evenness value (E^H = 0.73) appears relatively high, this largely reflects low overall richness rather than a genuinely diverse community, since individuals are distributed among fewer tree species. The Margalef index (3.35) indicates moderate richness typical of forest canopies but still lower than the herb layer. These patterns suggest that the tree stratum is either in an early successional stage, recovering from disturbance, or naturally dominated by a limited number of species. The results reveal gradient of decreasing diversity from herbs to shrubs to trees. Herbs form the most diverse and evenly distributed layer,

Table 4. Diversity indices of shrub species

Species name	Family	F	RF	D	RD	A	RA	IVI	A/F
Abrus precatorius L.	Fabaceae	6.82	1.09	0.14	0.27	2.00	0.86	2.22	0.29
Bambusa polymorpha Munro	Poaceae	4.55	0.72	0.98	1.96	21.50	9.22	11.91	4.73
Bambusa tulda Roxb.	Poaceae	6.82	1.09	0.50	1.00	7.33	3.15	5.24	1.08
Byttneria pilosa Roxb.	Sterculiaceae	15.91	2.54	0.48	0.96	3.00	1.29	4.78	0.19
Calamus heteracanthus Zipp. ex Blume	Palmae	4.55	0.72	0.09	0.18	2.00	0.86	1.77	0.44
Calamus leptospadix griff.	Palmae	2.27	0.36	0.05	0.09	2.00	0.86	1.31	0.88
Calotropis gigantea (L.) Dryand.	Apocynaceae	13.64	2.17	0.39	0.78	2.83	1.22	4.16	0.21
Cassia occidentalis L.	Fabaceae	20.45	3.26	0.82	1.64	4.00	1.72	6.62	0.20
Chassalia curviflora (Wall.) Thwaites	Rubiaceae	4.55	0.72	0.16	0.32	3.50	1.50	2.55	0.77
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	77.27	12.32	11.77	23.62	15.24	6.54	42.48	0.20
Citrus limon (L.) Burm. f.	Rutaceae	2.27	0.36	0.05	0.09	2.00	0.86	1.31	0.88
Clerodendrum indicum (L.) Kuntze	Lamiaceae	4.55	0.72	0.23	0.46	5.00	2.14	3.33	1.10
Clerodendrum japonicum (Thunb.) Sweet	Lamiaceae	6.82	1.09	0.41	0.82	6.00	2.57	4.48	0.88
Clerodendrum philippinum Schauer	Lamiaceae	6.82	1.09	0.27	0.55	4.00	1.72	3.35	0.59
Clerodendrum viscosum Vent.	Lamiaceae	50.00	7.97	5.39	10.81	10.77	4.62	23.40	0.22
Clerodendrum wallichii Merr.	Lamiaceae	11.36	1.81	0.57	1.14	5.00	2.14	5.10	0.44
Coffea bengalensis Roxb. ex Schult.	Rubiaceae	9.09	1.45	0.32	0.64	3.50	1.50	3.59	0.39
Combretum indicum (L.) DeFilipps	Combretaceae	2.27	0.36	0.07	0.14	3.00	1.29	1.79	1.32
Dendrocalamus longispathus Kurz	Poaceae	9.09	1.45	0.82	1.64	9.00	3.86	6.95	0.99
Desmodium triquetrum (L.) DC.	Fabaceae	4.55	0.72	0.16	0.32	3.50	1.50	2.55	0.77
Desmodium velutinum (Willd.) DC.	Fabaceae	4.55	0.72	0.16	0.32	3.50	1.50	2.55	0.77
Ervatamia coronaria (Jacq.) Stapf	Apocynaceae	2.27	0.36	0.07	0.14	3.00	1.29	1.79	1.32
Flemingia strobilifera (L.) W.T. Aiton	Fabaceae	18.18	2.90	0.61	1.23	3.38	1.45	5.58	0.19
Helixanthera parasitica Lour.	Loranthaceae	2.27	0.36	0.05	0.09	2.00	0.86	1.31	0.88
Jatropha curcas L.	Euphorbiaceae	2.27	0.36	0.05	0.09	2.00	0.86	1.31	0.88
Lantana camara L.	Verbenaceae	50.00	7.97	6.14	12.31	12.27	5.26	25.55	0.25
Leea guineensis f. comoriensis Desc.	Leeaceae	2.27	0.36	0.02	0.05	1.00	0.43	0.84	0.44
Maesa indica (Roxb.) A. DC.	Myrsinaceae	6.82	1.09	0.11	0.23	1.67	0.71	2.03	0.24
Manihot esculenta Crantz	Euphorbiaceae	9.09	1.45	0.55	1.09	6.00	2.57	5.12	0.66
Melastoma malabathricum L.	Melastomaceae	31.82	5.07	2.36	4.74	7.43	3.19	13.00	0.23
Melocanna baccifera (Roxb.) Kurz	Poaceae	31.82	5.07	5.14	10.31	16.14	6.92	22.30	0.51
Meriandra strobilifera Benth.	Asteraceae	13.64	2.17	0.36	0.73	2.67	1.14	4.05	0.20
Mezoneuron cucullatum (Roxb.) Wight. & Arn.	Fabaceae	15.91	2.54	0.55	1.09	3.43	1.47	5.10	0.22
Microcos paniculata L.	Malvaceae	11.36	1.81	0.70	1.41	6.20	2.66	5.88	0.55
Micromelum integerrimum (Buch.-Ham. ex DC.) Wight & Arn. ex M. Roem.	Rutaceae	11.36	1.81	0.52	1.05	4.60	1.97	4.83	0.40
Mimosa himalayana Gamble	Fabaceae	4.55	0.72	0.05	0.09	1.00	0.43	1.24	0.22
Osbeckia chinensis L.	Melastomaceae	6.82	1.09	0.34	0.68	5.00	2.14	3.92	0.73
Parthenium hysterophorus L.	Asteraceae	2.27	0.36	0.16	0.32	7.00	3.00	3.68	3.08
Ricinus communis L.	Euphorbiaceae	9.09	1.45	0.18	0.36	2.00	0.86	2.67	0.22
Sarcochlamys pulcherrima Gaudich.	Urticaceae	9.09	1.45	0.25	0.50	2.75	1.18	3.13	0.30
Senna alata (L.) Roxb.	Fabaceae	11.36	1.81	0.39	0.78	3.40	1.46	4.05	0.30
Sesbania cannabina (Retz.) Pers.	Fabaceae	2.27	0.36	0.11	0.23	5.00	2.14	2.74	2.20
Solanum torvum Sw.	Solanaceae	38.64	6.16	2.18	4.38	5.65	2.42	12.96	0.15
Urena lobata L.	Malvaceae	52.27	8.33	4.98	9.99	9.52	4.08	22.40	0.18
Ziziphus oenopolia (L.) Mill.	Rhamnaceae	13.64	2.17	0.18	0.36	1.33	0.57	3.11	0.10
Total		627.27	100	49.84	100	233.11	100	300.00	31.75

Table 5. Diversity indices of tree species

Scientific name	Family	F	RF	D	RD	A	RA	IVI	A/F
Aegle marmelos (L.) Correa	Rutaceae	2.27	0.44	0.02	0.21	1.00	0.68	0.86	0.44
Alangium chinense (Lour.) Harms	Alangiaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.25	0.44
Albizia chinensis (Osbeck) Merr.	Fabaceae	11.36	2.22	0.18	1.70	1.60	1.09	4.73	0.14
Albizia lebbek (L.) Benth	Fabaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.79	0.88
Albizia procera (Roxb.) Benth	Fabaceae	29.55	5.78	0.55	5.11	1.85	1.26	13.92	0.06
Alstonia scholaris (L.) R. Br.	Apocynaceae	6.82	1.33	0.09	0.85	1.33	0.91	2.57	0.20
Anthocephalus cadamba (Roxb.) Miq.	Moraceae	4.55	0.89	0.05	0.43	1.00	0.68	4.20	0.22
Antidesma ghaesembilla Gaerth	Euphorbiaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.01	0.44
Artocarpus chaplasha Roxb.	Moraceae	4.55	0.89	0.14	1.28	3.00	2.05	3.69	0.66
Artocarpus heterophyllus Lam.	Moraceae	6.82	1.33	0.18	1.70	2.67	1.82	7.16	0.39
Artocarpus lakoocha Roxb.	Moraceae	2.27	0.44	0.07	0.64	3.00	2.05	3.68	1.32
Bombax ceiba L.	Bombacaceae	4.55	0.89	0.05	0.43	1.00	0.68	3.21	0.22
Callicarpa arborea Roxb.	Verbenaceae	20.45	4.00	0.41	3.83	2.00	1.37	10.02	0.10
Callistemon linearis (Schrad. & J.C.Wendl.) Colv. ex Sweet	Myrtaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.10	0.44
Careya arborea Roxb.	Lecythidaceae	2.27	0.44	0.02	0.21	1.00	0.68	2.07	0.44
Carica papaya L.	Cariaceae	4.55	0.89	0.05	0.43	1.00	0.68	1.69	0.22
Citrus sinensis (L.) Osbeck	Rutaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.01	0.44
Delonix regia (Hook.) Raf.	Fabaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.97	0.44
Dillenia indica L.	Dilleniaceae	2.27	0.44	0.02	0.21	1.00	0.68	2.04	0.44
Dillenia pentagyna Roxb.	Dilleniaceae	9.09	1.78	0.16	1.49	1.75	1.20	5.59	0.19
Erythrina fusca Lour.	Fabaceae	2.27	0.44	0.02	0.21	1.00	0.68	2.11	0.44
Fernandoa adenophylla (Wall. ex G.Don) Steenis	Bignoniaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.96	0.88
Ficus auriculata Lour.	Moraceae	4.55	0.89	0.07	0.64	1.50	1.02	18.03	0.33
Ficus benghalensis L.	Moraceae	2.27	0.44	0.02	0.21	1.00	0.68	1.63	0.44
Ficus hispida L.f.	Moraceae	13.64	2.67	0.18	1.70	1.33	0.91	7.66	0.10
Ficus racemose L.	Moraceae	2.27	0.44	0.02	0.21	1.00	0.68	2.76	0.44
Ficus semicordata Buch.-Ham. ex Sm.	Moraceae	6.82	1.33	0.07	0.64	1.00	0.68	3.16	0.15
Firmiana colorata (Roxb.) R.Br.	Malvaceae	13.64	2.67	0.23	2.13	1.67	1.14	6.35	0.12
Garuga pinnata Roxb.	Burseraceae	2.27	0.44	0.02	0.21	1.00	0.68	2.56	0.44
Gmelina arborea Roxb.	Lamiaceae	18.18	3.56	0.45	4.26	2.50	1.71	8.93	0.14
Grewia serrulata	Tiliaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.40	0.88
Hevea brasiliensis (Willd. ex A.Juss.) Müll.Arg.	Euphorbiaceae	2.27	0.44	0.82	7.66	36.00	24.59	8.76	15.84
Holarrhena antidysenterica (L.) Wall.	Apocynaceae	13.64	2.67	0.25	2.34	1.83	1.25	6.29	0.13
Jatropha curcas L.	Euphorbiaceae	2.27	0.44	0.09	0.85	4.00	2.73	1.55	1.76
Lagerstroemia microcarpa Wight	Lythraceae	2.27	0.44	0.02	0.21	1.00	0.68	1.41	0.44
Lagerstroemia parviflora Roxb.	Lythraceae	40.91	8.00	1.34	12.55	3.28	2.24	21.90	0.08
Lannea coromandelica (Houtt.) Merr.	Anacardiaceae	4.55	0.89	0.05	0.43	1.00	0.68	3.46	0.22
Macaranga denticulata (Blume) Mull.Arg.	Euphorbiaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.33	0.88
Macaranga peltata (Roxb.) Mull.Arg.	Euphorbiaceae	20.45	4.00	0.32	2.98	1.56	1.06	7.55	0.08
Mallotus tetracoccus (Roxb.) Kurz	Euphorbiaceae	6.82	1.33	0.09	0.85	1.33	0.91	2.99	0.20
Mangifera indica L.	Anacardiaceae	6.82	1.33	0.16	1.49	2.33	1.59	3.94	0.34
Microcos paniculata L.	Malvaceae	2.27	0.44	0.07	0.64	3.00	2.05	1.79	1.32

Cont...

Table 5. Diversity indices of tree species

Scientific name	Family	F	RF	D	RD	A	RA	IVI	A/F
Mitragyna tubulosa (Arn.) Kuntze	Rubiaceae	20.45	4.00	0.34	3.19	1.67	1.14	7.53	0.08
Oroxylum indicum (L.) Kurz	Bignoniaceae	11.36	2.22	0.14	1.28	1.20	0.82	4.07	0.11
Parkia speciosa Hassk.	Fabaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.28	0.88
Phyllanthus emblica L.	Phyllanthaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.38	0.88
Protium serratum (Wall. ex Colebr.) Engl.	Burseraceae	2.27	0.44	0.09	0.85	4.00	2.73	2.68	1.76
Psidium guajava L.	Myrtaceae	2.27	0.44	0.02	0.21	1.00	0.68	2.25	0.44
Pterospermum acerifolium (L.) Willd	Malvaceae	2.27	0.44	0.09	0.85	4.00	2.73	2.51	1.76
Sapium baccatum Roxb.	Euphorbiaceae	11.36	2.22	0.11	1.06	1.00	0.68	3.97	0.09
Securinega virosa (Roxb. ex Willd.) Baill.	Euphorbiaceae	2.27	0.44	0.05	0.43	2.00	1.37	1.46	0.88
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	11.36	2.22	0.27	2.55	2.40	1.64	5.81	0.21
Sterculia villosa Roxb.	Malvaceae	20.45	4.00	0.34	3.19	1.67	1.14	8.97	0.08
Stereospermum personatum (Hassk.) Chatterjee	Bignoniaceae	20.45	4.00	0.43	4.04	2.11	1.44	10.54	0.10
Streblus asper Lour.	Moraceae	2.27	0.44	0.02	0.21	1.00	0.68	0.99	0.44
Syzygium cumini (L.) Skeels	Myrtaceae	13.64	2.67	0.23	2.13	1.67	1.14	6.69	0.12
Tamarindus indica L.	Fabaceae	4.55	0.89	0.07	0.64	1.50	1.02	6.98	0.33
Tectona grandis L.f.	Lamiaceae	15.91	3.11	0.86	8.09	5.43	3.71	12.98	0.34
Terminalia bellirica (Gaertn.) Roxb.	Combretaceae	13.64	2.67	0.14	1.28	1.00	0.68	5.96	0.07
Toona ciliata M.Roem.	Meliaceae	13.64	2.67	0.20	1.91	1.50	1.02	6.32	0.11
Trema orientalis (L.) Blume	Cannabaceae	13.64	2.67	0.27	2.55	2.00	1.37	5.88	0.15
Trevesia palmata (Roxb. ex Lindl.) Vis.	Araliaceae	2.27	0.44	0.02	0.21	1.00	0.68	1.01	0.44
Vitex altissima L.f.	Verbenaceae	15.91	3.11	0.23	2.13	1.43	0.98	6.65	0.09
Ziziphus jujuba Mill.	Rhamnaceae	6.82	1.33	0.09	0.85	1.33	0.91	2.99	0.20
Total		511.36	100	10.68	100	146.43	100	300	43.32

F=Frequency, RF=Relative frequency, D=Density, RD=Relative Density, A=Abundance, RA=Relative Abundance, IVI=Important Value Index, A/F= Abundance to Frequency ratio

contributing substantially to overall vegetation heterogeneity. Shrubs exhibit intermediate diversity with signs of species dominance, while the tree layer is the least diverse and most dominated. This structure reflects ecological conditions that favour herbaceous species richness and suggests varying levels of disturbance, succession, or competitive interactions across vegetation strata in the study area.

Vegetation dynamics: The comprehensive study of the forest understory, shrub layer, and canopy revealed distinct patterns in biodiversity and species dominance across different life forms. In total, the study documented 4,665 individual herbs, 2,193 shrubs, and 470 trees, highlighting the complex, multi-layered nature of the ecosystem. For the herbaceous layer, the Asteraceae family was the most species-rich, while Poaceae dominated in terms of individual count. This dichotomy between species diversity and numerical dominance is a common ecological pattern. The grass *Imperata cylindrica* exhibited the highest Importance Value Index (IVI) (17.24), confirming its significant influence on the community structure. As noted by Sharma et al. (2023), higher IVI values indicate broad ecological amplitude and adaptability, suggesting *I. cylindrica* is well-suited to the local conditions and plays a foundational role. Within the shrub community, 45 species across 20 families were identified. The invasive species *Chromolaena odorata* showed remarkable dominance, leading in frequency, density, and IVI (42.48). This high IVI suggests *C. odorata* has strong regeneration capability and a significant competitive advantage over native species, a typical behavior for successful invasive plants which often form dense thickets. Tree layers identified 64 species from 26 families. Moraceae had the highest species richness, while Euphorbiaceae recorded the most individuals. *Lagerstroemia parviflora* had the highest IVI. A specific observation highlighted the distinct abundance of *Hevea brasiliensis* (rubber tree), attributed to its monocultured status within parts of the study area. This finding illustrates how anthropogenic activities, such as establishing monocultures, can dramatically alter natural community composition and abundance patterns, influencing overall

forest structure and function. The vegetation in this area has a contiguous distribution. Regular and random distributions were not observed in this study. The dominance of contiguous distribution may be because most species reproduce vegetatively in addition to their normal seed/spore production. In natural conditions, contagious distribution is the most common (Singh et al., 2016). The reason for the higher number of species could be the availability of soil moisture and other environmental factors present in this area due to more vegetation cover higher forest density promotes higher species diversity (Yaqoob et al., 2014). Overall, the data demonstrates that dominant species, identified through high IVI values, dictate the social standing and structure of their respective communities, reflecting a mix of natural adaptability (*I. cylindrica*, *L. parviflora*) and human influence (*H. brasiliensis* monoculture, invasive *C. odorata*).

Table 6. Frequency, density, abundance, IVI, and distribution pattern of different life form (Mean±SE)

Parameters studied	Herb	Shrub	Tree
Frequency	10.55±0.919	13.94±2.430	7.99±0.979
Density	0.95±0.146	1.11±0.332	0.17±0.029
Abundance	7.78±0.597	5.18±0.638	2.29±0.547
Important Value Index	2.68±0.245	6.67±1.232	4.69±0.644
Distribution pattern	1.34±0.129	0.71±0.124	0.68±0.246

Biodiversity in HEP sites: The high diversity index indicates a forest with high species diversity, abundance, and richness (Adekunle et al., 2013, Naidu and Kumar 2016). In the present study, the Simpson dominance index for herbs, shrubs, and trees fell within the range of 0.61 to 0.96, which is higher than the value obtained in previous studies (Singh et al., 2011). Similarly, the Shannon diversity index for Herbs, Shrubs and Trees was found to be within the range of 1.01 and 3.47, which falls in the range of typical Indian forests (Singh et al., 2011, Shahid and Joshi 2016, Sharma et al., 2023) and is less than the index value of the Pachamalai Reserve Forest (Kanagaraj et al., 2017) and tropical forests in Eastern Ghat, Andhra Pradesh (Naidu and Kumar 2016). However, the value of Shannon diversity can be higher in high-altitude regions such

Table 7. Diversity indices of herb, shrub and tree of adjoining areas of Dumbur HEP

Transect	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	Average
Herb												
Taxa (S)	25	19	11	17	34	32	31	46	43	31	50	30.82
Individuals	652	549	354	341	307	386	208	465	441	466	395	414.91
Dominance (D)	0.08	0.11	0.15	0.18	0.07	0.05	0.05	0.07	0.05	0.04	0.05	0.08
Simpson (1-D)	0.92	0.89	0.85	0.82	0.93	0.95	0.95	0.93	0.95	0.96	0.95	0.92
Shannon (H)	2.81	2.51	2.09	2.19	3.09	3.20	3.13	3.31	3.35	3.27	3.47	2.95
Evenness e^H/S	0.66	0.65	0.74	0.53	0.65	0.76	0.74	0.60	0.66	0.85	0.64	0.68
Margalef index	3.70	2.85	1.70	2.74	5.76	5.21	5.62	7.33	6.90	4.88	8.20	4.99
Shrub												
Taxa (S)	7	9	5	9	8	18	18	27	23	30	22	16
Individuals	152	223	252	171	156	132	162	224	235	220	266	199.36
Dominance (D)	0.18	0.23	0.31	0.22	0.21	0.15	0.14	0.10	0.10	0.10	0.12	0.17
Simpson (1-D)	0.82	0.77	0.69	0.78	0.79	0.85	0.86	0.90	0.91	0.90	0.88	0.83
Shannon (H)	1.81	1.68	1.34	1.85	1.75	2.29	2.32	2.64	2.67	2.84	2.44	2.15
Evenness e^H/S	0.87	0.60	0.76	0.71	0.72	0.55	0.56	0.52	0.62	0.57	0.52	0.64
Margalef index	1.19	1.48	0.72	1.56	1.39	3.48	3.34	4.80	4.03	5.38	3.76	2.83
Tree												
Taxa (S)	3	15	4	14	17	15	10	22	21	15	15	13.73
Individuals	12	73	11	34	58	53	46	44	49	43	47	42.73
Dominance (D)	0.39	0.27	0.26	0.10	0.12	0.24	0.36	0.06	0.07	0.11	0.12	0.19
Simpson (1-D)	0.61	0.73	0.74	0.90	0.88	0.76	0.64	0.94	0.93	0.89	0.88	0.81
Shannon (H)	1.01	1.93	1.37	2.44	2.44	2.03	1.49	2.97	2.81	2.45	2.38	2.12
Evenness e^H/S	0.92	0.46	0.99	0.82	0.68	0.51	0.45	0.88	0.79	0.77	0.72	0.73
Margalef index	0.80	3.26	1.25	3.69	3.94	3.53	2.35	5.55	5.14	3.72	3.64	3.35

T1, T2, T3……T11 represent locations of the study areas as mentioned in Table 1

as the Indian Eastern Himalayas (Sharma et al., 2019). The evenness of all Herbs, Shrubs and Trees in this study ranges from 0.45 0.99. Other authors have also found evenness within the range of the present study (Shahid and Joshi 2016). The average value of the Margalef index in the present study was 3.72, ranging from 0.80 to 8.2, which is slightly lower than the range of values for tropical forests reported by previous researchers (Kumar et al., 2010, Singh et al., 2011, Naidu and Kumar 2016). Plant species richness can influence the physical structure. Hence, it is helpful in determining plant community structure and a critical indicator of the microclimatic conditions in an area (Schuldt et al., 2019).

The vegetation of the study area is vital for sustaining the livelihoods of the local people, as most of the surrounding communities are forest-dwelling communities (Naidu and Kumar 2016). It is interesting to note that almost a thousand planned HEPs have been proposed in areas of biodiversity importance that are characterized by the presence of high endemics and threatened biodiversity. Post-project areas may show lower biodiversity due to the impacts of inundation, compaction, trampling, etc., and the creation of artificial lakes due to hydel-power projects may cause inundation of farming land, resulting in forest biodiversity loss. Moreover, creating a reservoir can cause the loss of terrestrial species due to habitat loss, which may persist until the final life of the HEP. opined that reservoir-based hydropower projects contradicts the United Nations' SDG 6 on Clean Water and SDG 15 on Life on Land, as such projects have often been linked with negative impacts on biodiversity. Urgent action must be taken by all stakeholders to perpetually obtain ecosystem services and conserve existing biodiversity without harming the local ecosystem. Furthermore, if the Dumber HEP is halted because of low energy generation, there would be many issues, ranging from resettlement, compensation, and livelihood, which can only be achieved through nature-based solutions for alternative livelihood activities (Panmei and Selvan 2024). The underlying values within a society can be represented through scenarios and require further research and broader discourse for a par-excellence scenario suitable for communities in the Dumbur HEP area. CBD regulations can protect access to bioresources. In the Local Biodiversity Outlooks 2, several studies on 'Biodiversity, climate change and sustainable development,' 'Transition towards living in harmony with nature,' and the 2050 vision for 'Nature and culture transitions' can be applied to the socio-economically weaker indigenous peoples in the Dumber HEP. The key messages in the document mentioned above pointed out that Aichi Biodiversity Target 18 of the Strategic Plan for Biodiversity 2011-2020, pertaining to traditional knowledge and customary sustainable use of biodiversity, has not been realized, and there is continued dismissal of the vital contributions of indigenous peoples to biodiversity conservation and sustainable use.

CONCLUSION

The present study revealed that the vegetation of the area is contagiously distributed, thereby indicating that the area is regenerated almost entirely through natural means. The present status of biodiversity in the area suggests that the future scenario is favourable when working together with communities for their livelihood and government-assisted community-based conservation. Hence, the outcome of this study calls for an urgent conservation initiative to conserve biological diversity, while ensuring food security, livelihood, and sustainable development.

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Effect of Altruistic Surrogacy of Treefall on Herbaceous Flora Colonisation in Subalpine Forest of Khangchendzonga Biosphere Reserve, Eastern Himalaya, Sikkim, India

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***Abstract*:** The present study represents the herb species' colonisation on the fallen trees in the subalpine forests in the Khangchendzonga National Park (KNP) West Sikkim, Eastern Himalayas. Around 5 per cent of the forest floor was taken up by fallen logs in various stages of decomposition. The study indicated that there must be no less than 13.50 trees with a diameter of at least 50 cm per 0.25 ha for successful colonization. Seedlings of herbaceous species differed in their probabilities of colonising under fallen logs, pits, and mounds but colonization of most species was substratum-specific. Several species generally colonised on pits, mounds, and logs. Pit colonisation by seedlings appeared to be larger in numbers than on logs and mounds. Most colonisation appeared to be local, from plants within 1 m of the log or pit. Summer species appeared to be superior colonisers and then spring-ephemeral species. Overall, plants with wind-dispersed seeds predominated in the colonisation of pits, and logs. The finding indicates that inclusion of other colonisation sites such as pits, mounds, and tree stumps would further favour the altruistic surrogacy of available colonisation areas. The existence of seasonal herbaceous species may be an indicator of the survival mechanisms of plant species to cope with changing climatic conditions and provide insights into how the species interact with their environment.

***Keywords*:** Colonisation, Eastern Himalayas, Khangchendzonga Biosphere Reserve

The Khangchendzonga National Park (KNP) part of the Khangchendzonga Biosphere Reserve (KBR) inscribed to the UNESCO World Heritage site list becoming the first “Mixed heritage site” of India. The region harbors a wealth of biodiversity within its pristine forests and alpine meadows, comprising a wide variety of plant and animal species, many of which are endemic to this locale (Chettri and Sharma 2006). This region exhibits a complex climate with bioclimatic zones ranging from near-tropical to alpine, including subtropical, warm temperate, cold temperate, subalpine, and alpine regions (Kanade and John 2018, Bhutia et al., 2024). Silver fir and Rhododendron trees (*Abies densa* & *Rhododendron* Spp.) are concomitant dominant feature of the subalpine forest of Khangchendzonga Biosphere Reserve in Eastern Himalaya. In these forests, diverse mixtures of *Rhododendron* species are frequently encountered as companion species. In the undisturbed stands, it has been estimated that the frequency of *Rhododendron* spp. would be around 12 to16 individuals in a 10 m x 10 m quadrat. *Abies densa* Griffith ex R. Parker, frequency is low compared to *Rhododendron* species but has higher basal coverage. Lower *Abies* tree-species frequency further reduces complexity in the region, increasing the capacity to understand the role of windthrow across the landscape.

The Himalayan forests are suffering from severe climatic and anthropogenic disturbances (Mittal et al., 2021). These subalpine forests are influenced by many disturbance factors, including fire, wind throw, drought, avalanches, and anthropogenic activities. Various agents of disturbance operate at different temporal and spatial scales, ranging from large-scale disturbances to perturbations affecting individual trees or small groups of trees. To maintain biodiversity, forest management must try to understand the role of natural disturbances in a given ecosystem. In silver fir and *Rhododendron* spp. dominated ecosystems, along with forest fire and other disturbances in pine forests are harmful to the ecosystem (Bhardwaj et al., 2009). Tree falls are a major consequence of windthrow in forests. However, windthrow could also play an important role in silver fir ecosystems (Ruel and Benoit 1999, Leblanc and Belanger 2000) but its general significance has not been quantified. It can occur as a consequence of unusually strong winds (Ruel and Benoit 1999), or by root rots (Whitney 1995). Uprooting exposes mineral soil and creates mixtures of organic and mineral soil (Ulanova 2000) that can be beneficial for seedling establishment. In addition, the fallen trees can become suitable seedbeds for conifer regeneration when they reach an adequate state of decay. However, in such forests as an important component in forests, knowledge of community structure and species diversity for understory herbaceous communities remains scarce (Wang et al., 2021).

Disturbances caused by wind occur in all forested

regions, ranging from a single tree's snap-off to uprooting trees over hundreds of hectares. Following a wind event, a dynamic interplay sets up between ecosystem legacies (e.g., surviving trees, deadwood, pit-and mound complexes) and altered environmental conditions (e.g., light, temperature, soil, water regime) while forests are susceptible to subsequent disturbances (Buma 2015, Palm et al., 2024). By mixing upper and lower horizons and creating mound-pit topography, windthrow has important effects on the heterogeneity of soil and the recruitment of plant species (Small et al., 2002). The pit and mound microtopography created by windthrow is a common feature in the subalpine forest.

Many plants respond to windthrow because of increased light and moisture. Ulanova (2000) observed that microsite creation by windthrow may play an important role in the regeneration process of boreal forests where the forest floor is covered by a thick carpet of moss. It influences litter accumulation, water and temperature regimes and could even affect herbivory patterns. Even small-scale disturbance can create regeneration microsites for seed germination and seedling growth. Herbaceous biomass was inversely related to the regeneration aspect, a pattern that seems largely due to reduced nutrients and invasion under closed canopies. This may be due to the relatively open canopy of forests, which allows for extensive growth (Dhakal et al.,2022). However, the extent to which such sites are available in forests and the relative degree to which plant species can colonies these sites are mostly unknown in the subalpine forests of the Eastern Himalaya. Present study addresses questions concerning windthrow and the pattern of herbaceous colonisation in the upper montane forests including colonisation sites in the form of treefalls and probability of summer herb and spring herb colonization related to dispersal types of species.

MATERIAL AND METHODS

Study sites: The KBR, situated in the mountainous regions of India-specifically in the Himalayas-exhibits elevation-associated species richness and diversity patterns (Parker et al., 2015). KBR named after well-known Mt. Khangchendzonga, (8586 meters tall) the third highest peak in the World lies in this region. The KBR lies in between 27º25′ and 22 º55′ N latitudes and 88 º03′ to 88 º38′ E longitudes encompassing one core zone (1784km^2) and buffer zones (835.9 km^2), with total area of 2619.9 km^2(Chettri et al., 2006). The three study areas were located at Phedi-Dungdang in Khangchendzonga Biosphere Reserve, Sikkim in Eastern Himalayas in a 100 ha reserve of old-growth *Abies* (silver fir) *Rhododendron* forests (Chettri et al., 2010). The geocoridinates of the three selected study sites *i.e.*, Dungdang, Lhasosa, and Bikhbari are 22°23′763″ N 88°04′919″ E, 22°23′358″ N 88°05′535″ E and 22°23′715″ N 88°04′695″ E, respectively. The three study areas were at least 1000 m apart. It is in the subalpine region at an elevation of 3000-3500 MSL. Important tree species at study sites are *Abies densa* Griffith ex Parker, *Buddleia colvilei* Thom., *Rhododendron* spp., and *Tsuga dumosa* Eichler, with a maximum canopy height of about 22 m.

Forests covered under the study area are undisturbed primary forests, approachable only by trekking 10 - 20 km distance from the nearest road. The climate of the study area is monsoonal and because of its proximity to the Bay of Bengal with very high rainfall. Three seasons are distinguishable in a year: winter (October-March), summer (March-May) and monsoon (June-September). The average annual rainfall ranges from 3500 to 400 mm, and the annual mean minimum and maximum temperatures of sub-zero in sunb-alpine and alpine areas; and 12 ºC and 16.9 ºC in temperate areas of the BR (Chettri et al., 2006). Since the State is the most humid region in the whole range of Himalayas the Biosphere also experiences a wide range of humidity which may be from 70% in the month of December to 92% in July, the annual means being around 82% (ENVIS). The soils are loose with 50-60% sand and acidic in nature (pH varies from 4.93 to 5.41). The organic carbon, nitrogen, and phosphorus contents of soils are fairly good (Singh and Sundriyal 2005). In each study area, the coverage of fallen trees on the forest floor was calculated by examining five plots per site measuring 50 meters by 50 meters. Each of the three study areas contains a fixed grid, and random sample plots were selected within each grid. The measurement of all fallen logs in each plot, ensuring that only those with a minimum diameter of 50 cm at the midpoint were included in our calculations. Logs lying horizontally on the ground were included; logs partly down but leaning against another tree were excluded. Furthermore, logs that have fallen and are now level with the ground but still visible were omitted.

Colonisation: In June 2020, a thorough examination was conducted on the colonisation of logs, pits, and mounds for summer herbs. In addition to that, in April 2021, a comprehensive study was carried out on the colonisation of these areas by spring herbs (Fig. 1).

The spring herbs are those that appear aboveground in early spring and flower mostly in March, April and May. During the monsoon season, a variety of summer herbs make their appearance. For all the groups, 150 logs, 150 pits and 150 mounds (70 in Dungdang, 40 in Lhasosha and 40 in Bikhbari) were randomly chosen along transects in each study area. The same tree was not sampled for the study of

the colonisation of logs, pits and mounds. All herbaceous species within 1 m of the edge of the log or pit were recorded to determine the availability of potential colonists nearby. Species were recorded if the individuals had overcome the cotyledon stage. For the colonisation of logs, individuals were recorded if rooted within the log itself. Colonisation of pits was divided into the far slope, the near slope and the centre. The far slope included all the slope of the pit excluding that at the base of the tree itself. The near slope, then, was just below the root mass at the base of the tree. The centre was the deepest area of the pit. For the colonisation of mounds, individuals were recorded if rooted in the exposed portion of the mound and colonisation of the upper portion of the mound was not considered because it may often contain a mosaic of buried old seed pools. The purpose of these divisions was to determine if these sites were differently colonised by plant species.

Statistical analysis: For statistical analysis, nonmetric multidimensional scaling (NMDS; Kruskal 1964), Community Analysis Package, version 4.1.3 (PISCES Conservation Ltd. 2007), Community Analysis Package, version 4.1.3 (PISCES Conservation Ltd. 2007) was used. Bray–Curtis similarity based on the species-specific abundance was used as a distance metric for NMDS and ANOSIM. Non-parametric Permutational Multivariate Analysis of Variance (PERMANOVA) post hoc test using Bray-Curtis dissimilarity is performed with the function of the "vegan" library.

RESULTS AND DISCUSSION

Treefalls: The mean percentage of the forest floor under fallen logs was 5.1 per cent. The sample areas averaged 13.5 logs of ≥ 50 cm diameter per 0.25 ha and were similar for all three study areas (Table 1). Not all logs included had a humus build-up on the surface that could support herbs at present. Inclusions of other colonisation sites such as pits, mounds and tree stumps would further increase the estimate of available colonisation areas.

Colonisation: The mean number of species recorded at a log, pit or mound were similar for all three study areas in both spring and summer, although the Bikhbari study area had a lower mean number of species in spring (Table 2). Logs were generally colonised by several species, averaging about two species from the summer flora and one species from the spring flora. As a group, the summer herbs were better colonisers of logs than the spring herbs, with a large majority of species found near the edge of a log colonising the logs.

However, even in spring flora, an average of 36-40% of the species at a site managed to colonise the log. Only a small percentage (0-18%) of the species found on the logs did not occur within 1 m of the logs. Therefore, colonisation appeared to be primarily from the nearby herbaceous contingent. The general pattern for the colonisation of pits and mounds was similar (Tables 3, 4). The percentage of species colonising pits and mounds during summer was also somewhat higher than the percentage colonising logs. The higher percentage of the summer flora than of spring flora

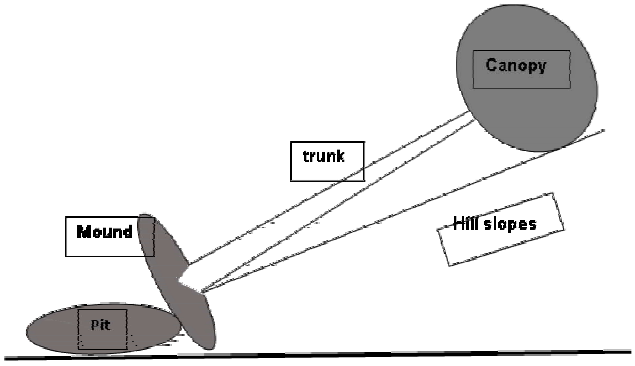

Fig. 1. Characteristics features of tree fall and demarcation of pit, mound and trunk for the sampling of herbaceous flora

Table 1. Percentage of forest floor area in fallen logs (Mean ± SD)

Study areas	Forest floor percentage under fallen logs	No. logs
Dungdang	6.60 ± 1.69	16.00 ± 2.73
Lhasosha	4.50 ± 1.25	12.80 ± 2.28
Bikhbari	4.10 ± 0.75	11.80 ± 1.78
Mean	5.10 ± 1.65	13.50 ± 2.28

Table 2. Number of species on a log and overall probability for colonisation of logs by spring and summer herbs (Mean ± SD)

Species colonisation	Season	Dungdang	Lhasosha	Bikhbari
Mean no. of spp. per site (edge and on a log)	Spring	2.90 ± 1.19	2.70 ± 0.99	2.00 ± 1.08
	Summer	4.30 ± 1.66	3.40 ± 1.53	3.30 ± 1.46
Mean no. of species on the log	Spring	1.20 ± 0.91	1.00 ± 0.78	1.00 ± 0.78
	Summer	2.70 ± 1.24	2.30 ± 1.12	1.90 ± 1.07
Per cent spp. on log edge	Spring	40.00 ± 1.12	40.10 ± 1.17	36.60 ± 1.83

Edge refers to the area of forest floor within 1 m periphery of the fallen log

colonised the pits from distances > 1 m (33-37 vs. 27-30%). The percentage of summer flora on an exposed surface of the mound was also higher than the percentage colonising during spring (47-51 vs. 41-48%).

Individual species varied greatly in their frequency of occurrence at sites and in their probability of colonising either logs or pits (Table 5, 6). Spring ephemeral species, such as *Juncus grisebachii* and summer species such as fern were highly successful in colonising the logs. In contrast, *Abies* and *Rhododendron* seedlings were much more successful at colonising pits than logs. This applies, however, to the percentage of pits and logs colonised and not the abundance of individuals, which were not analyzed in this study. The probability of colonising a pit or log from a distance > 1 m was highest in some of the summer species. However, plants of this group had no single, specific type of seed. Out of 14 species under 17 genera encountered in pits and logs but not within the surrounding 1 m of the forest floor, *Poa annua*, *Polygonum tortuosum*, and *Polygonum polystachya* have hooks which may have attached to fur or feathers; *Hemiphragma heterophyllum* have fleshy fruits ingested by birds or mammals; *Selinum* spp., have ballistic mechanism; *Rhododendron* seeds have no obvious mechanism for dispersal in space but the minute seeds probably remain viable in the soil over longer periods, hence, disperse in time. *Abies* seeds have wings and are dispersed by wind to new microsites like exposed mounds and pits. As a group, wind-dispersed seeds tended to predominate in the colonisation of pits and logs from > 1 m.

Colonisation from distances > 1 m was not uncommon, especially in the summer species. In the summer species, colonisation from > 1 m accounted for 44.4% of the occurrences of species in logs and 62.3% of the occurrences on pits; in the spring species and this colonisation accounted for 53.3% on logs and 54.5% in pits. Thus, species that were not necessarily established in the nearby neighbourhood in the recent past are accumulated by treefalls and the holes that accompany them.

Species association and significance testing: The clear separation of the communities along the first two axes, indicates that NMDS produced a two-dimensional solution (stress = 0.10) with three plant associations that could be clearly recognized (Fig. 2). The NMDS revealed significant variation in substrate types, with some species groups having a stronger association with particular habitat types than others. Closely spaced plots suggest that their species compositions are comparable. There is a constant fluctuation in species composition among substrates, as seen by the species distribution in ordination space. The seedling of *Abies* and *Rhododendron* that are grouped at the right side of the biplot are substrate specific and show better colonisation for pits and mound habitat. A substantial compositional difference between communities is described by the *post hoc* PERMANOVA.

The projected result of increasing spatial heterogeneity is the formation of mixed stands of *Rhododendron* and *Abies* following windthrow. Pandey et al. (2018) conducted a study

Table 3. Number of species in pits and overall probability for colonisation of pits by spring and summer herbs (Mean ± SD)

Species colonisation	Season	Dungdang	Lhasosha	Bikhbari
Mean no. of spp. per site (edge and on pit)	Spring	3.60 ± 1.05	3.70 ± 0.95	3.40 ± 0.91
	Summer	4.30 ± 1.59	4.90 ± 1.25	3.70 ± 1.22
Mean no. of species on pit	Spring	2.20 ± 0.77	2.30 ± 0.71	2.02 ± 0.71
	Summer	2.70 ± 1.07	2.90 ± 0.92	2.60 ± 0.98
Per cent spp. on edge also on pit	Spring	45.60 ± 3.12	48.40 ± 3.34	47.90 ± 3.06
	Summer	54.40 ± 2.91	51.60 ± 3.71	52.10 ± 3.31
Per cent species on pit only	Spring	27.50 ± 3.31	30.70 ± 4.96	28.900 ± 4.12
	Summer	33.90 ± 3.15	37.90 ± 3.94	37.5 ± 3.35

Table 4. Number of species on the exposed portion of mounds and overall probability for colonisation of mounds by spring and summer herbs (Mean ± SD)

Species colonisation	Season	Dungdang	Lhasosha	Bikhbari
Mean no. of species on the mound	Spring	2.40 ± 0.96	2.00 ± 0.92	2.00 ± 0.94
	Summer	2.50 ± 1.14	2.20 ± 1.03	1.90 ± 1.13
Per cent species on the mound only	Spring	46.30 ± 4.33	41.90 ± 4.10	48.20 ± 3.82
	Summer	47.10 ± 3.82	47.80 ± 3.90	51.90 ± 3.35

on timberline structure and woody taxa regeneration towards tree line along atitudinal gradients in Khangchendzonga National Park, Sikkim and revealed that humus, elevation and slope. The predominant species of the herb, small tree and shrub genera varies with the effect of microclimatic conditions (Moran et al., 2023). The forest floor was rapidly colonised by the typical plant life that develops on fallen trees, pits, and mounds. It can be accomplished through *Rhododendron* and *Abies* species seedling establishment or vegetative growth. When tree falls, pits and mounds are formed, the tree's root system may weaken and eventually collapse, exposing mineral soils. The growth of seedlings got more favourable conditions in shallow pits formed by uprooted silver fir *(Abies densa)* than in deeper pits as per the

Table 5. Probabilities for colonisation of logs by spring and summer herbs

Taxon	species letter codes	Dispersal of seeds	N_e	% N_e on log	% N_{max} on log only
Spring					
Cirsium falconeri (Hook. F.) Petr.	Cfal	Hooks/burs	132	12.0	0.0
Elsholtzia flava Benth.	Efla	Insects	134	10.7	4.4
Fragaria daltoniana J. Gay	Fves	Birds	129	14.0	0.0
Gaultheria trichophylla Royle	Gtri	Wind	137	08.7	3.6
Hemiphragma heterophyllum Wall.	Hhet	Birds	118	21.3	8.8
Juncus grisebachii Buchenau	Jgri	Water	143	04.7	1.9
Megacodon stylophorus (Clarke) Sm.	Msty	Wind	137	08.7	0.0
Panax bipinnatifidus Seem.	Pbip	Birds	136	09.3	0.0
Panax sikkimensis R. N. Banerjee	Psik	Birds	130	13.3	0.0
Parsenecio quinquelobus (Wall. ex D.C.) Y.L. Chen	Pqui	Wind	123	18.0	0.0
Polygonum tortuosum D. Don	Ptor	Hooks/burs	104	30.7	12.6
Primula calderiana Balf. f. & R.E. Cooper	Pcal	Water	113	24.7	0.0
Saxifraga spp.	Sax	Water	123	18.0	0.0
Senecio raphanifolius Wall. Ex. DC.	Srap	Wind	110	26.7	0.0
Stellaria sikkimensis Hook. f.	Ssik	Water	116	22.7	9.3
Summer					
Anaphalis margaritacea (L.) Benth. & Hook. f.	Amar	Wind	121	19.3	0.0
Anaphalis triplinervis (Sims) C.B. Clarke	Atri	Wind	103	31.3	0.0
Buplerum longifolium L.	Blon	Ballistic	122	18.7	0.0
Chrysanthemum atkinsonii C. B. Clarke	Catk	Wind	121	19.3	0.0
Clintonia udensis Trautv. & C.A. Mey.	Cude	Ant	131	12.7	0.0
Cremanthodium reniforme (DC.) Benth.	Cren	Wind	117	22.0	0.0
Dubyaea hispida DC.	Dhis	Wind	128	14.7	0.0
Fern spp.	Fspp	Wind	140	06.7	1.8
Gaultheria pyroloides Hook. f. &Thom. Ex Miq.	Gpyr	Wind	103	31.3	8.3
Halenia elliptica D. Don	Hell	Wind	130	13.3	3.5
Juncus clarkei Buchenau	Jclar	Water	131	12.7	3.4
Juncus khasiensis Buchenau	Jkha	Water	134	10.7	2.8
Ligularia fischeri (Ledeb.) Turcz.	Lfis	Wind	128	14.7	0.0
Pilea spp.	Pspp	Ant	101	32.7	8.7
Poa annua L.	Pann	Hooks/burs	121	19.3	5.1
Polygonum polystachya T.M. Schust. & Reveal	Ppol	Hooks/burs	107	28.7	7.6
Potentilla peduncularis D. Don	Pped	Wind	104	30.7	8.1
Selinum spp.	Sspp	Ballistic	93	38.0	10.1

N_e = number of sites in which the species occurred on the soil surface within 1 m of the edge of a log; N_{max} = 150 sites

report of Vodde et al. (2010). The dispersal of seeds to these sites results partly from the relationships between treefalls and wind that act as dispersal agents of the forest herbs. one-third of the plant species that colonised logs and pits are wind-dispersed. The study area is affected by strong wind currents. Due to the direction of the wind, seeds that are dispersed by the wind would end up in fallen logs, pits, and mounds Wind direction, and its variability, is important for determining the area over which seeds are dispersed (Augspurger 2024). Medium-sized gaps were the most suitable for seed germination and radicle growth as they promote the regeneration of endangered species in the natural forest (Zhu et al., 2021). In light gaps, fallen logs are a common landing spot for plant seeds such as *Primula calderiana, Juncus* spp., and *Stellaria sikkimensis*. The rain from hill slopes often washes these logs down, leading to the accumulation of seeds. A key factor in the evolution of dispersal methods among the herbs of the upper montane forest is the orientation of animal-dispersed seeds toward possible colonisation sites, such as treefalls. For these forests to thrive, animal-dispersed seeds must be able to discern parent plants and locate optimal areas for growth and development. The ant-dispersal is a strategic advantage as it facilitates relocation to a secure germination site. Although fallen logs may only cover 5% of the forest floor in the study areas, their impact on the total area available for seed colonisation cannot be overlooked. This percentage could still have significant consequences that demand attention. The disturbance of soil caused by windthrow creates a suitable environment for the growth and maturation of silver fir and *Rhododendron* species by exposing mineral soils or a mixture of organic minerals favourable for germination and survival. This may be just one of the mechanisms involved (Ruel and Pineau 2002). Out of every species that was found,

Table 6. Probabilities for colonisation of pits by spring and summer herbs

Taxon	Dispersal type	N_e	% N_e on pit	% N_{max} on pit only
Spring				
Abies seedling	Wind	129	86.0	24.0
Fragaria vesca	Birds	29	19.3	0.0
Gaultheria trichophylla	Wind	31	20.7	5.8
Hemiphragma heterophyllum	Birds	35	23.3	6.5
Panax bipinnatifidus	Birds	8	5.3	0.0
Panax sikkimensis	Birds	28	18.7	0.0
Polygonum tortuosum	Hooks/burs	51	34.0	0.0
Primula calderiana	Water	45	30.0	0.0
Rhododendron seedling	Wind	104	69.3	19.3
Senecio raphanifolius	Wind	49	32.7	0.0
Stellaria sikkimensis	Water	29	19.3	5.4
Summer				
Abies seedling	Wind	130	86.7	21.6
Anaphalis margaritacea	Wind	19	12.7	0.0
Anaphalis triplinervis	Wind	21	14.0	0.0
Buplerum longifolium	Ballistic	21	14.0	0.0
Chrysanthemum atkinsonii	Wind	35	23.3	0.0
Clintonia udensis	Ant	26	17.3	0.0
Cremanthodium reniforme	Wind	30	20.0	0.0
Dubyaea hispida	Wind	19	12.7	0.0
Ligularia fischeri	Wind	22	14.7	0.0
Pilea spp.	Ant	57	38.0	9.5
Polygonum polystachya	Hooks/burs	47	31.3	7.8
Rhododendron seedling	Wind	114	76.0	18.9
Selinum spp.	Ballistic	61	40.7	10.1

See Table 5 for details

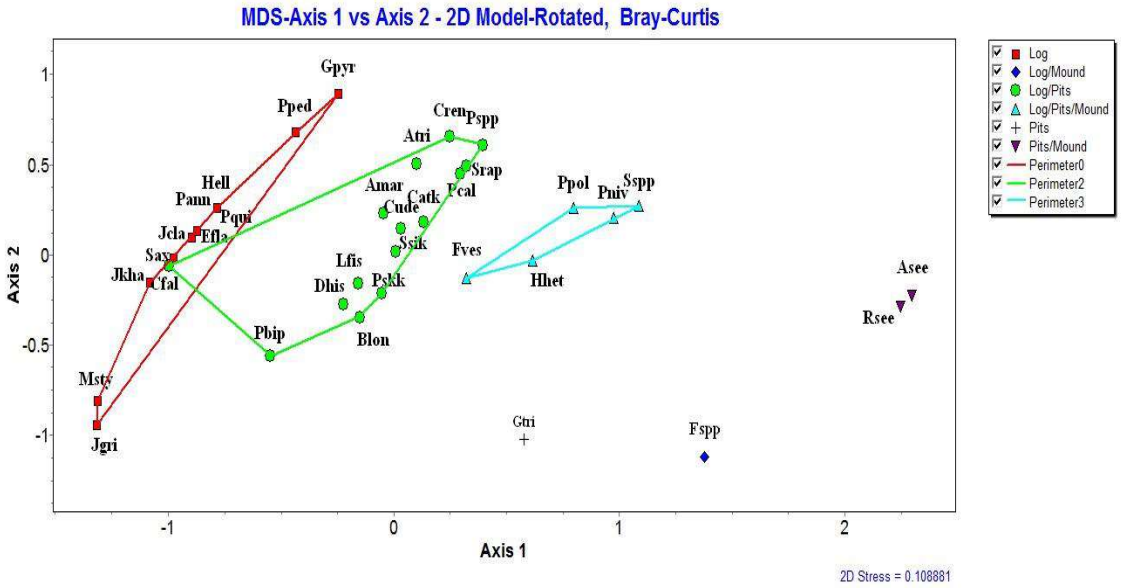

Fig. 2. Non-metric multidimensional ordination (NMDS) of plant community in present study (Refer Table 5 column 2 for scientific names of the species letter code used in this figure; The four-letter code represents the name of the plant species, with first letter corresponding to the genus name and the subsequent letters being initials of species name)

43 percent grew in the log and pits, 34 percent grew in the log substrate, 5 per cent grew in the log, pits, and mound substrate combined, and the other species, such as *Rhododendron* and *Abies* (seedlings), preferred growing in both pits and mound substrate.

CONCLUSION

This research, conducted in the subalpine forest of Khangchendzonga Biosphere Reserve, marks the inaugural documentation and represents the initial exploration into the herb species colonisation of fallen trees. The colonisation of seasonal herbaceous species in the studied forests may facilitate indicators of plant survival mechanisms in response to changing climatic conditions, shedding light on the intricate interactions between these species and their environment. It plays a pivotal role in the preservation of biodiversity by conserving fallen trees in subalpine forest ecosystems. Through a comprehensive analysis, the study identifies promising harmonious assembly of herbs in various substrates such as fallen logs, pits, and mounds. Around 5 per cent of the forest floor comprises fallen logs in different stages of decomposition, emphasizing the significance of these elements for potential altruistic surrogacy in colonisation. Colonisation patterns vary, with substratum-specific preferences, and pits demonstrate higher seedling colonisation than logs and mounds. Localized colonisation is prevalent, particularly within 1m of the log or pit. Summer species are identified as superior colonisers, exhibiting better long-distance dispersal capabilities than spring-ephemeral species. Wind-dispersed seeds emerge as the predominant factor in colonisation dynamics. The study emphasizes the importance of considering various colonisation sites, such as pits, mounds, and logs, in afforestation planning to favour altruistic surrogacy. The conservative estimate provided by the study offers insights into the forest cover available for colonisation in the recent past, present, or near future. Furthermore, the presence of seasonal herbaceous species serves as an indicator of plant survival mechanisms in response to changing climatic conditions, providing valuable insights into species-environment interactions.

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AUTHOR'S CONTRIBUTION

Arun Chettri, Arun Kumar Rai, Sailendra Dewan and Srijana Mangar have contributed in conceptualisation, methodology writing, data collection, drafting, analysis and interpretation. They have also reviewed and approved the final manuscript.

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Assessment of Species Diversity in Coffee-Based Agroforests and Natural Forests in Kodagu, Central Western Ghats

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***Abstract*:** Kodagu district in Central Western Ghats, recognized for its rich biodiversity, includes diverse land-use systems such as natural forests, coffee agroforests, and plantations. This study assessed species diversity in *Coffea arabica* and *Coffea canephora*-based agroforestry across moist deciduous and evergreen vegetation types in Kodagu. Using diversity indices and Bray-Curtis cluster analysis, the study compared tree density, species richness, and ecological dominance between coffee plantations and natural forests. The results revealed that coffee plantations and Shannon–Wiener index of 3.38 to 3.96 and species richness of 59 to 90. The importance value index (IVI) indicated that exotic species, such as *Grevillea robusta*, dominate coffee agroforests in moist deciduous vegetation type, while native species dominate evergreen forests, moist deciduous forests and coffee agroforests of evergreen vegetation type. In cluster analysis evergreen forest forms a distant cluster with similarity value of 0.9, suggesting higher diversity in this land use system. The findings highlight the ecological significance of natural forests and the role of coffee agroforests in biodiversity conservation. The study emphasizes the need for conservation strategies to balance agroforestry expansion and biodiversity preservation in Kodagu.

Keywords: Kodagu, Coffee based- agroforestry, Forests, Diversity, Conservation

The Western Ghats landscape in peninsular India stands out as a distinctive mosaic that intertwines natural forests with human-modified production landscapes, creating a unique blend of biodiversity and anthropogenic interventions. This complex tapestry includes diverse elements such as coffee agroforests, tea plantations, as well as monoculture and mixed-species forest plantations (Devagiri et al., 2019). Kodagu in Central Western Ghats stands as one of the lushest and most verdant landscapes in India, forming an integral part of the Western Ghats. The 81 % of the district's geographical area is adorned with tree cover, creating a green expanse that contributes significantly to the ecological richness of region. This district is a repository of diverse ecosystems, including natural forests, sacred groves, coffee agroforests, and forest plantations. These varied landscapes play a pivotal role in sustaining the diversity of species, encompassing approximately 8 % of India's extensive plant wealth (Bhagwat et al., 2008). Coffee is an important example of a crop traditionally cultivated under native shade trees, with strong benefit for biodiversity conservation and carbon storage.

Kodagu district, renowned for its rich biodiversity and dense woodlands, hosts coffee plantations that account for approximately 33% of its landscape. The region's coffee agroforests have been found to harbor significant species diversity. Pioneering studies by Elouard et al. (2000), Bhagwat (2002) and Sathish (2005) compared coffee agroforests with adjoining natural forests, revealing that species richness within coffee-based agroforestry systems can be comparable to, or even exceed, that of natural forests. However, Kodagu's landscape has undergone substantial changes over the past few decades, with considerable forest degradation and deforestation driven by the expansion of coffee estates. The introduction of the fast-growing *Grevillea robusta*, an exotic species commonly found in coffee plantations, has led to further modifications of tree cover of the region. These changes, driven by the desire for higher coffee yields and the economic benefits of harvesting *G. robusta*, have raised concerns about the impact on native biodiversity. This diverse set of environmental conditions provides an opportunity to explore how agroforestry systems (AFS) respond to variations in precipitation, taking into account both plant functioning and farmers' management practices across different environmental scenarios. Considering the dynamic nature of land-use change and varying climatic conditions in Kodagu, the present study was conducted to assess the species diversity in coffee based agroforests of Kodagu.

MATERIAL AND METHODS

Study site: The study was carried out in the tree-dominated landscapes of Kodagu, situated in the Central Western Ghats spread between 11°56ˈand 12°56ˈ N latitude and 75°22ˈ and 76°12ˈ E longitude. During the study period, annual rainfall in the evergreen vegetation ranged from 2,167.8 mm in 2023 to 5,110.0 mm in 2022. In contrast, the moist deciduous

vegetation experienced annual rainfall between 859.7 mm in 2023 and 1,826.6 mm in 2022.

Experimental details and sampling design: Kodagu district was divided into two bioclimatic zones based on vegetation type and average annual rainfall: the evergreen zone (regions receiving more than 2,500 mm of annual rainfall) and the moist deciduous zone (regions receiving 1,500-2,500 mm of annual rainfall). Within each vegetation type, three different land use systems were randomly selected: *C. arabica* plantations, *C. canephora* plantations and natural forests adjoining these coffee plantations, which served as controls. Coffee plantations that fall under 25-70 yr age group were selected. Nested sampling approach was adopted for the collection of data on trees (Pascal and Pelissier 1996). In each land use systems, 15 quadrats of size 40 m × 40 m were laid out randomly to carry out the tree enumeration. In each sample plots, all the woody plants were counted and identified by using field key (Pascal and Ramesh 1987). Total tree height and girth at breast height of all the trees with GBH ≥ 30 cm in each sample plots were measured by using laser hypsometer and measuring tape, respectively. Diversity parameters such as Shannon Weiner diversity index, evenness index, index of dominance and vegetation structural parameters such as tree density and importance value index (IVI) were estimated (Curtis and McIntosh 1950). Species richness is the number of different species represented in an ecological community, landscape or region. The diversity indices were calculated using PAST ver. 4.03 software and IVI was analysed in MS- excel using aggregated data of different land use systems and vegetation types. Bray- Curtis cluster analysis was also performed in PAST software.

IVI (%) = Relative frequency (Rf) + Relative density (RD) + Relative dominance (Rd)/3

RESULTS AND DISCUSSION

The vegetation types, tree-based land use systems in evergreen vegetation type recorded higher H' value and lower dominance indicating comparatively higher diversity than moist deciduous vegetation type. The evergreen vegetation type forests exhibited higher species richness and diversity with H' of 3.96, species richness of 90, followed by *C. arabica* plantations, indicating that natural forests support more diverse species. *C arabica* and *C. canephora* have higher evenness values of 0.54 and 0.49 compared to forests (0.23), suggesting that the species in coffee agroforests are more evenly distributed. Natural forests have lower dominance (0.03), meaning no single species dominates. In contrast, *C. robusta* (0.05) shows slightly higher dominance (Table 1). In moist deciduous vegetation type, *C. canephora* based agroforestry exhibited higher H' of 3.01 and species richness of 39 species. Forests and *C. canephora* plantations showed the same dominance value (0.08), while *C. arabica* has a slightly higher dominance (0.10), meaning certain species are more dominant in *C. arabica* plantations (Table 2).

The favourable environmental conditions in evergreen forests- such as consistent rainfall, moderate temperatures, nutrient-rich soils, and diverse topography- create stable habitats that support a wide range of plant species. These conditions promote higher species richness and functional diversity by allowing a variety of species to thrive in different ecological niches. Additionally, the protection-oriented management in evergreen forests limits human disturbances like grazing, logging, and non-timber forest product

Table 1. Vegetation structure and diversity attributes in natural forest and coffee plantations of evergreen vegetation type

Parameters	Forest (N=15)	*Coffea arabica* (N=15)	*Coffea canephora* (N=15)
Shannon's - Wiener diversity index (H')	3.96	3.49	3.38
Species evenness (H/S)	0.23	0.54	0.49
Dominance (D)	0.03	0.04	0.05
Species richness	90	59	60
No. of stems ha^{-1}	380 ± 14.22	352 ± 22.2	278 ± 19.21

Table 2. Vegetation structure and diversity attributes in natural forest and coffee plantations of moist deciduous vegetation type (Mean ± Standard error)

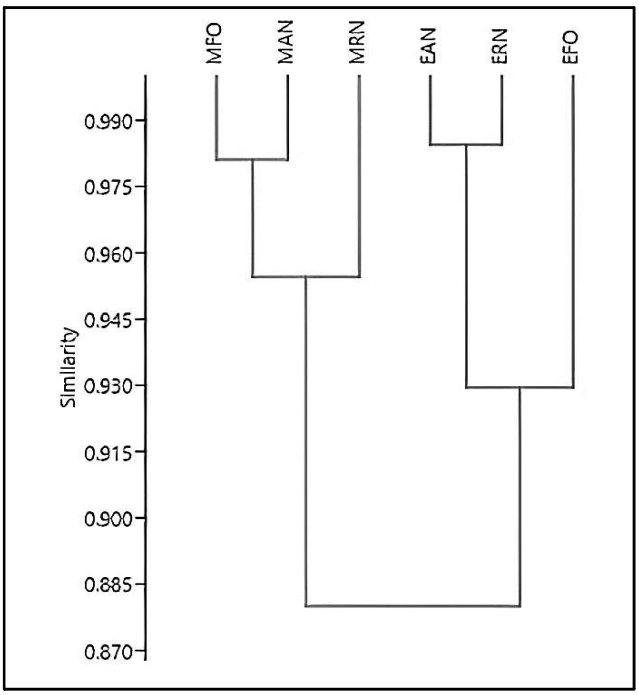
Parameters	Forest (N=15)	*Coffea arabica* (N=15)	*Coffea canephora* (N=15)
Shannon's - Wiener diversity index (H')	2.81	2.69	3.01
Species evenness (H/S)	0.55	0.45	0.40
Dominance (D)	0.08	0.10	0.08
Species richness	30	33	39
No. of stems ha^{-1}	318 ± 10.22	355 ± 28.77	292 ± 9.69

collection, which helps preserve biodiversity by maintaining natural regeneration cycles and preventing habitat degradation (Devagiri et al., 2019). In contrast, the disturbances in moist deciduous forests disrupt the ecological balance, reducing habitat quality and hindering species richness. The combination of optimal abiotic factors and reduced human impact in evergreen forests fosters a more diverse and resilient ecosystem, contributing to the higher diversity observed in these regions. Similar to the present study Devagiri et al. (2019) reported higher H' of 2.90 and 49 species in the evergreen forests of Kodagu.

In evergreen vegetation type, forests exhibited the highest stem density (380), followed by *C. arabica* (352). In moist deciduous vegetation, *C. arabica* recorded higher tree density (355). Tree density and basal area in plantations and natural forests of the tropics are influenced by precipitation. Climatic variables *viz.,* mean annual rainfall and rainfall seasonality may be key factors that directly or indirectly affect the density of tropical species (Mensah et al., 2023). Apart from precipitation interplay of various climatic factors *viz*., temperature, altitude and soil properties operating in evergreen vegetation might influence density. Management interventions like selective felling, weeding might have contributed to lower number of trees in coffee compared to natural forests. The higher stand density in *C. arabica* may be attributed to the fact that few *C. arabica* cultivars exhibit a general positive trend in yield with increasing shade, as highlighted by Koutouleas et al. (2022). Thus, to achieve this positive trend more shade trees are maintained. Whereas *C. canephora* has higher ability to sustain productivity even under high temperature and high-water vapour deficit than *C. arabica* plants (DaMatta and Ramalho 2006). Thus, lower tree density is observed in *C. canephora*.

Guillemot et al. (2018) reported that tree density was more in higher precipitation zone compared to moderate precipitation zone in the Cauvery watershed areas of Kodagu. Current study confirms this trend of higher stem density in evergreen vegetation with higher precipitation. Stem density per hectare (trees with dbh 10cm) in tropical landscapes varies from 245 stems ha^{-1} (low) to intermediate (420-617 stems ha^{-1}) and high value of > 639 stems ha^{-1} (Suratman 2012). Based on this classification, basal area of the plots of the present study can be categorized as low to intermediate. Swamy et al. (2010) reported stand density of 257 to 644 stems ha^{-1} in evergreen forests of Western Ghats. The mean tree density recorded in evergreen forests of the present study are within this range. Similar to the current study observations, Sundarapandian and Swamy (1999) also observed higher stem density in evergreen forests (748 stems ha^{-1}) than moist deciduous forests (332 to 450 stems ha^{-1}).

The importance value index (IVI) aids in understanding species distribution and community structure, particularly in varying environmental conditions. In evergreen vegetation type, forests recorded IVI values ranging from 1.45 to 45.21, with *Hopea parviflora* recording the higher IVI value, followed by *Aporosa lindliyana* (24.30) and *Syzygium cumini* (13.46) and *Knema attenuata* recorded the lower value of 1.45. In *C. arabica* based agroforestry *Artocarpus heterophyllus* reported higher IVI of 21.25, followed by *Grevillea robusta* and *Mangifera indica* and *Gmelina arborrea* recorded the lowest of 3.19. In *C. canephora* plantations. *Lagerstroemia microcarpa* exhibited higher IVI of 20.11, followed by *Grevillea robusta*. *Cinnamomum malbathrum* recorded lower IVI of 3.01. In moist deciduous vegetation type IVI ranged from 3.26 in *C. canephora* plantations to 18.04 in *C. arabica* plantations. In moist deciduous forests *Terminalia tomentosa* recorded the higher IVI of 14.52 and *Dalbergia latifolia* lower of 3.38. In *C. arabica* plantations *G. robusta* exhibited higher IVI value of 18.04, followed by *S. cumini* and *Pterocarpus marsupium* exhibited lower IVI value of 3.73. In *C. canephora* plantations also *G.robusta* exhibited higher value of 16.16 and *Leucaena leucocephala* lower of 3.26. The higher IVI in evergreen vegetation type may be attributed to higher basal area contributing to higher relative dominance (Fig. 1). Maheswarappa and Vasudeva (2018) recorded IVI in the



EFO- Evergreen forests, EAN- Evergreen *C. arabica* based agroforestry, ERN- Evergreen *C. canephora* based agroforestry, MFO- Moist deciduous forests, MAN- Moist deciduous *C. arabica* based agroforestry, MRN- Moist deciduous *C. canephora* based agroforestry

Fig. 2. Dendrogram showing similarity between land uses based on species diversity

range of 8.07 to 17.87 in evergreen forests which is similar to present study findings. In coffee agroforests *G. robusta* was the dominant tree species. Similar observations were recorded by Devagiri et al. (2019) and Sathish et al. (2022), highlighting that coffee agroforests with large native trees is replaced with silver oak. The primary reason for this shift may be the existing harvest regulations and tenure systems, which restrict the harvest and sale of native trees while

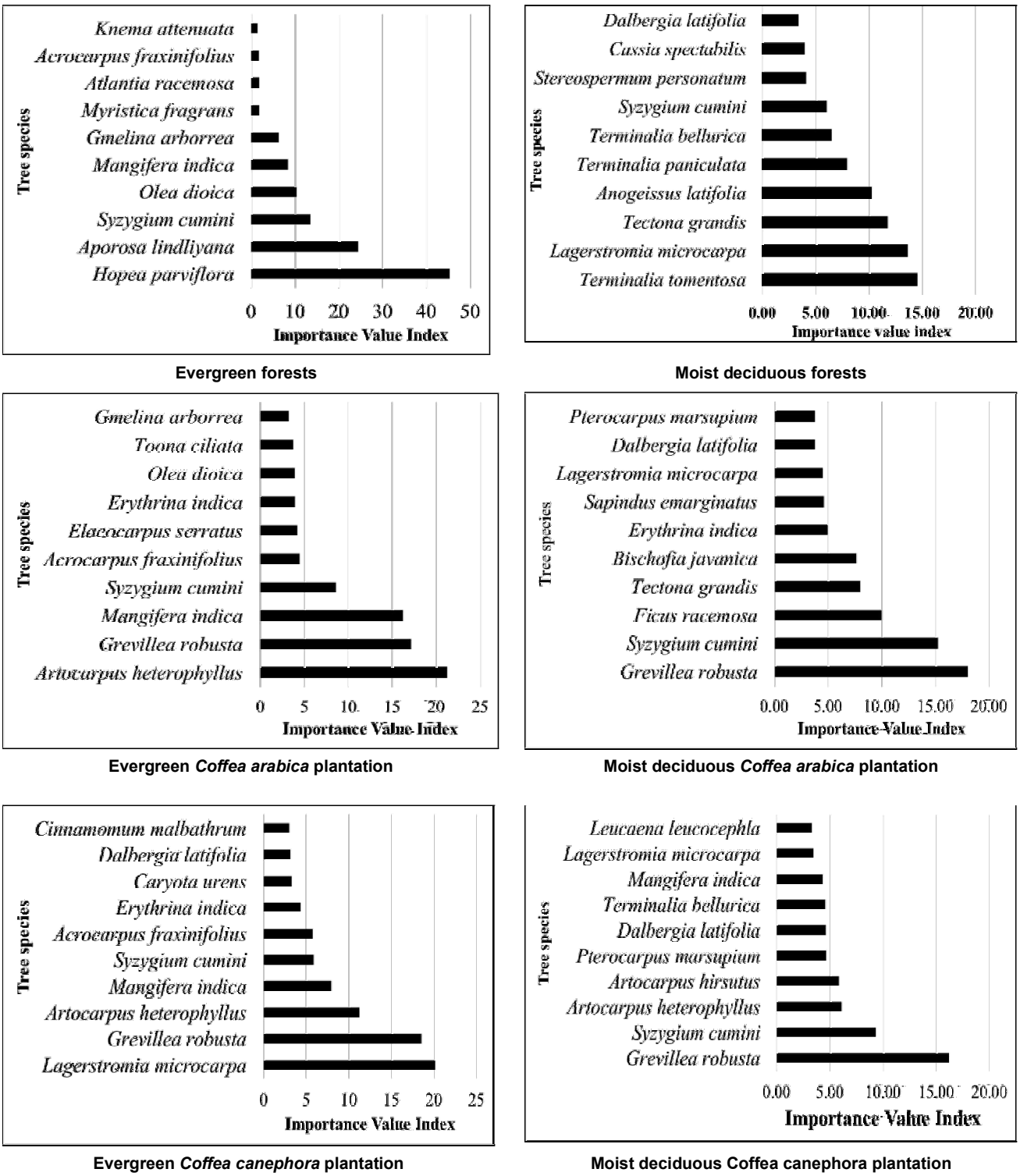


Fig. 1. Importance value index of tree-based land use systems of Kodagu

encouraging the cultivation of fast-growing exotic species like silver oak. Although *G. robusta* dominates the landscape in many coffee agroforests, particularly in moist deciduous regions, it ranks only as the second most dominant species in agroforests situated within evergreen vegetation zones. This reduced dominance in evergreen regions can be attributed to the more favourable environmental conditions, which support a wider variety of species. Additionally, many of these coffee agroforests in evergreen zones originated from remnant evergreen forests, which has contributed to maintaining a higher level of species diversity. This contrast highlights the ecological variability between different vegetation zones, where the dominance of *G. robusta* is moderated by local environmental factors, such as climate and soil conditions, as well as the presence of remnant native species.

Cluster analysis: The Bray- Curtis cluster analysis was performed for different tree-based land use systems based on similarity values of diversity indices (Fig. 2). There were two clusters, among them moist deciduous forests and *C. arabica* plantation in moist deciduous vegetation exhibited highest similarity, clustering at around 0.99, indicating that these two land uses share the most similar characteristics. *C. canephora* in moist deciduous vegetation type is closely linked to this group, clustering at 0.97. The next cluster involves *C. arabica* and *C. canephora* plantations in evergreen vegetation type with similarity value of 0.95. Evergreen forest forms the distant cluster, joining EAN- ERN at below 0.9. This suggests evergreen forests is distinct due to higher diversity. The cluster analysis suggests that while coffee plantations and forests within the same vegetation type share ecological similarities, evergreen forests stand out as distinct due to their greater biodiversity. Zamora et al. (2016) also highlighted that coffee plantations can serve as biodiversity refuges, natural forests, particularly undisturbed ones, consistently show higher species richness and distinct compositions which aligns with the present study findings.

CONCLUSION

This study provides a comprehensive analysis of species diversity in coffee-based agroforests and natural forests within the Kodagu region of the Western Ghats. The findings illustrate important ecological patterns and relationships between natural ecosystems and agroforestry landscapes, shedding light on the impact of human interventions such as coffee cultivation on biodiversity. The comparison between moist deciduous and evergreen zones further highlights the importance of vegetation type in determining species diversity. The study confirmed that evergreen zones, which experience higher rainfall, support more diverse and complex ecosystems than the moist deciduous zones. The findings highlight the ecological significance of natural forests and the role of coffee agroforests in biodiversity conservation. The study emphasizes the need for conservation strategies to balance agroforestry expansion and biodiversity preservation in Kodagu.

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Non-Woody Crop Loss to Bonnet Macaque and Langur Relative to Fragmentation Amidst Territorial Moist Deciduous Forests, Central Western Ghats, India

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Abstract: A study was conducted on farmers' perception regarding per cent loss of non-woody crops to two species of monkeys - Bonnet Macaque (BM) (*Macaca radiata*) and Langur (*Semnopithecus hypoleucos*) - in the territorial moist deciduous forests of central Western Ghats, India. The losses were compared between farms located deep inside dense moist deciduous forests (DMDF) v/s farms in fragmented moist deciduous forests (FMDF). The hypothesis was that the farms in DMDF should have less crop loss than FMDF as monkeys, especially BM, from elsewhere cannot be brought and released there, more alternate food available to monkeys in such forest, and almost near natural ecosystem around should buffer perturbations, if any. The farms visit were derived from a system of 16 square grids of 5 km^2 each, systematically distributed, with a random start. Using pre-tested semi-structured schedules with open ended questions, 26 farmers were personally interviewed in DMDF, and 28, in FMDF. From the farms in the two forest systems cumulatively, 11 non-woody crop species were listed, of which paddy and banana were the two most frequent. Comparing DMDF: FMDF situations, the per cent loss of paddy, banana, sugarcane, maize, and cotton to BM were 7.1:6.76, 32:24.51, 24.89:6.1, 13.11:8.75, and 12.27:11 respectively. The loss of paddy, banana, sugarcane and cotton to langur were 0.05:0.2, 42.12:40.22, 0.58:0 and 26.29:11.5, respectively. Paddy and sugarcane were lost significantly more to BM; banana and cotton were lost more to Langur. In FMDF, 80.59% of cardamom was lost to BM. Maize and lentils were raided by both the species comparably. Contrary to our hypothesis, there was no significant difference in the crop loss between DMDF and FMDF.

Keywords: Crop loss, Monkey, Macaque, Langur, Western Ghats, Fragmentation

Crop loss to non-human primates has been occurring in different parts of the world, leading to human-primate conflict. Such conflicts have decades of history, and have been reviewed for different parts of the world, say, for Asia and Africa -e.g. Hockings and Humle (2009) reviewed it for great apes, and Priston and McLennan (2013) for macaques. Monkey conflicts with farmers have been occurring in India also for decades. The conflict intensified in the Uttara Kannada District (UKD) over the last two decades with the two most common monkey species - Bonnet Macaque (BM) (*Macaca radiata* E. Geoffroy Saint-Hilaire) and Langur (*Semnopithecus hypoleucos* Blyth 1841) (Menon 2014). Likely very contributive to this intensification, two new issues emerged. One is, monkeys (especially BM), were captured at problem areas (including from the open Deccan Plateau) and translocated to new areas, usually onto well traversed highways in midst of forests in Western Ghats (WG). This has been strongly suspected by local people, supported by anecdotal evidences and media, and noted by primatologists (Kumara et al., 2010, Sinha 2013, Kumara et al., 2016). The second issue is that forest fragmentation can aggravate conflicts further, creating cultivation-forest edges that favor crop raiding by primates, supported by studies across the globe (Tweheyo et al., 2005, Hockings and Humle 2009, Guinness and Taylor 2014, Siljander et al., 2020, Koirala et al., 2021). Bhat and Vijaya Kumara (2024) reported that crop loss from BM was significantly and consistently higher in fragmented semi-evergreen forests (FSEF) than dense semi-evergreen forests (DSEF). The magnitude of conflict also depends on the crop type and the primate species involved in the conflict. Here we present the result of a study aimed to compare the extent of crop loss from BM and Langur in farms located deep inside large expanse of dense moist deciduous forests (DMDF) relative to farms in fragmented moist deciduous forests (FMDF).

MATERIAL AND METHODS

Study area: The study area was the belt of Moist Deciduous Forest (MDF), in the eastern parts of UKD (Fig. 1). The belt occurs after the crest of the WG and on eastern slopes. It is about 140 km long and 20 km wide, covering roughly 2800 km^2 area lying between 15°29' N:74°21'E and 14°24'N:74°54'E. The terrain is mainly undulating, with rough terrain at one place in the west, tending to a river valley. The altitude is about 620 m MSL. Climate is tropical, with about 2500 mm rainfall in the western side of the belt and about 1500 mm in the eastern side. Maximum temperatures in summer reach about 38°C and the minimum in winter about 10°C.

The farm locations were derived from a system of 16 square grids (each of 5 km^2) distributed systematically. These

grids were part of a larger study, and had a system generated random beginning, overlaid onto Google Earth Pro using QGIS. Grid size 5 km^2 was chosen as that was considered equivalent to the largest known home range sizes of monkey troops and was used by several earlier workers to study monkeys (Sinha 2013, Kumara et al., 2016, Erinjery et al., 2017, Kumar et al., 2018). This grid size is quite compact for intensive study; at the same time, large enough to accommodate the diverse situations that exist in a village, including farm landscapes and surrounding forests, matching the ecology of monkeys.

Locating and deciding a farm or cluster of farms in DMDF or FMDF situation involved three steps: Firstly, by studying in detail the Google Earth Pro live map wherein we located the grids that had already been generated (Fig. 1). The expanse of forest in and around a particular grid, whether it matched DMDF situation or FMDF situation was discerned in this step. The second step was, to strengthen our decisions on farm location, type of forest and whether it was fragmented or not, we simultaneously studied The forest maps of South India (Belgaum-Dharwad-Panaji and Shimoga) by Pascal et al. (1997). Thirdly, with the help of local people or guided by the maps, we reached the intended farm locations in the field and did ground truthing. A farm/cluster of farms located amidst a vast expanse of good forest cover, with very few cultivation/open patches nearby, and away from a well traversed primary road was considered deep located (DMDF). The reverse of it, with broken forest around, and several farms or network of farms or open areas near to a primary road, fragmented (FMDF). Using the dimensions of 5km^2 grid, four parameters were fixed to differentiate DMDF and FMDF (Table 1).

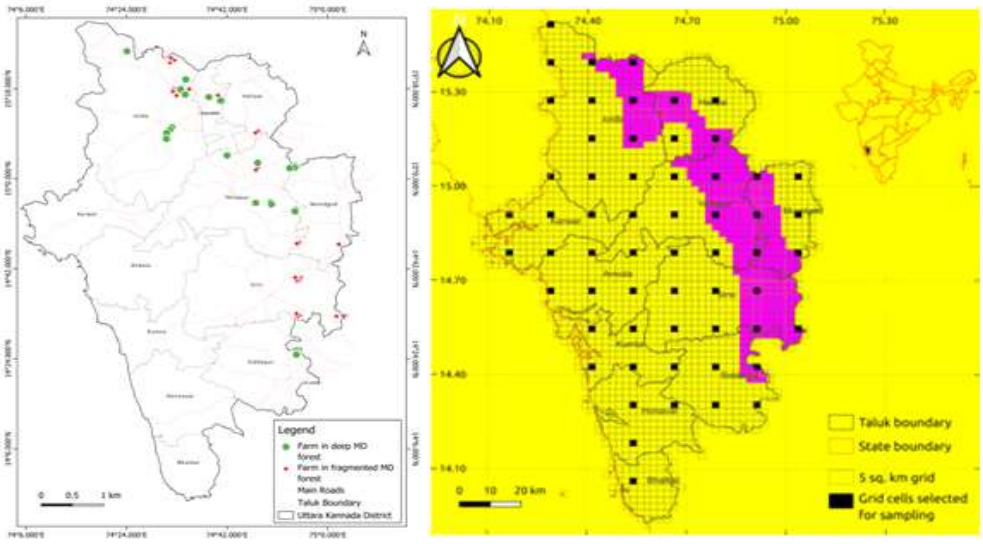

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Fig. 1.a. Study area of sampled locations in MDF belt and b) Pink highlighted area indicating moist deciduous territorial belt, Uttara Kannada district, with 16 grids shown in it

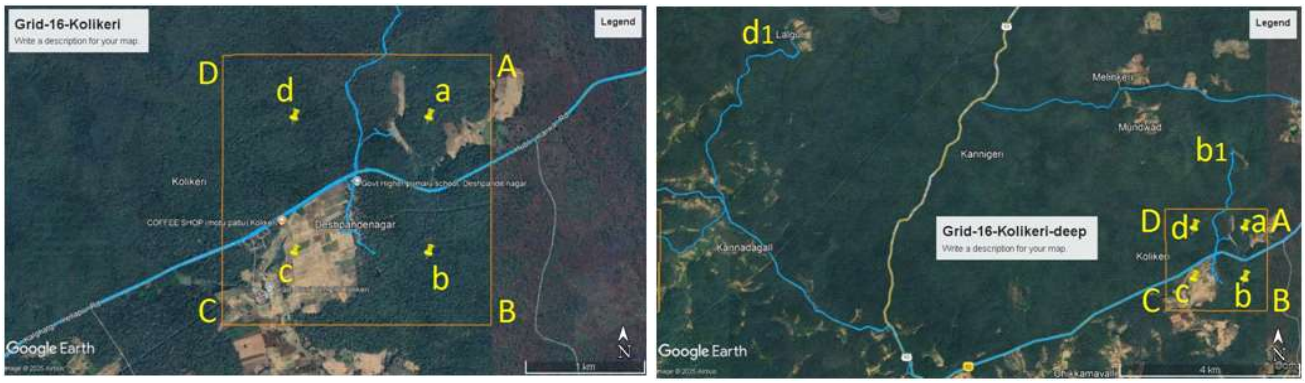

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Fig. 2. Grid, sub-grids, centroids, selection of farms, fragmented and deep situations, a) Showing a grid ABCD of 5 km^2, with centroids a,b,c,d in respective sub-grids. a and c have farms, and that is FMDF situation and b) Sub-grids b and d do not have farms in them. So, b1 and d1 have been taken from DMDF as replacements for b and d

The 5 km^2 grid was divided into four sub-grids of 1.25 km^2 each as spatial replicates, with one centroid at the centre of each sub grid (Fig. 2). If a particular sub-grid had farms in it, the farmer nearest to the centroid was considered for the interview (Fig. 2a), provided he/she consented (Hill 1997). If no consent, another farmer nearest to the first was considered, and so on, and interviewed. If a sub-grid did not have farms in it, the occasion was utilized as a chance to look for a farm located deep inside forest, DMDF, somewhere in the MDF belt (Fig. 2b).

The study was carried out between July 2021 and June 2024. Farmers were interviewed using pre-tested semi-structured schedules with open ended questions, asking about crops grown and perceived losses (worked out in terms of percentage) to the two species of monkeys – BM and Langur (Fig. 3). Our movements in the field were tracked with GPS GARMIN 78s, and the tracks overlaid onto Google Earth Pro for any clarifications for the site.

Statistical analysis: The data were analyzed using Excel software for descriptive statistics, and SPSS software for non-parametric test of significance and Mann Whitney U Test also see Table 2.

RESULTS AND DISCUSSION

Twenty six farmers were interviewed in DMDF, and 28, in FMDF. Eleven non-woody crop species were encountered - paddy (*Oryza sativa* L.), banana (*Musa paradisica* L.), sugarcane (*Saccharum officinaru*m L.), maize (*Zea mays* L.), black-pepper vine (*Piper nigrum* L.), cotton (*Gossypium hisrsutum* L.), cardamom (*Elettaria cardamomum* L. Maton.), lentils, ginger (*Zingiber officinale* Rosc.), papaya (*Carica papaya* L.) and patchouli (*Pogostemon cablin* Benth.).

Papaya was damaged in one farm due to macaque and surprisingly, in not due to langur. Ginger and pachouli were grown only by one farmer each in DMDF; both not damaged by either of the monkey species. Paddy and banana were the most frequently grown crops. Loss of paddy to BM was considerable and consistent, and to Langur, negligible; the differences between them highly significant in both DMDF as well as FMDF. Sugarcane also, in both systems, loss significantly more to BM than to langur. Loss of cardamom too, significantly more to BM than to langur in FMDF. Langur raided cotton significantly more than BM in DMDF and banana in FMDF. Loss of sugarcane to macaque significantly higher in DMDF than FMDF. The series of percent losses from entire list of crops in DMDF for BM when tested against that in FMDF, did not differ significantly; same with langur (Table 3, Fig. 4). BM raided paddy, sugarcane, and cardamom more; Langur raided banana and cotton more. Maize and lentil were raided by both the species comparably. In earlier reports in DSEF v/s FSEF in the upper parts of WG, percent damages by BM were 2.95 v/s 10.26 in paddy and 1.38 v/s 13.36 for banana (Bhat and Vijaya Kumara 2024). In the Kali Tiger Reserve (KTR) ratio of percent losses to BM: langur were 3.32:0.17 in paddy, 10.82:19.66 in banana. In the same KTR MDF BM: langur scores were 7.66:0.37and 14.05:64.06 in paddy and banana respectively (Bhat and Vijaya Kumara 2024a). BM feeding more on paddy, sugarcane, and cardamom than langur may be explained by their biology and ecology. Macaque are general feeders, and feed more on fruits, while langur are mainly leaf eaters (Singh et al., 2000, Singh et al., 2011, Menon 2014). Rhesus macaque (RM) (*Macaca mulatta* Zimmerman) showed strong preference to raid maize over rice in Nepal (Koirala et

Table 1. The overall parameters to decide a farm location as in DMDF v/s FMDF, for studies on crop loss to monkeys, Uttara Kannada District

General parameters	Farm(s) in DMDF	Farm(s) in FMDF
Percent forest cover in a grid of 5 km^2 subtended around the farm/cluster of farms	More than 85%*	Less than 85%
Straight distance (derived from Google Earth Pro) from well traversed all season primary roads, with forests in between[#]	Not less than 1.1 km (1.12 km is half the length/breadth of 5 km^2 grid)	Less than 1.1 km
The interviewed farm or cluster of farms should be surrounded by good expanse of forests; should not be connected to another farms/cluster of farms/open area that touches a well traversed all season primary road[#].	Forest all around the interviewed farm/cluster of farms; the ring of forest around not less than 600m horizontally (half the length/ breadth of a sub-grid of 1.2 km (details ahead)	No intervening forest; or connected directly to road/ network of cultivated/open areas; less than 600 m of intervening forest ring
Length of Forest: Cultivation edge/interface (measure of forest fragmentation) inside the grid, relative to perimeter of grid (modified from Rivas et al., 2022)	Less than 8.8 km (i.e., the perimeter of 5 km^2 grid)	More than 8.8 km

* In one case the grid had only 80% forest cover, but still considered DMDF because other vegetation-scape criteria met the conditions; [#] These two forest features more relevant to deter BM that might have been brought from open areas of Deccan Plateau and released onto roads in forested areas; such macaques are used to open areas but may not be able to penetrate dense forests immediately and reach the farms inside

Table 2. Socio-economic status of farmers/respondents

Particulars	DMDF situation	FMDF situation	Remark
Age of farmers/respondents:			
Average age	58	48	
Maximum age	84	78	
Minimum age	35	27	
Gender of farmers/respondents:	24 M, 1 F	27M, 1F	
No. of interviews in which ladies/girls of the family also participated with male members	6	11	Tells participation of female members in the interview
Land holding:			
Average	5.45acres	4.1 acres	
Largest	22 acres	18 acres	
Smallest	1.5 acres	1 acre	
Formal education of farmers/respondents themselves			
No. with no formal schooling	6	5	
No. with up to primary education	12	13	
No. with up to high school	5	8	
No. with up to Pre-University	1	1	
No. of graduates	1	1	
No. of interviews during which younger generation of the family, with formal schooling, also participated along with senior members	14	3	Improves the quality and quantitative assessment during the interview
Highest level of education in family, in younger generation:			Improves general and quantitative awareness of elders
Graduate/post graduate	13	8	
High School and above	12	18	
Primary	-	2	
Dependency on farming:			
No. farmers dependent only on farming and allied	22	25	
No. farmers with other occupations in addition to farming	3	3	

Table 3. Per cent mean loss, in non-woody crops due to monkeys in two systems of moist deciduous forests (DMDF and FMDF), Central Western Ghats, Karnataka, India

Farm location	From 26 farms amidst DMDF			From 28 farms amidst FMDF		
Non-woody Crop species	No. of farmers reported percent loss (n)	Crop loss due to macaque. (%)	Crop loss due to langur (%)	No. of farmers reported percent loss (n)	Crop loss due to macaque. (%)	Crop loss due to langur. (%)
Paddy	22[#]	7.1 [0-15.56]	0.05 [0-1.25]	22	6.76 [0-25.5]	0.2 [0-1.8]
Banana	17	32 [0-79.69]	42.12 [0-90]	20	24.51 [0-90]	40.22 [0-90]
Sugarcane	5	24.89 [3.5-75]	0.58 [0-2.92]	5	6.1 [0-16.5]	0.0
Maize	3[*]	13.11 [6.82-22.5]		4	8.75 [4.5-12.86]	6.79 [5.82-8.57]
Pepper vine	2	0.00	0.00	5	18.26 [0-78]	2.0 [0-10]
Cotton	4	12.27 [3.95-26.25]	26.29 [11.05-37.5]	2	11	11.5 [8-15]
Cardamom	1	0.00	0.00	4	80.59 [36.67-100]	0.0
Lentils	-	-	-	2	10.75 [5-16.5]	10.75 [5-16.5]

Figures in parentheses indicate the range

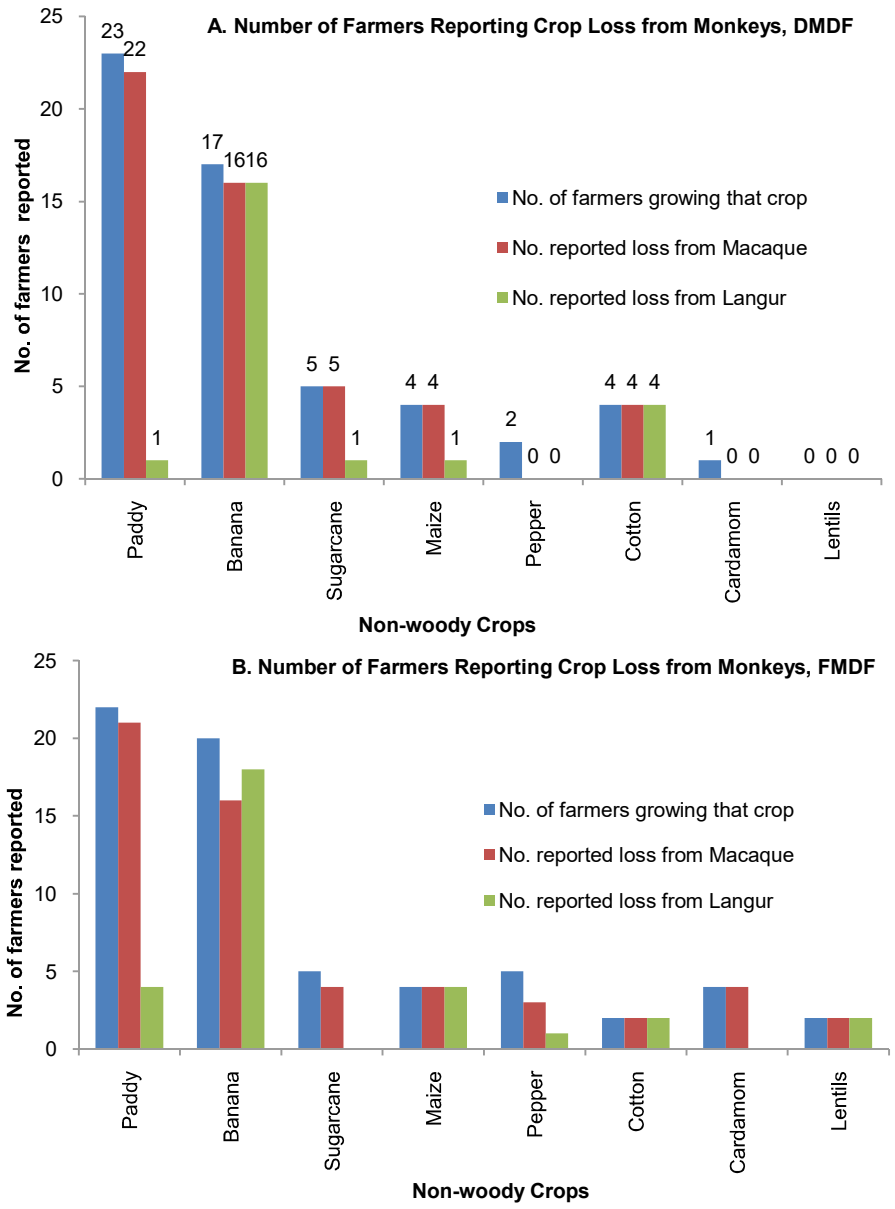

Fig. 3. Number of farmers growing the respective non-woody crops, and loss from monkeys amidst dense v/s fragmented moist deciduous forest system

Table 4. Nature of loss to non-woody crops from the two monkey species

Crop species	Bon. Mac.	Langur
Paddy	Panicle eaten in crop season; of standing crop as well as harvested and spread in field for drying.	Grain eaten in crop season; of standing crop.
Banana	Succulent shoots eaten; green fruit eaten	Green fruit eaten
Sugarcane	Stem eaten	Stem eaten
Maize	Cob eaten in crop season	Cob eaten in crop season
Cotton	Succulent boll, shoots, leaves eaten	Succulent boll, shoots, leaves eaten
Pepper vine	Mainly physical damage; feed on berries, but less	Mainly physical damage; feed on berries, but less
Cardamom	Shoots eaten, whole plants split	-
Lentil	Whole plant, inflorescence, beans eaten	Whole plant, inflorescence, beans eaten
Papaya	Young leafy shoots and grown fruits eaten	-

a b

Fig. 4. a) Sugarcane damaged by macaque, b) Banana bunch damage by langur

al., 2021). Maize was raided highest (58.43%), followed by rice and lentil by Assamese macaque (*Macaca assamensis* McClelland) in Nepal (Ghimire S and Chalise M 2018). In Chamba region (Himachal Pradesh), out of the total loss of maize, RM contributed 31 and 38% respectively in 2014-15 and 2015-16. Himalayan (Chamba) Langur (*Semnopithecus ajax* Pocock) contributed 20% and 14% in the same two years (Ahuja 2017). In Himachal Pradesh, RM raided maize and caused about 26% loss to all non-woody crops put together (Saraswat et al., 2015). In China, sugarcane loss was 7.69% of the crop (Li and Essen 2021).

CONCLUSION

Eleven non-woody crops were reported by farmers in the MDF territorial belt of UKD, Central Western Ghats. Of these, paddy and banana are the two most frequent crops, followed by sugarcane, maize, pepper vine, cotton, cardamom and lentils. Paddy and sugarcane were impacted by macaque quite frequently in both DMDF and FMDF, cardamom in FMDF, while langur interaction with these crops was almost negligible in frequency and extent of damage. Langur raided banana more and to some extent cotton, than BM. Maize and lentil loss were almost comparable between both the monkey species. Contrary to our hypothesis, FMDF and DMDF did not differ much with respect to the extent of crop loss. But this should not be taken as a nod for further forest fragmentation.. This study can serve as a bench mark to compare such crop and monkey interactions for future times in space as well as time.

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Plant Species Composition and Diversity in Tropical Dry Mixed-Deciduous Forest of Telangana, India

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Abstract: Tropical dry deciduous forests (TDDF) are among the most threatened ecosystems in India, yet they play a critical role in biodiversity conservation and ecosystem service provision. The present study assessed the structure, composition, and diversity of plant species in the Narsapur Reserve Forest (NRF), Medak District, Telangana, India. The objective of the study was to document floral diversity to support management interventions and enhance ecosystem services. Thirty transects (250 m × 4 m) and 180 quadrats (1×1 m) were laid to record trees, shrubs, herbs, grasses, and climbers between March 2021 and February 2022. A total of 13,601 woody individuals (81 species, 31 families) and 4,881 herbaceous individuals (59 species, 26 families) were recorded, representing 140 species across 51 families. *Cleistanthus collinus* and *Chloroxylon swietenia* dominated the woody stratum, while *Justicia micrantha* was most abundant in the herbaceous layer. Diversity indices revealed higher species richness and evenness among trees and shrubs compared to the herbaceous community. The stand structure indicates low abundance of large and canopy forming trees. Ensuring protection and preventing biotic pressure in post-monsoon phase may support survival of seedlings and regeneration of canopy forming trees such as *Terminalia* spp., *Madhuca longifolia*, *Boswellia serrata*, *Albizia procera* and improve overall structure. The findings highlight the ecological significance of NRF and underline the need for regulating anthropogenic disturbances, controlling invasive species, and maintaining canopy cover to sustain biodiversity and ecosystem functioning. These results provide a baseline for developing effective conservation and management strategies in TDDF landscapes.

Keywords: Tropical dry deciduous forest, Species diversity, Community structure, Narsapur Reserve Forest, Ecosystem management

Forests play an important role of sustaining life and livelihoods of those associated with it, with its primary objective being ensuring the ecological and environmental stability for the landscape. Maintaining forests is thus a crucial way of ensuring these objectives and can be done by improving management practices and sustainable utilization of forested landscapes (Anderson-Teixeira et al., 2013). Forest structures are influenced by disturbances and this further influence sits development and dynamics (Zenner 2005). Understanding forest structure is essential for analyzing the intricate relationships between patterns and processes within forest ecosystems. Tree diversity indices are important quantitative measures for describing forest structure (Aguirre et al., 2003, Lexerod and Eid 2006, Pommerening 2002). These indices are also essential variables for reconstructing forest structures in spatially explicit growth models and for computer visualizations (Hasenauer 2006). Anthropogenic factors frequently impact the diversity and structure of forests, making it essential to study forests based on their quantitative characteristics to predict future patterns (Khurana 2009). In past years, many researchers have undertaken studies regarding community structure and organization in natural forests in different climatic zones of India (Shadangi et al., 2000, Pande, 2001, Sagar et al., 2003, Thakur et 2005, Bhadra et al., 2010, Hegde et al., 2011, Ahmed, 2012, Bajpai et al., 2012, Jayakumar and Nair, 2012, Sahu et al., 2012, Thakur et al., 2017, Bilyaminu et al., 2021, Saharan et al., 2021). Among the sixteen subgroups of Indian forests, Tropical Dry Deciduous Forests (TDDF) are the most dominant, occupying 2,17,713 k, which constitutes 34.8% of the total forest cover in the country (Champion and Seth 1968, Reddy et al., 2015). TDDF are subject to natural disturbances such as drought, fire, and herbivory. However, human activities introduce additional disturbances, loss of movement corridor for the wildlife (Jaybhaye et al., 2022), including increased fire frequency (Pausas and Ribeiro 2013, Knorr et al., 2014) and the mortality of young trees (Chaturvedi et al., 2017), potentially altering long-term species composition (Zida et al., 2007). Recent studies suggest that TDDF are highly vulnerable to climate change, altered rainfall regimes, and invasive species, which further exacerbate biodiversity loss and regeneration failure (Deb et al., 2018, Lewis et al., 2004). Despite their ecological and socio-economic importance, these forests remain under-represented in long-term ecological monitoring programmes across India. Updated assessments of community structure and diversity are therefore necessary to evaluate ecosystem resilience and to

inform adaptive management strategies (Sadia et al., 2024, Tiruvaimozhiet al., 2025).Given these challenges, detailed studies on the vegetation composition and structure of TDDF are essential for improving ecosystem functions. Over the years, numerous researchers have conducted studies on community structure and forest organization in various climatic zones of India, though, very few studies are focused on TDDF (Kumar et al., 2010, Sahu et al., 2012, Raha et al., 2023). In this context, site-specific studies on floristic diversity, forest structure, and disturbance regimes can generate crucial baselines for restoration and policy interventions, particularly under India's commitments to the Convention on Biological Diversity (CBD) and the UN Decade on Ecosystem Restoration (2021–2030) (Chaturvedi et al., 2023). The present study focuses on the structure, composition, and diversity of plant species in the TDDF of Medak district, Telangana, India. The primary aim is to document and assess the floral diversity to support future management interventions and enhance the ecosystem services provided by these forests.

MATERIAL AND METHODS

Study site: The study area lies between the latitude 17°42'54.55"N longitude 78°18'20.85"E and latitude 17°43'25.83"N longitude 78°18'17.55"E in the Narsapur reserved forests of Medak district (Fig. 1). The study area falls under Champion and Seth, 1969 forest type of 5 A/C 3, Southern tropical dry mixed-deciduous forest. The forest soil is of sandy loam type. Some regions of the Narsapur range also have black cotton soils comprising clay loams, clay and silt clay in some low-lying areas. The district generally experiences a dry climate. The climate of this region is characterized by a hot summer and generally dry weather except with some passing showers during the south-west monsoon season. The period of March to May is the hottest prolonged summer season followed by the south-west monsoon, which lasts from June to October. This is followed by a mild cold season from November to February, which is the winter season. The average annual rainfall of the district ranges from 700 to 800 mm. The average minimum temperature for the year 2022 was 20.29 °C, the average maximum temperature was 31.34 °C and the total rainfall was 982 mm. The meteorological trend for survey duration 2021 to 2022 (IMD 2023) showed that on an average minimum temperature was 20.29°C, average maximum temperature was 31.18°C, average rainfall was 1023.55 mm with total 445 rainy days in two years. In the study area, the effect of dry season is visible from mid-November month as the trees enter senescent stage and herbaceous species dry. The sampling was carried out from March 2021 to February 2022. Sampling was carried out avoiding locations prone to intensive biotic pressure, road, human habitations and urban park. During the study period no fire was recorded in the area. Trees and shrubs were recorded when the plants were identifiable with leaves and other phenological features. Seasonal sampling was carried out for herbaceous species in summary, monsoon and post-monsoon seasons.

Field sampling and calculation: Sampling was done by enumerating thirty transects of 250 m long and 4 m wide. Diameter and girth of woody plants was measured at breast height 1.37 m above ground level and trees of girth size ≥1 cm (dbh) were included in the sample. For herbs and grasses, quadrats of 1 m × 1 m were laid at every 50 m distance in each transect. Therefore, sampling was done in 6 quadrats per

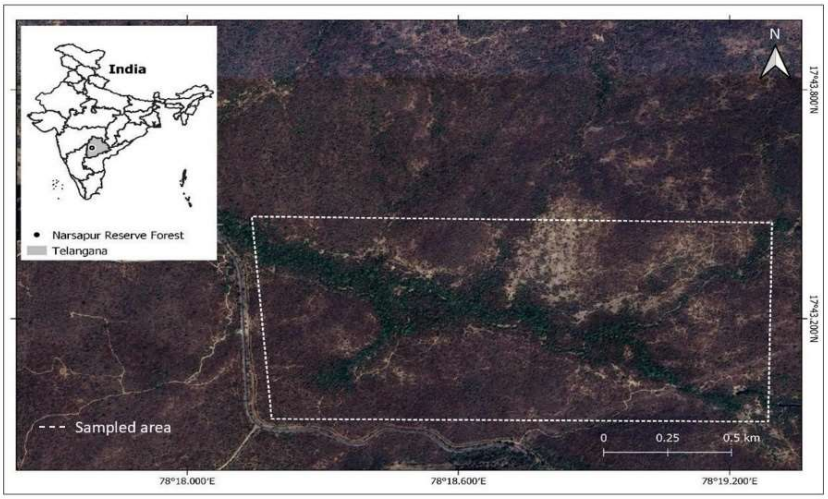

Fig. 1. Location of the study area in the Narsapur Reserve Forest, Medak District, Telangana, India

transect, total 180 quadrats (Fig. 3). Canopy cover was estimated as proportion of canopy open at each 1 m × 1 m quadrat using ocular observation to assess the influence of canopy openness on herb and grass community (if any). All the shrubs, herbs, climbers and grasses were also surveyed. Plant community structure (frequency, density, abundance, basal area, relative density, relative frequency, relative dominance and importance value index) were computed from the quadrat data following Misra (1968). The species density per hectare was calculated by dividing the total number of individuals across all transects by the total sampled area. Basal area for each individual was determined based on its girth, and for multi-stemmed individuals, the basal area of each stem was calculated separately (Shankar 2001). The basal areas of all individuals within a species were summed to determine the total basal area for that species. The stand basal area represented the sum of basal areas for all species in the community. For each species, the frequency, density, and basal area values were converted into relative values by dividing each respective value by the total frequency, density, and basal area of all species. The Importance Value Index (IVI) for species was calculated by adding together the relative density, relative frequency, and relative basal area.

The community characteristics were estimated using standard methods. Species dispersion was analyzed through the variance-to-mean ratio (Greig-Smith, 1983), where a ratio of 1 signifies random dispersion, > 1 indicates uniform dispersion and < 1 suggests increasingly clumped dispersion.

Species diversity was calculated by using the Shannon diversity index following Magurran (2004) as:

$$D_{Mg} = \frac{S-1}{ln\,(N)}$$

where, *H'* = Shannon index of general diversity, p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), ln is the natural

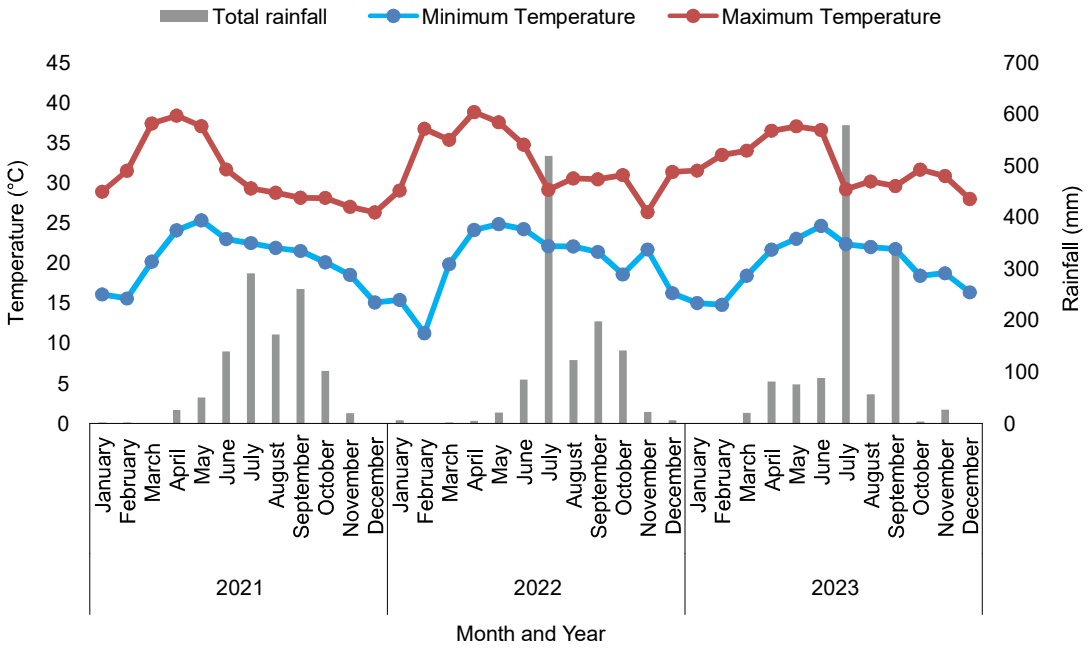

Fig. 2. Climatic pattern of Narsapur during the study period (2021 to 2023)

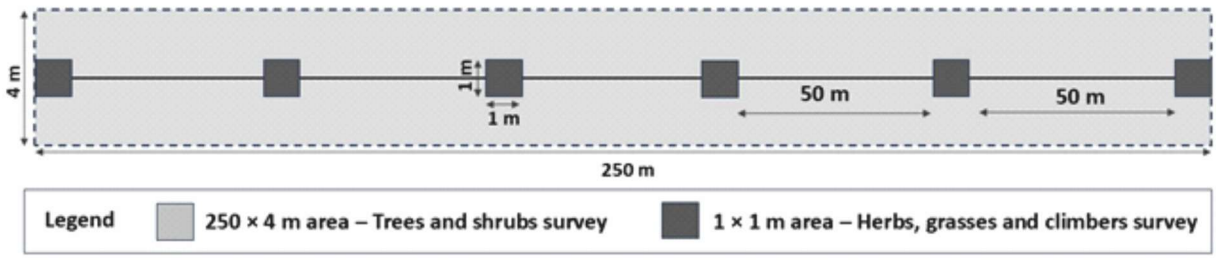

Fig. 3. Transect layout and placement of quadrats on each transect

log, 'Σ' is the sum of the calculations, and 's' is the number of species. The index of dominance was calculated following Simpson, 1949 (Magurran 2004) as:

$$H' = -\sum_{i=1}^{N} p_i \times lnp_i$$

where, Cd =Simpson's index of dominance, *pi* = proportion of the IVI of i^{th} species. Margalef index was used as a simple measure of species richness within a community Species richness was calculated by counting the total number of species observed in each habitat and also by the Margalef index as given by Magurran (2004):

$$Cd = \sum p_i^2$$

where, *S* = number of species, *N* = total number of individuals in the sample. Dominance=1-Simpson index. Ranges from 0 (all taxa are equally present) to 1 (one taxon dominates the community completely). Fisher's alpha was used as a diversity index, defined implicitly by the formula S=×ln(1+n/ α) where S is the number of taxa, n is the number of individuals and α is Fisher's alpha. The data were statistically tested in PAST Version 2.17c (Hammer et al., 2001) and visualized using MS-Excel. An exponential curve was fitted to depict the stand's population structure (girth and height class distributions) and chi-square test of goodness of fit evaluated the curve fit. The transects were clustered using a paired-group algorithm and Bray-Curtis similarity measure in PAST software. Family Importance Value (FIV) was calculated according to Mori et al., (1983) as a sum of relative diversity, relative dominance, and relative density. For herbs, grasses, and climbers Family Importance Value (FIV) was calculated according to Uranov (1935), where the Family Importance Index (I_b) is the multiplication of the Abundance (A_b) and Frequency (F_b) of the species. Species were organized according to decreasing IVI values and were placed under four different classes: 0-1%, 1-3%, 3-5% and >5%.

RESULTS AND DISCUSSION

Species composition: A total of three hectares of the Narsapur Reserve Forest in Telangana State were sampled across 30 randomly selected transects, documenting 13,601 individuals. The survey identified 81 tree and shrub species (Group A) belonging to 31 families. Transect 10 recorded the highest number of species. Additionally, 4,881 individuals of herbs, grasses, and climbers (Group B) were documented, representing 59 species from 26 families (Fig. 4). Overall, the study identified 140 plant species (81 from Group A and 59 from Group B) spanning 51 unique families in the Narsapur Reserve Forest. *Cleistanthus collinus* (Roxb.) Benth. ex. Hook. f. was the most abundant species with an absolute abundance of 1,941 individuals, contributing to 14.27% of the relative abundance. Following *Cleistanthus collinus*, *Chloroxylon swietenia* DC. were the second most abundant species with 1,318 individuals (9.69% relative abundance). Together, these two species contribute to over 23% of the cumulative abundance (19.05% for *Chloroxylon swietenia*), highlighting the skewness in species distribution where a few species dominate. *Holarrhena pubescens* Wall. ex G. Don and *Tectona grandis* L. rank third and fourth in terms of abundance, contributing 6.74% and 5.94% relative abundance respectively. These species account for a significant proportion of the cumulative abundance, reaching

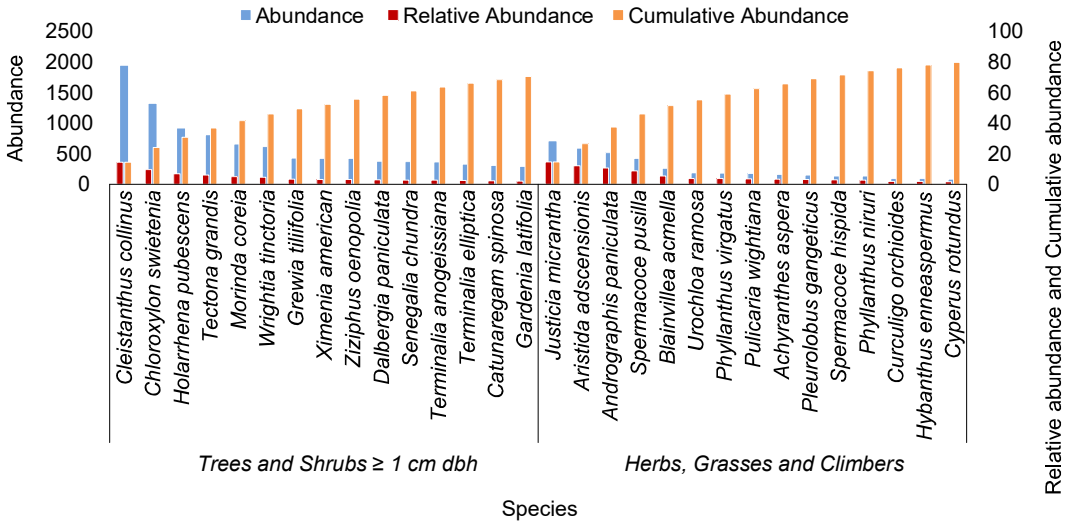

Fig. 4. Abundance values of top 15 species according to decreasing relative abundance

36.64%. The cumulative abundance reaches 70.25% by the inclusion of these species, reflecting the presence of many low-abundance species that contribute minimally to the overall abundance such as *Madhuca longifolia* var. *latifolia* (Roxb.) A. Chev., *Diospyros melanoxylon* Roxb., *Ficus mollis* Vahl, *Aegle marmelos* (L.) Corrêa and *Morinda coreia* Buch. Ham., but are crucial for maintaining ecological balance. In the herbaceous and climbing plant layer, *Justicia micrantha* Wall. was the most abundant species with 711 individuals and 14.57% of the herbaceous community. *Aristida adscensionis* L. and *Andrographis paniculata* (Burm. f.) Wall. with relative abundances of 12.07% and 10.63%, follow *Justicia micrantha* in dominance, accounting for 37.27% of the cumulative abundance. The dominance of *Justicia micrantha* as an herb in the understory vegetation is likely attributed to its adaptability and competitive advantage such as rigorous fruiting or maybe attributed to efficient photosynthesis, under the given ecological conditions of TDDF; however, further research is needed to confirm this.

The Importance Value Index (IVI) of dominant species like *Cleistanthus collinus* and *Lannea coromandelica* (Houtt.) Merr.were observed to be 32.64% and 22.49% respectively, followed by co-dominant species *Tectona grandis*(18.61%) and *Chloroxylon swietenia* (14.05%) with the lowest values belonging to *Senegalia chundra* (Roxb. ex Rottler) Maslin (6.25%) and *Grewia tiliifolia Vahl* (6.10%) amongst the top 15 species with highest IVI values of all species in the transects (Table 1). Amongst herbs, grasses and climber's category, *Justicia micrantha* (22.30%), *Andrographis paniculata* (18.37%) and *Aristida adscensionis* L. (18%), were found to be dominant over others. *Phyllanthus virgatus* G. Frost and *Curculigo orchioides* Gaertn. constitute the dominated category with IVI values of 7.69%, 7.62% and 7.30% respectively and *Hemidesmus indicus* (L.) R. Br.*, Cryptolepis dubia* (Burm. f.) M. R. Almeida and *Spermacoce hispida* L. have the lowest IVI values of 5.03%, 4.64% and 4.03%.

Considering all 81 species of trees and shrubs, in terms of IVI values, 26 species were between 0-1%, 24 species were in the range of 1-3% IVI values and 14 species in range 3-5%, and 17 species had IVI values of more than 5%. For herbs, grasses and climbers, out of a total of 59 species, 23 were in the range of 0-1% IVI values, 17 species fall in 1-3% IVI values and 6 species in range 3-5%, while 13 species were found to have IVI more than 5%.

The summary of diversity indices for trees and shrubs (≥1 cm dbh) and herbs, grasses, and climbers reveals notable patterns in species richness, diversity, and dominance across the plant life forms sampled (Table 2). However, the number of species was higher than the average number of herbs, grasses, and climbers recorded in the area 12.93 . The species richness observed in the sampled area of Narsapur reserved forest is similar to the species reported by Suthariet al., (2016) in protected area of Mallur Gutta sacred groove, Telangana. Since the number of individuals of trees and shrubs were also higher in the sample, the Shannon diversity index (H') for trees and shrubs was high 2.92, while the corresponding value for herbs, grasses, and climbers was 2.11. The index value stands close to the observations from other dry deciduous forests for Telangana as well as other dry deciduous forests of India such as reported by Naidu et al. (2017), Sahu et al. (2012) and Murthy et al. (2022). The Simpson index (1-*D*) for trees and shrubs was relatively high at 0.91 indicating low dominance and a high degree of diversity. In contrast, the herbaceous layer exhibited a lower Simpson index of 0.84 suggesting a higher dominance of some species and low variation in the composition among the sampling locations in the understory. It is probably due to the canopy cover. The average canopy cover in the sampling was recorded as 55 ranging from 80 to 25%. It was observed that higher canopy cover facilitated the herbaceous communities, with invasive species like *Lantana camara* L. intensely invaded the areas with low canopy cover of native tree species. The results of the present study coincide with the results of the studies by Sagar et al. (2012) as well as Sharma and Raghuvanshi (2011) in similar habitats. Fisher's alpha diversity index for trees and shrubs was 10.07, markedly greater than that of herbs, grasses, and climbers, which had a value of 3.42. The dominance index (D) for trees and shrubs was 0.09 ± 0.03 (CV% = 36.60), reflecting low dominance by any single species within this group. However, the dominance in the herbaceous layer was higher at 0.16, indicating that a few species tend to dominate in this layer. The evenness index for trees and shrubs was 0.49, which was lower than that for herbs, grasses, and climbers, which had an evenness of 0.66 Margalef's index for species richness in trees and shrubs was 6.10, while for herbs, grasses, and climbers was 2.36 .

The higher Shannon index in the woody vegetation suggests a more even distribution of species compared to the herbaceous stratum, which displays lower species evenness. Phytosociological analysis of the herbaceous vegetation indicated that tropical forests can harbor a variety of herbs and climber species according to changes in vegetation and availability of space and light. Fisher's alpha index indicates that the tree and shrub stratum support a higher degree of rare species diversity compared to the herbaceous stratum. Similar results were also reported by Sagar et al. (2012). The significantly higher value of Margalef's index for trees and shrubs reflects a richer species composition in this stratum, consistent with the findings for

species richness and diversity. The results indicate that trees and shrubs exhibit greater species richness, diversity, and evenness than herbs, grasses, and climbers, while dominance is higher in the herbaceous layer. The woody vegetation tends to host more rare species, as evidenced by the higher Fisher's alpha values, while the herbaceous vegetation has a more uniform distribution of species, as indicated by the higher evenness index for present observations. Margalef's index in the present study is comparable to that done in Kawal Wildlife Sanctuary, Telangana by Murthy (2015), where he reported that the Margalef's species richness index was 5.20. The present data can be compared with the large number of similar plots

Table 2. Different diversity indices of plant species for all transects [Values = mean ± SD (CV%)]

Indices/Variables	Trees and shrubs ≥1 cm dbh	Herbs, grasses and climbers
Species richness	38.23±6.97 (18.23)	12.93±3.53 (27.31)
Shannon diversity	2.92±0.29 (9.82)	2.11±0.30 (14.23)
Simpson	0.91±0.03 (3.67)	0.84±0.05 (6.25)
Fisher's *α*	10.07±1.72 (17.08)	3.42±1.03 (29.98)
Dominance	0.09±0.03 (36.60)	0.16±0.05 (32.90)
Evenness	0.49±0.07 (15.91)	0.66±0.08 (12.30)
Margalef	6.10±0.91 (14.95)	2.36±0.60 (25.47)

Values = Mean ± SD (CV%)

Table 1. IVI values of top 15 plant species in the order of decreasing IVI values

Life form	Species	RD	RF	RBA	IVI
Trees and shrubs ≥1 cm dbh	*Cleistanthus collinus* (Roxb.) Benth.	14.27	2.62	15.76	32.65
	Lannea coromandelica (Houtt.) Merr.	1.96	2.62	17.92	22.49
	Tectona grandis L.	5.94	2.53	10.14	18.61
	Chloroxylon swietenia DC.	9.69	2.62	1.75	14.06
	Morinda coreia Buch-Ham.	4.82	2.62	3.84	11.28
	Dalbergia paniculata (Roxb.) Thoth.	2.77	2.62	5.37	10.76
	Holarrhena pubescens Wall.	6.74	2.62	1.05	10.41
	Boswellia serrata Roxb.	0.67	1.40	7.76	9.82
	Terminalia anogeissiana Gere and Boatwr.	2.66	2.53	3.01	8.20
	Wrightia tinctoria (Roxb.) R.Br.	4.49	2.27	0.81	7.57
	Madhuca longifolia (Roxb.) A.Chev.	1.63	2.62	3.17	7.41
	Terminalia elliptica Willd.	2.42	2.53	2.44	7.39
	Ximenia americana L.	3.10	2.53	1.43	7.05
	Senegalia chundra (Roxb.) Maslin	2.71	2.53	1.01	6.25
	Grewia tiliifolia Vahl	3.15	2.35	0.60	6.10
Herbs, grasses and climbers	*Justicia micrantha* Wall.	14.57	7.73	-	22.30
	Andrographis paniculata (Burm.f.) Wall.	10.63	7.73	-	18.37
	Aristida adscensionis L.	12.07	5.93	-	18.00
	Spermacoce pusilla Wall.	8.60	5.41	-	14.02
	Blainvillea acmella (L.) Philipson	5.35	5.15	-	10.50
	Pleurolobus gangeticus (L.) J.St.-Hil.	3.05	4.64	-	7.69
	Phyllanthus virgatus G. Forst.	3.75	3.87	-	7.62
	Curculigo orchioides Gaertn.	1.88	5.41	-	7.30
	Urochloa ramosa (L.) T.Q.Nguyen	3.81	3.35	-	7.16
	Pulicaria wightiana (DC.) C.B. Clarke	3.59	3.35	-	6.94
	Achyranthes aspera L.	3.24	2.84	-	6.07
	Phyllanthus niruri L.	2.68	2.58	-	5.26
	Hemidesmus indicus (L.) R.Br.	1.17	3.87	-	5.03
	Cryptolepis dubia (Burm.f.) M.R.Almeida	0.78	3.87	-	4.64
	Spermacoce hispida L.	2.75	1.29	-	4.03

D- Density, F- Frequency, BA- Basal area, RD- Relative density, RF- Relative frequency, RBA- Relative basal area, IVI- Importance Value Index

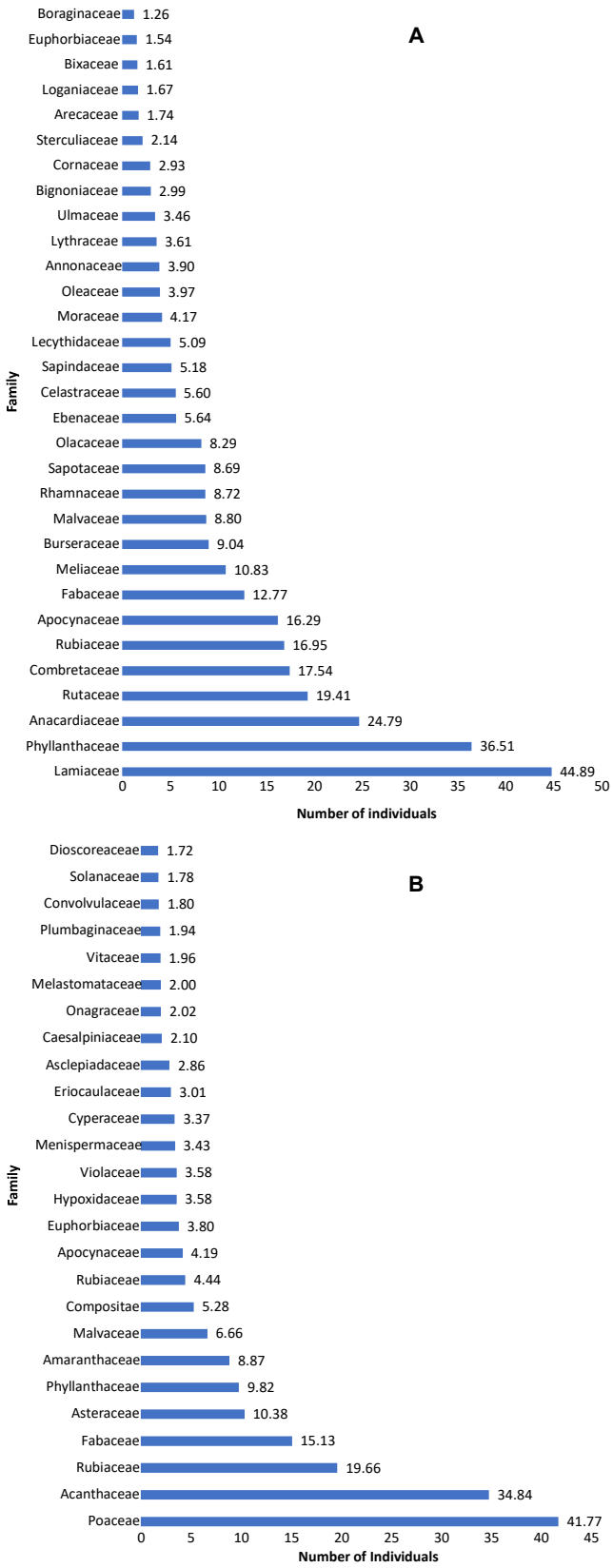

Fig. 5. Family index values (FIV) of different plant species of Narsapur forest. (A) Trees and shrub families, (B) Herb, grasses and climber families

inventoried in India and elsewhere in the tropics. Species richness ranging from 51 to 24 ha^{-1} with mean value of 38.2 ha^{-1} was recorded during the present study in case of woody vegetation. The mean value in the present study is higher than that of 21 species ha^{-1} in Kolli hills of India (Chittibabu and Parthasarathy 2000), 31 species ha^{-1} in dry deciduous forests of western India (Kumar et al., 2010), and similar to species composition in reserved forests of southern Eastern Ghats of Andhra Pradesh (Rao et al., 2011).

Total 31 families were observed constituting tree and shrub species while 26 families were recorded for the herbs, grasses and climbers. For the trees and shrubs, Lamiaceae (FVI = 44.89) was the most dominant family, followed by Phyllanthaceae (36.51) and Anacardiaceae (24.79). Together these three families constitute more than 100 % in the index value (Fig. 5A). For herbs, grasses and climbers, Poaceae was the most dominant family (FVI = 41.77), followed by Acanthaceae (34.84), Rubiaceae (19.66) and Fabaceae (10.38) (Fig. 5B). These families have the highest representation of tree and shrub species within the sampled area. This suggests that species within these families play a crucial role in shaping the structure and function of the ecosystem in this forest. In terms of woody plants (trees and shrubs), the top 10 families comprised of 82.60% of the total number of stems, while for herbaceous plants (herbs, grasses and climbers) constituted to 89.36% of the total number. Fabaceae was found to be the most speciose family in the present study with 17 species. Pragasan and Parthasarathy (2010), indicated dominance of Mimosaceae, followed by Euphorbiaceae, Rubiaceae, Rutaceae and Melastomataceae, a trend similar to the current study. Panda et al., (2013) observed that Euphorbiaceae, Rubiaceae, Fabaceae and Combretaceae were the families having highest abundance in terms of tree numbers in the northern part of the Eastern Ghats. In present study also Phyllanthaceae (closely related to Euphorbiaceae), Fabaceae and Rubiaceae were the dominant families.

Dominance- diversity curve: Both the dominance diversity curve of trees and shrubs as well as of herbs, grasses and climbers shows log normal distributions. The dominance diversity curve expressed in log normal series (Fig. 6A) indicates that *Cleistanthus collinus* and *Chloroxylon swietenia* are the dominant tree species that utilize most of the available resources and ecological niches, while the remaining species utilize the leftover resources within the forest stand.

In terms of herbs, grasses and climbers the log series distribution indicates that *Justicia micrantha*, *Aristida adscensionis* and *Andrographis paniculate.* The distribution pattern here seems to follow a typical log-normal or

geometric series model, which is common in ecological communities where a few species dominate while the majority are much rarer (Whittaker 1965).The steep initial decline suggests that a few species dominate the community in terms of abundance, while many others are less common and the long tail indicates that there are many species with low abundance, reflecting high species richness but unequal distribution of abundance across species.

Dispersion pattern of plant species: Dispersion of plant species can give valuable information on how individuals are arranged in a space. Many factors influence dispersion patterns like ecological functions, habitat requirements and niche occupancy. The ratio of the variance to the mean can then be used to determine whether the pattern is uniform or clumped, and is referred to as the index of dispersion (Krebs 1999). If the variance to mean ratio is more than one it

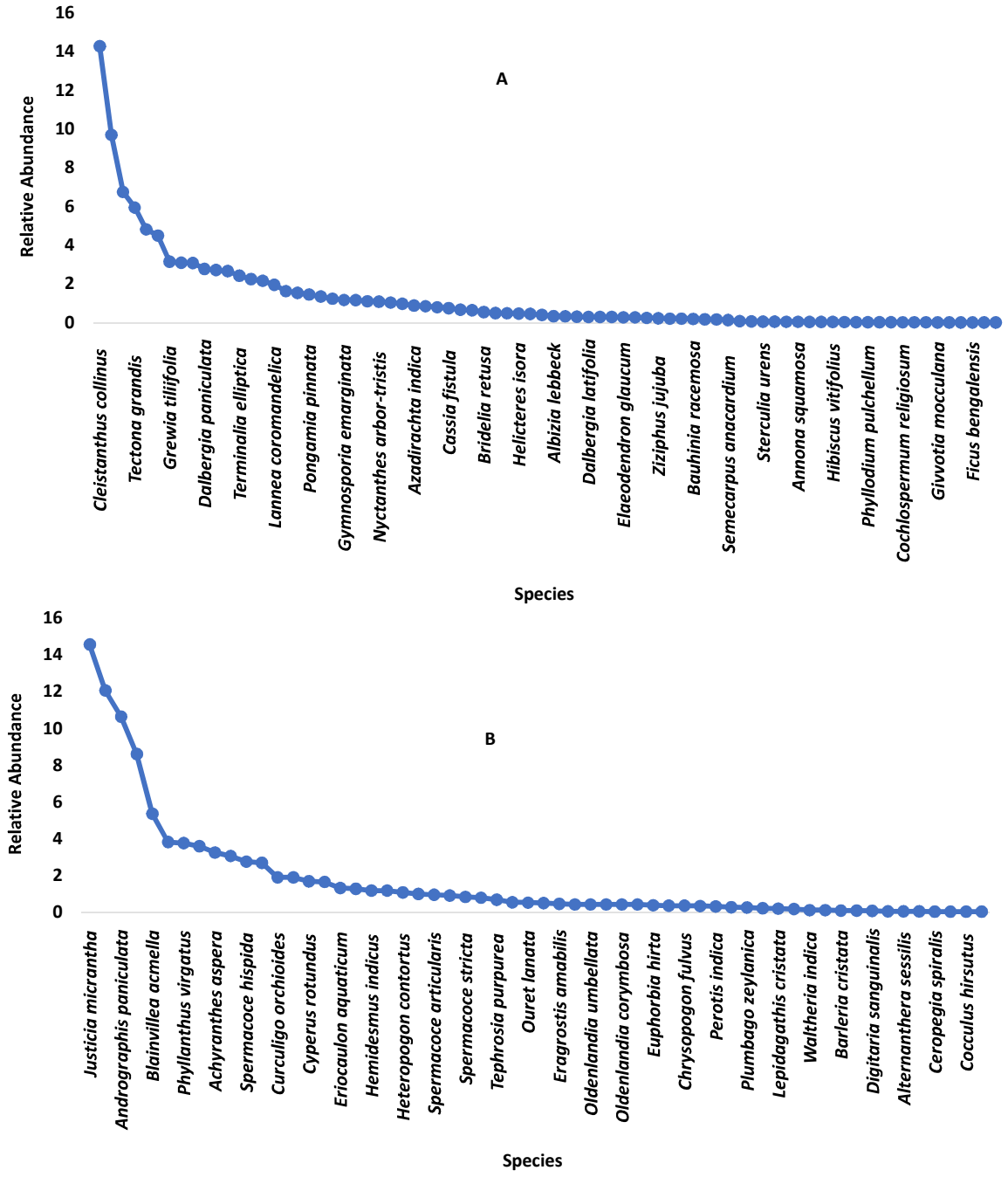

Fig. 6. Dominance – Diversity curve for plant species of Narsapur forest: (A) Tree and shrub species, (B) Herb, grass and climber species

Table 3. Dispersion pattern of trees and shrubs for all 30 transects of the 'Narsapur' forest of Telangana, arranged according to decreasing variance to mean ratio

Species	Variance	Mean	Chi-sq	Ratio	Aggregation
Wrightia tinctoria (Roxb.) R.Br.	1123.55	20.37	1599.82	55.17	Aggregated
Cleistanthus collinus (Roxb.) Benth.	954.56	64.70	427.86	14.75	Aggregated
Chloroxylon swietenia DC.	778.00	43.93	513.55	17.71	Aggregated
Holarrhena pubescens Wall. ex G.Don	634.32	30.57	601.81	20.75	Aggregated
Pongamia pinnata (L.) Pierre	378.19	6.57	1670.16	57.59	Aggregated
Tectona grandis L.f.	356.89	26.93	384.28	13.25	Aggregated
Ziziphus oenopolia (L.) Mill.	229.90	13.97	477.35	16.46	Aggregated
Grewia tiliifolia Vahl	223.86	14.27	455.04	15.69	Aggregated
Catunaregam spinosa (Thunb.) Tirveng.	198.10	10.20	563.22	19.42	Aggregated
Alangium salviifolium (L.f.) Wangerin	193.76	6.97	806.55	27.81	Aggregated
Grewia tiliifolia Vahl.	193.50	6.23	900.22	31.04	Aggregated
Gardenia latifolia Aiton	170.58	9.80	504.78	17.41	Aggregated
Terminalia anogeissiana Gere andBoatwr.	151.58	12.07	364.30	12.56	Aggregated
Ximenia americana L.	133.55	14.03	275.98	9.52	Aggregated
Nyctanthes arbor-tristis L.	122.02	4.90	722.18	24.90	Aggregated
Morindacoreia Buch.-Ham.	108.90	21.83	144.65	4.99	Aggregated
Phoenix sylvestris (L.) Roxb.	104.70	2.30	1320.13	45.52	Aggregated
Senegaliachundra (Roxb.) Maslin	92.42	12.30	217.91	7.51	Aggregated
*Ixora pavetta*Andrews	76.55	5.27	421.49	14.53	Aggregated
Diospyros chloroxylon Roxb.	65.87	3.83	498.30	17.18	Aggregated
Gymnosporia emarginata (Willd.) Thwaites	62.15	5.30	340.06	11.73	Aggregated
Dalbergia paniculata (Roxb.) Thoth.	54.87	12.57	126.63	4.37	Aggregated
Grewia hirsuta Vahl	48.39	5.60	250.57	8.64	Aggregated
Soymida febrifuga (Roxb.) A.Juss.	37.57	6.13	177.63	6.13	Aggregated
Bridelia retusa (L.) A.Juss.	37.36	2.47	439.24	15.15	Aggregated
Helicteresisora L.	37.06	2.10	511.76	17.65	Aggregated
Terminalia elliptica Willd.	36.86	10.97	97.47	3.36	Aggregated
Lagerstroemia parviflora Roxb.	29.15	4.43	190.68	6.58	Aggregated
Lannea coromandelica (Houtt.) Merr.	28.33	8.87	92.65	3.19	Aggregated
Miliusa tomentosa (Roxb.) Finet andGagnep.	26.79	2.20	353.09	12.18	Aggregated
Dolichandrone atrovirens (Roth) K.Schum.	25.60	4.70	157.94	5.45	Aggregated
Madhuca longifolia (Roxb.) A.Chev.	25.00	7.37	98.41	3.39	Aggregated
Mitragyna parvifolia (Roxb.) Korth.	24.82	2.07	348.32	12.01	Aggregated
Cassia fistula L.	21.77	3.40	185.65	6.40	Aggregated
Azadirachta indica A.Juss.	20.34	4.00	147.50	5.09	Aggregated
Olax scandens Roxb.	15.20	2.90	151.97	5.24	Aggregated
Boswellia serrata Roxb.	13.90	3.03	132.85	4.58	Aggregated
Elaeodendron glaucum (Rottb.) Pers.	13.70	1.23	322.19	11.11	Aggregated
Phyllanthus emblica L.	10.91	1.30	243.31	8.39	Aggregated
Diospyros melanoxylon Roxb.	9.86	5.00	57.20	1.97	Aggregated
Pterocarpus marsupium Roxb.	9.29	2.23	120.61	4.16	Aggregated
Strychnos potatorum L.f.	8.49	1.30	189.46	6.53	Aggregated
Albizia odoratissima (L.f.) Benth.	7.77	3.60	62.56	2.16	Aggregated

Cont...

Table 3. Dispersion pattern of trees and shrubs for all 30 transects of the 'Narsapur' forest of Telangana, arranged according to decreasing variance to mean ratio

Species	Variance	Mean	Chi-sq	Ratio	Aggregation
Holoptelea integrifolia (Roxb.) Planch.	7.57	1.47	149.64	5.16	Aggregated
Gmelina arborea Roxb.	6.00	0.93	186.29	6.42	Aggregated
Aegle marmelos (L.) Corrêa	5.98	1.23	140.57	4.85	Aggregated
Terminalia bellirica (Gaertn.) Roxb.	5.83	1.40	120.86	4.17	Aggregated
Buchanania lanzan Spreng.	4.92	1.80	79.33	2.74	Aggregated
Terminalia arjuna (Roxb.) Wight and Arn.	4.51	1.10	118.82	4.10	Aggregated
Rotheca serrata (L.) Steane and Mabb.	3.90	0.97	116.86	4.03	Aggregated
Dalbergia latifolia Roxb.	3.87	1.30	86.38	2.98	Aggregated
Butea monosperma (Lam.) Kuntze	3.43	0.77	129.61	4.47	Aggregated
Albizia amara (Roxb.) Boivin	3.37	0.93	104.86	3.62	Aggregated
Bridelia montana (Roxb.) Willd.	3.37	0.73	133.45	4.60	Aggregated
Albizia lebbeck (L.) Benth.	3.36	1.50	65.00	2.24	Aggregated
Ziziphus jujuba Mill.	2.90	1.00	84.00	2.90	Aggregated
Bauhinia racemosa Lam.	1.64	0.87	54.77	1.89	Aggregated
Semecarpus anacardium L.f.	0.87	0.60	42.00	1.45	Aggregated
Careya arborea Roxb.	0.86	0.37	68.09	2.35	Aggregated
Hibiscus vitifolius L.	0.83	0.17	145.00	5.00	Aggregated
Bergera koenigii L.	0.83	0.17	145.00	5.00	Aggregated
Ziziphus xylopyrus (Retz.) Willd.	0.83	0.17	145.00	5.00	Aggregated
Annona squamosa L.	0.58	0.20	84.00	2.90	Aggregated
Schleichera oleosa (Lour.) Oken	0.49	0.30	47.67	1.64	Aggregated
Vachellia leucophloea (Roxb.) Maslin, Seigler and Ebinger	0.46	0.23	57.29	1.98	Aggregated
Sterculia urens Roxb.	0.46	0.23	57.29	1.98	Aggregated
Tamarindus indica L.	0.37	0.20	54.00	1.86	Aggregated
Cordia dichotoma G.Forst.	0.30	0.10	87.00	3.00	Aggregated
Ficus mollis Vahl	0.26	0.13	56.00	1.93	Aggregated
Peltophorum pterocarpum (DC.) Backer	0.16	0.10	47.00	1.62	Aggregated
Phyllodium pulchellum (L.) Desv.	0.16	0.10	47.00	1.62	Aggregated
Limonia acidissima L.	0.13	0.07	58.00	2.00	Aggregated
Pterospermum xylocarpum (Gaertn.) Oken	0.13	0.07	58.00	2.00	Aggregated
Bombax ceiba L.	0.09	0.10	27.00	0.93	Uniform
Cochlospermum religiosum (L.) Alston	0.06	0.07	28.00	0.97	Uniform
Albizia procera (Roxb.) Benth.	0.03	0.03	29.00	1.00	Random
Cipadessa baccifera (Roxb. ex Roth) Miq.	0.03	0.03	29.00	1.00	Random
Ficus benghalensis L.	0.03	0.03	29.00	1.00	Random
Givotia moluccana (L.) Sreem.	0.03	0.03	29.00	1.00	Random
Premna tomentosa Willd.	0.03	0.03	29.00	1.00	Random
Prosopis cineraria (L.) Druce	0.03	0.03	29.00	1.00	Random

Table 4. Dispersion pattern of herbs, grasses and climbers for all 30 transects of 'Narsapur' forest of Telangana, arranged according to decreasing variance to mean ratio

Species	Variance	Mean	Chi-sq	Ratio	Aggregation
Aristida adscensionis L.	422.24	19.63	623.68	21.51	Aggregated
Justicia micrantha Wall.	279.46	23.70	341.95	11.79	Aggregated
Spermacoce pusilla Wall.	252.28	14.00	522.57	18.02	Aggregated
Urochloa ramosa (L.) T.Q.Nguyen	156.99	6.20	734.32	25.32	Aggregated
Achyranthes aspera L.	140.00	5.27	770.86	26.58	Aggregated
Spermacoce hispida L.	132.40	4.47	859.58	29.64	Aggregated
Blainvillea acmella (L.) Philipson	131.67	8.70	438.89	15.13	Aggregated
Andrographis paniculata (Burm.f.) Nees	128.36	17.30	215.16	7.42	Aggregated
*Phyllanthus virgatus*G.Forst.	114.30	6.10	543.39	18.74	Aggregated
Hybanthus enneaspermus (L.) F.Muell.	100.82	3.07	953.43	32.88	Aggregated
Heteropogon contortus (L.) P.Beauv.	83.24	1.73	1392.62	48.02	Aggregated
Pulicaria wightiana (DC.) C.B.Clarke	80.49	5.83	400.14	13.80	Aggregated
*Phyllanthus debilis*J.G.Klein	76.45	4.37	507.70	17.51	Aggregated
Eriocaulon aquaticum (Hill) Druce	66.19	2.13	899.75	31.03	Aggregated
Setaria pumila (Poir.) Roem. and Schult.	56.09	1.90	856.16	29.52	Aggregated
Cynodon dactylon (L.) Pers.	42.52	1.60	770.75	26.58	Aggregated
Spermacoce articularis L.f.	34.67	1.53	655.74	22.61	Aggregated
Pleurolobus gangeticus (L.) J.St.-Hil.	33.55	4.97	195.90	6.76	Aggregated
Abutilon indicum (L.) Sweet	29.10	2.07	408.32	14.08	Aggregated
Cyperus rotundus L.	27.10	2.73	287.51	9.91	Aggregated
*Spermacoce stricta*Sesséand Moc.	22.71	1.33	494.00	17.03	Aggregated
Curculigo orchioides Gaertn.	22.62	3.07	213.87	7.37	Aggregated
Eragrostis viscosa (Retz.) Trin.	13.37	0.73	528.91	18.24	Aggregated
Chamaecrista pumila (Lam.) V.Singh	13.33	0.67	580.00	20.00	Aggregated
Oldenlandia corymbosa L.	13.33	0.67	580.00	20.00	Aggregated
Pseudanthistiria umbellata (Hack.) Hook.f.	13.33	0.67	580.00	20.00	Aggregated
Hemidesmus indicus (L.) R.Br.	12.78	1.90	195.11	6.73	Aggregated
Blepharis maderaspatensis (L.) B.Heyne	12.40	1.47	245.09	8.45	Aggregated
Oldenlandia umbellata L.	9.82	0.67	427.00	14.72	Aggregated
Chrysopogon fulvus (Spreng.) Chiovenda	9.63	0.57	493.00	17.00	Aggregated
Ouret lanata (L.) Kuntze	9.52	0.83	331.40	11.43	Aggregated
Crotalaria pusilla Roxb.	7.06	0.80	256.00	8.83	Aggregated
Tephrosia purpurea (L.) Pers.	6.51	1.10	171.55	5.92	Aggregated
Grona triflora (L.) H.OhashiandK.Ohashi	5.29	0.87	177.08	6.11	Aggregated
Ludwigia hyssopifolia (G.Don) Exell	5.22	0.53	284.00	9.79	Aggregated
Cenchrus pedicellatus (Trin.) Morrone	4.78	0.67	208.00	7.17	Aggregated
Cryptolepis dubia (Burm.f.) M.R.Almeida	3.86	1.27	88.32	3.05	Aggregated
Perotis indica (L.) Kuntze	3.78	0.50	219.00	7.55	Aggregated
Euphorbia hirta L.	3.35	0.60	162.00	5.59	Aggregated
Vitis aestivalis Michx.	2.87	0.43	192.38	6.63	Aggregated
Plumbago zeylanica L.	2.80	0.40	203.00	7.00	Aggregated
Corchorus aestuans L.	1.68	0.33	146.00	5.04	Aggregated
Evolvulus alsinoides (L.) L.	0.83	0.17	145.00	5.00	Aggregated
Lepidagathis cristata Willd.	0.70	0.30	67.67	2.33	Aggregated
Waltheria indica L.	0.56	0.17	97.00	3.34	Aggregated
Solanum nigrum L.	0.53	0.13	116.00	4.00	Aggregated
Abrus precatorius L.	0.48	0.27	52.00	1.79	Aggregated
Barleria cristata L.	0.33	0.13	71.00	2.45	Aggregated
Digitaria sanguinalis (L.) Scop.	0.30	0.10	87.00	3.00	Aggregated
Acalypha indica L.	0.13	0.07	58.00	2.00	Aggregated
Alternanthera sessilis (L.) DC.	0.13	0.07	58.00	2.00	Aggregated
Crotalaria pallida Aiton	0.13	0.07	58.00	2.00	Aggregated
Ceropegia spiralis Wight	0.03	0.03	29.00	1.00	Random
Cissampelos pareira L.	0.03	0.03	29.00	1.00	Random
Cocculus hirsutus (L.) W.Theob.	0.03	0.03	29.00	1.00	Random
Dioscorea hispida Dennst.	0.03	0.03	29.00	1.00	Random

indicates that individuals in this population are exhibiting a clumped spacing pattern in the sampled habitat. If this ratio is less than one, it indicates a uniform distribution. Whereas if it is one, that indicates individuals are randomly distributed in space. In case of trees and shrubs, out of 81 species, 73 species are clumped or aggregated and 2 species are uniform and 6 species are random in dispersion. In case of herbs, grasses and climbers, 55 are aggregated and 4 are random in dispersion. In trees, all of the 15 highest IVI values were aggregated while in herbs and climbers, also all were aggregated and, out of top 15 IVI values species (Table 3, 4).

CONCLUSION

The TDDFs of NRF, Telangana shows high species richness as well as wide species diversity. Difference in Fisher's alpha values indicate that the forest has more woody diversity as compared to herbaceous community, as it is in case of tropical dry deciduous forests. Although the number of species within individual transects (alpha diversity) remained relatively stable, there were notable differences in species composition between transects. This led to moderate compositional heterogeneity (beta diversity) and a substantial Shannon diversity index for trees and shrubs. The high species richness was due to presence of many rare species. The ongoing disturbances, such as small-scale timber extraction, fires, and grazing, are prevalent and impacting the regeneration of certain species. If these disturbances remain controlled, the Narsapur forests will likely retain a healthy demographic structure. However, an increase in disturbance levels could potentially weaken the forest structure and pose a serious threat to the tropical forest ecosystem. There is a significant demand for comprehensive information and updates on forests, which are essential for tracking progress toward sustainable forest management. The results of this study suggest that management actions should prioritize interventions to increase canopy cover, eradication of invasive species such as *Lantana camara*, and strict grazing controls to facilitate regeneration. Community-based forest management approaches, integrating local stakeholders, can further enhance conservation outcomes and ensure sustainable use of ecosystem services. Moreover, long-term monitoring plots should be established in TDDF landscapes to track changes in floristic composition under climate and anthropogenic pressures, thereby guiding adaptive restoration strategies. The information presented in this paper will provide a solid foundation for forest managers and other stakeholders to prioritize conservation actions aimed at conserving biodiversity in the forested landscapes of India.

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AUTHOR'S CONTRIBUTIONS

Ratnaker Jauhari, Bharati Patel: Conceptualization, Methodology, Software; Krishna Chaitanya, Yashwanth Reddy, Yasaswinee Rout: Data curation; Bharati Patel, Vivek N. Chovatiya: Writing- original draft preparation; Bharati Patel, Vivek N. Chovatiya: Visualization, investigation; Ratnaker Jauhari, Bharati Patel: Supervision; Bharati Patel, Vivek N. Chovatiya: Software, validation; Bharati Patel, Vivek . Chovatiya: Reviewing and editing.

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Exposure Visits and Biodiversity Conservation: Can Field Visits affect the Conservation Cognizance?

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***Abstract*:** The study attempted to assess the change in students' cognizance towards biodiversity and conservation due to exposure visits. About 163 students, who visited the Institute of Forest Biodiversity (ICFRE-IFB), Hyderabad, during February and March 2023 for an exposure visit, form the respondent group. The survey schedule consisted of two components: i) a structured survey-where students were asked to respond to pre-defined questions, and ii) students were requested to do annotated drawings before and after the visit. Survey responses were subjected to statistical tests and correspondence analysis. Pre- and post-visit drawings were analyzed based on i) change in the number of components, and ii) improvement in clarity on biodiversity conservation. The students who thought biodiversity conservation was unessential before the visit have changed their perception and understood its importance. Besides, students who earlier were unconcerned about conservation, in the post-visit mentioned that they are personally concerned about biodiversity conservation. Moreover, students revealed a high level of learning and enjoyment through the visit. Correspondence analysis revealed that learning is highly associated with the level of enjoyment. Analyzing the annotated drawings indicated that there is an increase in the number of components by 1.3 units, and an improvement in the clarity about biodiversity conservation.

***Keywords*:** Biodiversity, Conservation, Annotated drawings, Correspondence analysis

India is one of the megadiversity countries in the world, hosting approximately 12% of the species recorded globally (Dar et al., 2022). Among the species reported from India, nearly 47% of reptiles and 61.2% of amphibians are predominantly endemic to the country (Deuti et al., 2022). The 10 biogeographical zones accommodate 45,500 plant species and 91,200 animal species (CBD 2023). The reported list of species is not yet saturated; in 2022 alone, 467 new animal species (Banerjee et al., 2023) and 339 new plant species (BSI 2023) were discovered, indicating the rich biodiversity status of India. However, increasing population, industrial development, and rapid urbanization have challenged the sustenance of biodiversity over the past decades by placing pressure on natural resources (Semy and Singh 2021). These anthropogenic disturbances have adversely affected biodiversity status, which, if left unchecked, may threaten the existence of humankind in the long run. Recognizing the importance of biodiversity, the Government of India has launched various conservation programmes like National Afforestation Programme (2000), National Biodiversity Action Plan (2009), National Plan for conservation of Aquatic Ecosystems, Recovery of Endangered species and Green India Mission (2014), *etc*. However, to scale up these initiatives and ensure their successful implementation, public participation is an essential component. To ensure public participation, the public need to be sensitized regarding the importance of biodiversity and its conservation (Barman et al., 2021). For this diffusion process, school students can be primarily targeted through education, as they not only form the future workforce but may also function as an excellent diffusion network to reach out to other age groups. Education in the form of capacity building, empowerment, and public engagement has been identified as an effective tool for the successful and sustainable implementation of actions. Education should take the form of transformative learning that can infuse critical and holistic thinking to foster behavioural change (Singh and Rahman 2012). To sensitize students, integrating well-planned compulsory education on biodiversity into curricula from the early age of 11 can help them gain knowledge and understanding related to the importance of biodiversity conservation while developing a sense of responsibility to protect it (Gayford 2010, De and Dwivedi 2023).

Though environmental science courses are included in the curriculum of Indian schools, there is a debate about whether such nature-related subjects should also consider field teachings along with the theoretical part, as the former ensures learning through field experience. To provide evidence that field-based experience improves students' learning, we formulated this study to evaluate the change in students' perceptions and awareness about biodiversity and

its conservation after a field visit to the ICFRE-Institute of Forest Biodiversity (IFB), Hyderabad, a research institute focused on biodiversity and related aspects. The major research questions addressed in the study are (i) Does a field visit help improve students' awareness related to biodiversity? (ii) Does a field visit help improve students' attitude towards biodiversity conservation? The study aimed to gather evidence via mixed-method approaches, and the insights may help policymakers design better curricula to optimize the students' learning curve.

MATERIAL AND METHODS

Present study was conducted at ICFRE-IFB, Hyderabad having an area of 40 ha in the backdrop of tropical dry deciduous forest, Dulapally reserve forest, enriched with diversified flora and fauna. The institute established field gene banks or field trials of threatened tree species such as Indian sandalwood, Red sanders and Indian rosewood and other species such as bamboos, mahua and teak. Nearly 50% of the institute's area has undisturbed natural forest patch which houses over 144 plant species, belonging to 55 plant families that includes 71 tree species, 50 species of birds including dove, peacock, quail, owl, *etc*., reptiles such as chameleon, garden lizard, snake, monitor lizard, etc., mammals such as bats, mongoose, rat, wild boar, wild cat, porcupine, squirrel, etc., and several insect species (Prasad et al., 2018). As part of the institute's extension mechanism, school students visit the institute for a field visit and interact with scientists of different disciplines. Hence, the present study was conducted to understand the effect of such an exposure visit on altering the attitude and cognizance of students towards biodiversity and its conservation.

Treatment: During the institute visit, the students were exposed to insect collection, seed collection and nurseries comprising rare and endangered plant species to give insights on the *ex-situ* biodiversity conservation. Later, the students were taken to the forest patch of the campus where they had the chance to observe various flora and fauna.

Data collection: For this study, a pre- and post-visit survey was conducted among 163 students who visited ICFRE-IFB, Hyderabad during February and March 2023. These included all students from both government and private schools who visited the institute during the period. The students were asked to make annotated drawings about biodiversity before and after the visit (Jensen 2014). In addition, students were requested to respond to pre-defined questions and the responses were measured using Likert scale to probe their perception and attitude towards conservation.

Data analysis: The pre- and post-visit drawings were evaluated based on two aspects: (i) change in number of components and (ii) change in clarity in mentioning the biodiversity components. Evaluation of pre and post-visit drawings were done independently by four researchers, and a consensus was reached after verification. For qualitative analysis, tabular and descriptive statistics were used at relevant places. Apart from this, a t-test was used to find differences among the pre- and post-visit data, and correspondence analysis was used to visualize the association between the level of enjoyment and the level of learning (Greenacre 2010, Mohankumar et al., 2023).

RESULTS AND DISCUSSION

The study comprised 163 students from six different schools, including 106 boys and 57 girls, with an average age of 14 years. Analysis of the response to the question about students' perception of the need for biodiversity conservation, the results revealed that 7 students who had thought that it was nonessential to conserve biodiversity earlier or who were unsure of biodiversity conservation had begun to understand and acknowledge the need for biodiversity conservation (Table 1). Similarly, 31 students who were unsure or not personally concerned about biodiversity conservation prior to the survey were personally concerned after their visit (Table 2).

Primarily, students' visits have positively impacted their understanding of biodiversity conservation. Studies have shown that personal visits influence the emotions of the visitors and increase their biophilia (Myers et al., 2004), and biophilia catalyses a positive conservation attitude towards a particular animal or plant among the students (Stokes 2007, Ballouard et al., 2012).

Table 1. Students' response to the question “Is there a need to conserve biodiversity? What do you think?”

Response	Pre-visit (n)	Post-visit (n)	Change (n)
Yes	152	159	+7
No	3	1	-2
Not sure	8	3	-5
Total	163	163	–

Table 2. Students' response to the question, “Are you personally concerned about conserving biodiversity?”

Response	Pre-visit (n)	Post-visit (n)	Change (n)
Yes	102	133	+31
No	16	12	-4
Not Sure	45	18	-27
Total	163	163	–

When students were asked to self-report their level of learning and enjoyment during the visit, the majority indicated the highest levels of both learning and enjoyment (Table 3). Similar results were also reported by Lavie Alon and Tal (2015) and Whitburn et al., (2023). To explore the potential link between learning and enjoyment levels, we used a correspondence analysis biplot, which showed a positive relationship between these levels (Fig. 1). Therefore, students were able to learn more joyfully during visits than in regular classroom setting. Several studies have also confirmed that emotional bonds with nature, especially at early ages, can significantly influence conservation behaviour (Cheng and Monroe 2012, Collado and Corraliza 2015). Hence, visits could be crucial in changing conservation behaviour among students. Hughes et al. (2011) also analysed the post-visit actions of Australian families and reported that the group involved demonstrated improvements in conservation knowledge, attitudes towards wildlife, and litter-picking frequency.

With the help of four researchers, the pre-visit and post-visit drawings were evaluated based on the number of components. To know the difference in the number of components between pre- and post-visit, a paired t-test was used. The result indicated that, on average, the visit had increased the number of components by 1.3 units (Table 4). Besides, we also evaluated the change in clarity of biodiversity among the students due to the exposure visit. The experts observed the pre- and post-visit drawings and classified them into three categories- positive change, no change and negative change. The post-visit drawings of 65% of students had an improvement in clarity as compared to pre-visit drawings (Table 5) (Fig. 2).

Table 4. Change in the number of biodiversity components in the pre- and post-visit drawings

Variable	Mean	Std. Err.	Std. Dev.
Number of components in the pre-visit drawings	3.59	0.18	2.26
Number of components in the post-visit drawings	4.92	0.19	2.40
Mean difference	-1.33***	0.15	1.93

*** Significant at 1 percent LoS

Table 5. Change in the clarity of biodiversity components in the pre- and post-visit drawings

Change in clarity	Frequency	Percentage
Negative change	9	5.52
No change	48	29.45
Positive change	106	65.03

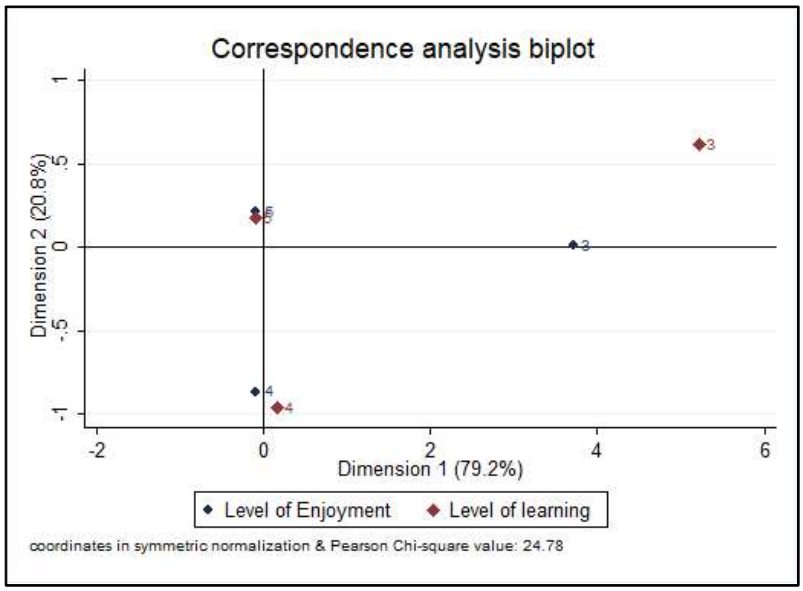

Fig. 1. Association between level of enjoyment and learning

Table 3. Level of learning and enjoyment

Attributes	Very low	Low	Moderate	High	Very high	Total
Rate your learning experience during your visit to the Institute of Forest Biodiversity, Hyderabad	0	0	2	26	135	163
Did you enjoy your visit to the Institute of Forest Biodiversity, Hyderabad?	0	0	4	31	128	163

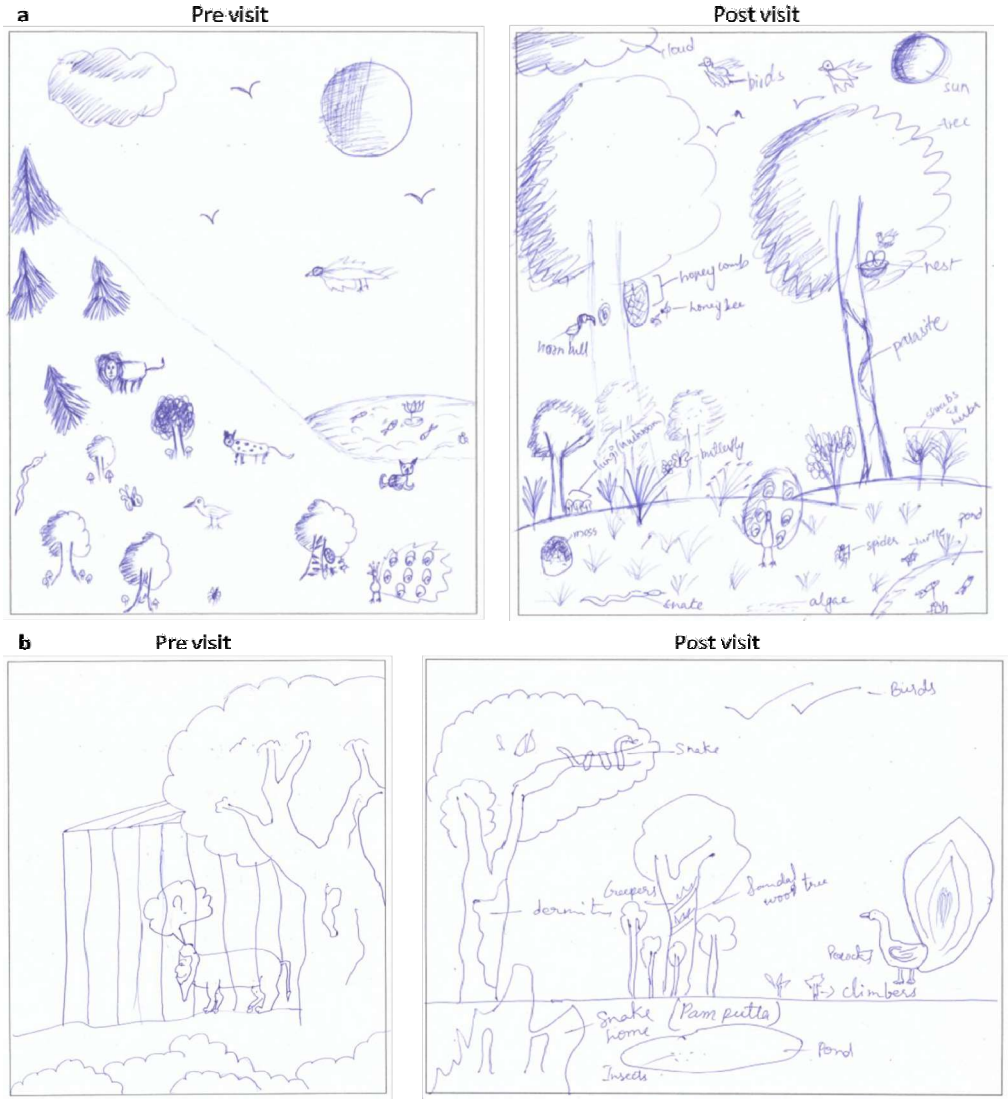

Fig. 2. Pre- and post-visit annotated drawings of (a) a 15-year-old girl and (b) a 14-year-old boy in response to the question to draw and label the components of biodiversity

Hence, engaging with nature at an early age could positively influence student's conservation behaviour. So, summer camps, treks, visits to natural parks, and zoological parks should be promoted and incorporated into student's curricula. Such guided visits with subject and field experts can play a potential role in educating even complicated issues related to biodiversity conservation (Whitehouse-Tedd et al., 2022) and sustainability (Counsell et al., 2023). Rather than using traditional teaching techniques, providing interactive multi-media screens, simulations, and visual effects would increase the probability of student's understanding of biodiversity (Lindemann-Matthies and Kamer 2006).

CONCLUSION

Analysis of pre- and post-visit annotated drawings clearly indicated the increased cognizance of students regarding biodiversity and conservation. Similarly, the analysis of structured survey data indicated the positive change in students' attitude towards biodiversity and its conservation. These results reiterate the need for guided exposure visits by students to biodiversity research, conservation, or related places at an early age to witness a positive change in students' attitude and perception towards biodiversity and its conservation. Apart from this, students may also act as efficient agents in diffusing the importance of biodiversity and its conservation among their networks, particularly parents

and elders. Hence, exposure visits could act as a magnificent tool to witness a positive change in the society.

AUTHOR'S CONTRIBUTION

Venkidusamy Kavi Sidharthan, Bharati Patel, Niranjan Sivalingam, Logesh Mohankumar, and Muthuprasad Thiyaharajan contributed equally to the conception, design, analysis, and manuscript preparation. Yuvaraj Praveen contributed to data collection and assisted in the review and editing of the manuscript.

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Assessment of Quantitative Profile of Plant Species of Forest Vegetation Along the Elevational Gradient in the Western Himalayas, India

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***Abstract*:** This study presents a quantitative ordination analysis of forest vegetation at different altitudes in the Nainital district of the western Himalayas, India. The forest sites examined were located at 29.3924° N, 79.4534° E, at elevations ranging from 400 to 2500 meters above sea level. The vegetation analysis was conducted using the quadrat method. Total 75 quadrats were randomly placed at each elevation site to assess the density, basal area, species diversity, and importance value index (IVI) of plant species. *Quercus floribunda* and *Q. leucotrichophora* dominated the higher altitude zone, while *Pinus roxburghii* and *Shorea robusta* dominated the middle. *Shorea robusta* and *Mallotus philippinensis* dominated the lower altitude zone. Species richness, density, basal area, and diversity ranged from 117-168, 580-717 individuals ha^{-1}, 52.8-69.9 m^2 ha^{-1}, and 2.4-2.1, respectively. The elevation significantly influences the forest vegetation parameters and species composition. Higher elevation remains structurally stable; middle elevation is more resilient, and lower elevation is more ecologically dynamic. Among all these elevations, the lower elevation is a more vulnerable site that requires urgent conservation and management efforts.

Keywords: Species composition, Basal area, Species diversity, Elevational gradient, Western Himalayas

Forest is defined as a plant community mainly composed of trees and other woody plants. Land covered by a tree canopy of more than 10 per cent and spanning an area greater than 0.5 hectares is considered a forest, based on the presence of trees and the lack of other dominant land uses (FAO 2022). Forests are a primary source of biodiversity globally, offering various ecosystem services to humanity and the earth's environment. Human well-being and livelihoods heavily rely on the Earth's ecosystems and biodiversity. In recent decades, describing this reliance in terms of a set of “services” provided by ecosystems has become common. Ecosystem services are defined here as “the benefits humans derive from ecosystems” (MEA 2005a). However, recently, the decline in biodiversity threatens ecosystem stability and human well-being worldwide. In India, nearly two-thirds of the population depends directly on climate-sensitive sectors such as agriculture, fisheries, and forests (Sathaye et al., 2006). Various abiotic and biotic factors influence forest structure and its functional dynamics (Chawla et al., 2008).

In India, the Himalayan forests are very diverse and complex ecosystems in the world due to variations in altitude, topography, geographical extent, and climatic conditions (Sundariyal and Sharma,1996, Sharma et al., 2017). In this region, the dominated forest tree species are Sal, Pine, and Oak tree species in the lower, middle, and higher elevational site, respectively. The Himalayan forests support diverse ecosystem services to upstream and downstream communities (Dhyani and Dhyani 2016, Negi et al., 2018). However, the nature of forest communities largely depends on the ecological characteristics of sites, species richness, diversity, distribution, abundance, and regeneration status of species (Pandita et al., 2019). Bhat et al. (2020) stated that assessing species composition, diversity, and structure has been a primary focus of ecological forest studies. Scientists have observed that forests and other natural habitats have receded in the last few decades. Consequently, forest biodiversity and productivity have declined in many parts of the world. So, there is need to improve our understanding of these sensitive sectors at local and regional levels to gain knowledge about the physical, ecological, and social systems and reduce the pressure on vulnerability and adaptability (Climate Change 2001).

The degradation and disruption of forests caused by anthropogenic pressure have altered the density, diversity, basal area, and IVI (Importance Value Index) of forest species in parts of the region. The change in forest composition and structure largely takes the form of rapid shifts in resource use patterns, land use systems, and climate variability, coupled with overgrazing and resource over-exploitation. The genetic diversity of trees is being threatened and eroded by the loss of tree populations, unsustainable harvesting, overgrazing, climate change, fire, and invasive species (FAO 2014). Projected declines in the

diversity and abundance of primary pollinators threaten food security, human health, and the cultural fabric and livelihoods of millions of mainly rural and indigenous communities (De Vos et al., 2015). Forest carbon stock refers to the carbon stored in forests across four pools – living biomass, dead wood, litter, and soil organic matter. Forests sequester atmospheric carbon during photosynthesis, which is stored in these four components but can also be released through processes like deforestation, fire, and decay. Consequently, forest carbon stock and its changes are critical indicators of forests' role in the carbon cycle and reflect the quality of forest management. Therefore, human society must recognize the importance of forest biodiversity for sustainable human and environmental health. Several studies on vegetation analysis have been conducted in different parts of the country . However, regarding the forests in the present study area, there is a lack of data on species structure across different vegetation layers (tree, shrub, and herb) along elevational gradients within the diverse climatic zones of the Nainital district in Uttarakhand, India. Due to numerous internal and external factors, most forested sites lack sufficient resources, as they have been heavily impacted by humans and climate change. The objectives of this study was to assess and illustrate the real-time occurrence and status of species in forest vegetation along the elevational gradient, and to examine the variation of species among different elevational forest sites..

MATERIAL AND METHODS

Study sites: The present studied forests are situated at three elevational ranges of 400-1000 m, 1000-1500 m, and 1500-2500 m, lying between coordinates 29.3924° N and 79.4534° E in Nainital. The study sites are in the nearly tropical, sub-tropical, and temperate climatic zones. The first two sites are in tropical and sub-tropical regions of the Shiwalik, while the third is in the temperate zone. The Shiwalik comprises highly degraded landmasses at elevations from 400 to 1500 m in the western Uttarakhand Himalayan region. Sal (*Shorea robusta)* forests with broad-leaved species and early successional riverine species like Shisham-Khair (*Dalbergia sissoo-Acacia catechu*) dominate the vegetation. Pine (*Pinus roxburghii*) along with other broad-leaved trees dominates the upper hill areas (Fig. 1).

The climate of the study sites is monsoon-type and influenced by temperature and rainfall patterns. The three distinct seasons—(i) dry and warm summer (mid-March to mid-June), (ii) wet and warm rainy season (mid-June to mid-September), and (iii) dry and cold winter (October to February) with frequent frost occurrences in a year. Geologically, the sites are the youngest hills, as the rocks are relatively recent and consist of sandstone conglomerate beds, quartzite, and unconsolidated segments of cobbles, shingles, pebbles, gravels, and boulders. The rocks are usually in contact with the sediments of the Indo-Ganga plain along prominent fault zones.

Meteorological information: The annual average precipitation of the study area was 1122.73 mm. Accordingly, the maximum and minimum precipitation were 326.27 mm in July and 0.0 mm in November, respectively. The highest temperature was 39.79 °C in June, and the lowest was 2.58

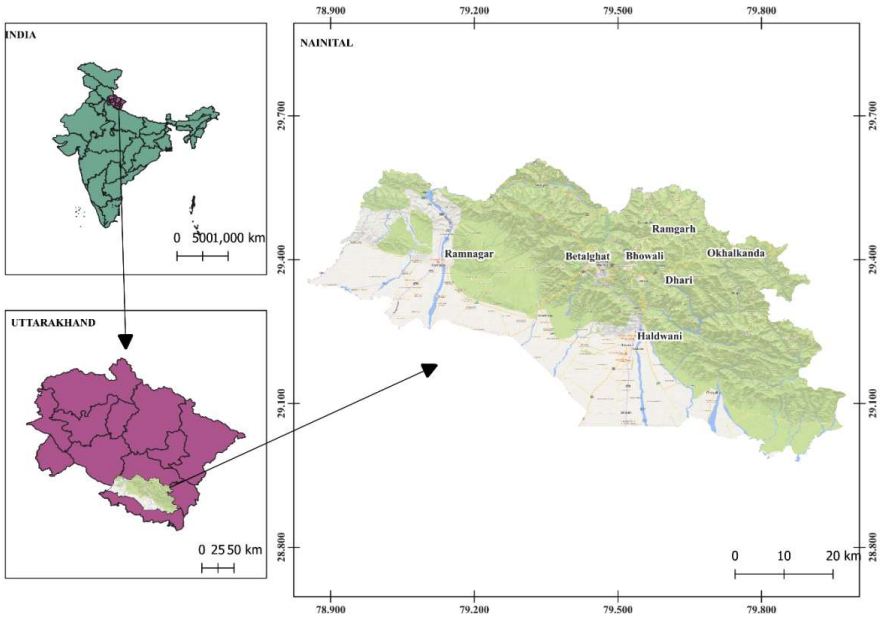


Fig. 1. Studied forest sites along the elevational gradient of western Himalaya, India

°C in December and January. The relative humidity was highest in August (86.15%), followed by September (81.59%), while the minimum was in April (28.11 %). This meteorological data for precipitation, temperature, and relative humidity illustrates climatic variation in the Nainital district (power.larc.nasa.gov 2007) (Fig. 2).

Vegetation sampling: Vegetation analysis for tree, shrub, and herb species across all three sites was conducted. The plant species were identified based on taxonomic features from literature (Osmaston, 1926) and Flora Simlensis (Collet 1971). Species analysis employed the quadrat method (Saxena and Singh, 1982, Lodhiyal and Lodhiyal, 2003). Total of 75 quadrats (25 in each sub-plot in each elevational forest site) were placed along each elevational gradient to assess the quantitative profile of plant species, including density, abundance, and frequency (Curtis and McIntosh 1950). The quadrats measured 10 m × 10 m for trees, 5 m × 5 m for shrubs, and 1 m × 1 m for herbs. Tree diameters were measured at breast height (1.37 m) using tree caliper. The diameter of shrub species was measured at 20 cm above ground to ensure accuracy during data collection. Species richness per unit area was determined (Whittaker 1972, Magurran 2013). Species diversity (H'), concentration of dominance (CD), and evenness (E) in each elevational zone were quantified using the Shannon-Wiener diversity index (Shannon and Wiener 1963), Simpson dominance index (Simpson 1949) and Pielou's evenness index (Pielou 1966). The indices were calculated as follows:

$$H' = -\sum_{i=1}^{s}\left(\frac{Ni}{N} + \ln\frac{Ni}{N}\right)$$

$$Cd = \sum_{i=1}^{s}(Ni/N)^2$$

$$E = \frac{H'}{\ln S}$$

Where, Ni = Total number of individuals of a species, N= Total number of individuals of all species, and S= Total number of species.

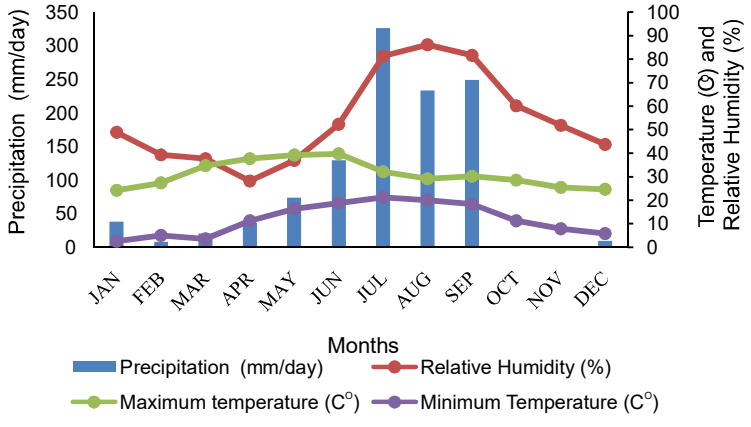
Statistical analysis: The data was statistically analyzed using correlation analysis, PCA, rank-abundance curve, and cluster analysis with the help of MS Excel and PAST software. Statistical analysis of the data was performed using correlation analysis, principal component analysis, rank-abundance curves, and cluster analysis using MS Excel and Past software. Rank-abundance curves were used to plot species dominance curves at different elevations. Cluster analysis was performed to classify the study sites based on similarity in their vegetation characteristics, revealing patterns of ecological similarity.

RESULTS AND DISCUSSION

Species richness: Total of 441 plant species were reported from the study area. Of these, 168 (38.1%), 159 (36.1%), and 114 (25.9%) species were at higher, middle, and lower elevations, respectively. The higher elevation, 52 (31.0%) trees, 33 (19.6%) shrubs, and 83 (49.4%) herbs were observed. At middle elevation, 54 (34.0%) trees, 33 (20.8%) shrubs, and 72 (45.3%) herbs were recorded. At lower elevation, 50 (43.9%) trees, 17 (14.9%) shrubs, and 47 (41.2%) herbs were identified (Fig. 3). To better represent the plant species, a hierarchical cluster was formed (Fig. 7).

Vegetation Analysis

Tree layer: In the higher elevation forest site (1500-2500 m), total tree density was 717 individuals ha^{-1} and basal area was 69.9 m^2 ha^{-1}. Species diversity, evenness, and dominance concentration were 2.1, 0.3, and 0.5, respectively (Table 1). The highest IVI values were for *Quercus floribunda* (93.0) followed by *Quercus leucotrichophora*, *Rhododendron arboreum*, *Pinus roxburghii*, *Lyonia ovalifolia* and *Quercus*



Source: power.larc.nasa.gov

Fig. 2. Meteorological information of the study sites

semecarpifolia (5.3). In the middle elevation forest sites (1000-1500m), total tree density was 580 individuals ha^{-1} and basal area was 52.8 m^2 ha^{-1}. Species diversity, evenness, and dominance concentration were 2.2, 0.3, and 0.6, respectively. The highest IVI was reported for *Pinus roxburghii* (145.6) followed by *Shorea robusta* and *Mallotus philippinensis*, In the lower elevation forest site (400-1000m), total tree density was 640 individuals ha^{-1} and basal area was 57.3 ha^{-1}. Species diversity, evenness, and dominance concentration were 2.4, 0.3, and 0.6, respectively. The highest IVI values were observed for *Shorea robusta* (142.3) followed by *Mallotus philippinensis*, *Eucalyptus tereticornis*, *Populus deltoides*, *Acacia catechu* and *Mangifera indica* (4.4).

Shrub layer: In the higher elevation forest site, total shrub density and basal area were 1654 individuals ha^{-1} and 1.5 m^2 $ha^{-1,}$ respectively. Species diversity, evenness, and concentration of shrub dominance were 3.2, 0.04, and 0.9, respectively. The highest density was for *Hypericum oblongifolium* (210) and *Eupatorium adenophorum* (170), followed by *Arundinaria falcata* and *Daphne cannabina*. In the middle elevation forest site, total shrub density and basal area were 966 individuals ha^{-1} and 4.5 m^2 ha^{-1}, respectively. Species diversity, evenness, and concentration of shrub dominance were 3.2, 0.04, and 0.9, respectively. *Eupatorium adenophorum* (96) and Lantana camara (87) showed the highest density, followed by *Woodfordia fruticosa* (78). In the lower elevation forest site, total shrub density and basal area were 982 individuals ha^{-1} and 0.6 m^2 ha^{-1}, respectively. Species diversity, evenness, and concentration of shrub dominance were 2.6, 0.1, and 0.9, respectively. *Lantana camara* (198) and *Adhatoda vasica* (95) had the highest density, followed by *Murraya koenighii* (90).

Herb layer: In the higher elevation forest site (1500-2500 m),

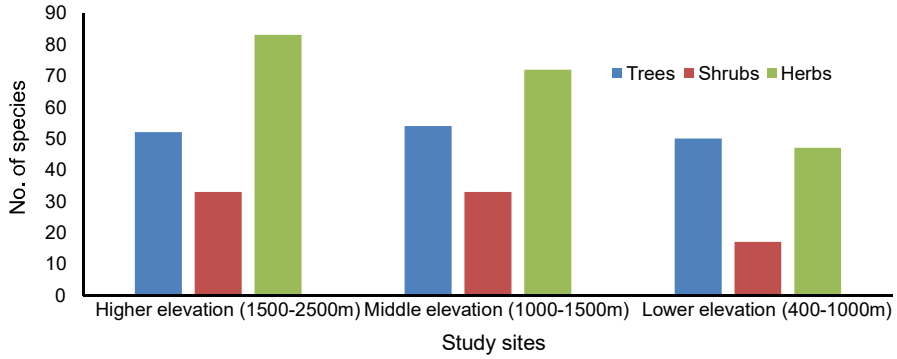


Fig. 3. Summary of plant species richness found in the study area

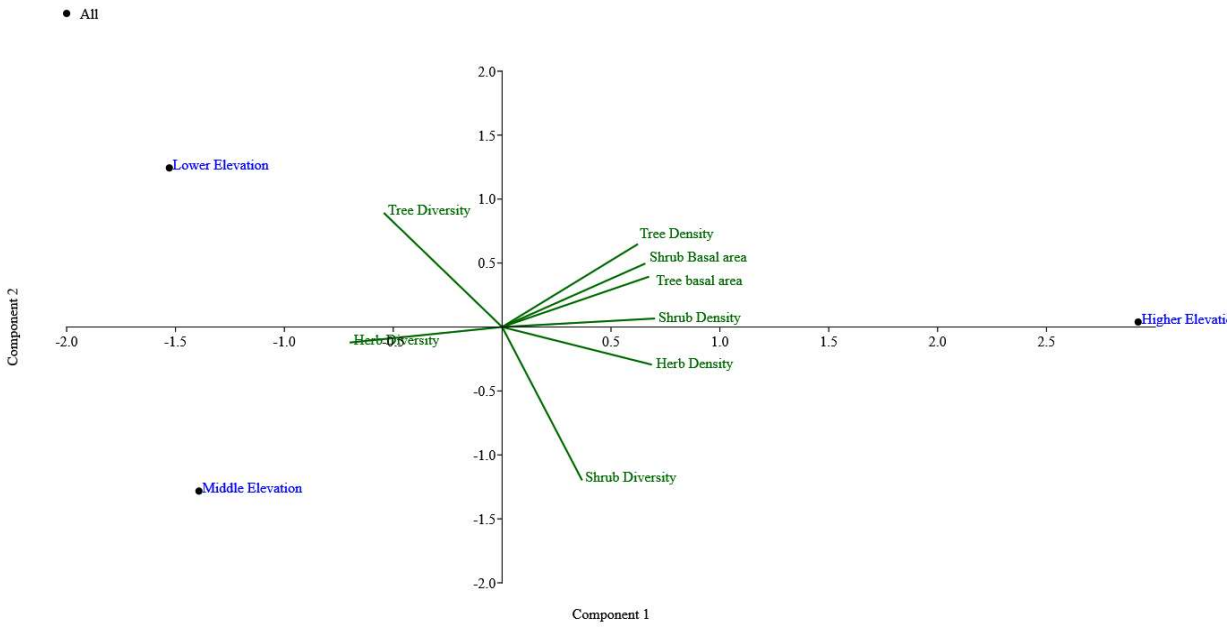


Fig. 4. PCA biplot for vegetation characteristics for different elevational gradient

the total herb density was 73.5 individuals m^2. Species diversity, evenness, and concentration of dominance of herbs were 3.4, 0.03, and 0.8, respectively. The highest density was for *Arthraxon lanceolatus* (13.5) and *Ageratum conyzoides* (11.5) followed by *Dicliptera bupleuroides*) and Justicia simplex (3.8). In the middle elevation forest site (1000-1500m), total herb density was 42.0 individuals m^2. Species diversity, evenness, and concentration of dominance of herbs were 3.7, 0.03, and 0.9, respectively (Table 1). The highest density was *Gonatanthus pumilus* (3.7) and *Geranium nepalense* followed by *Lindenbergia indica* and *Dioscorea bulbifera* . In the lower elevation forest site (400-1000m), total herb density was 27.6 individuals m^2. Species diversity, evenness, and concentration of herb dominance were 3.4, 0.03, and 0.9, respectively (Table 1). The highest density was *Wedelia wallichii* (2.9) and *Hypoxis aurea* (2.7), followed by *Barleria cristata* and *Carex condensate* (1.8).

Ordination analysis: To identify the pattern of the vegetation parameter a total of 9 vegetation characteristics of different layers i.e. (tree density, tree basal area, tree diversity, shrub density, shrub basal area, shrub diversity, herb density and herb diversity were selected for the PCA ordination analysis. The PCA biplot shown that tree density, tree basal area, shrub density, and shrub basal area was high in higher elevation. While shrub diversity is dominant at middle and herb density and herb diversity id dominant in lower elevation respectively. While the shrub diversity and herb density were similar in all the elevation (Table 2, 3, Fig. 4).

Correlation analysis: Correlation analysis between elevation and tree density shows a positive-moderate relationship ($R^2 = 0.31$). While shrub and herb density show a positive-strong relationship with elevation (Fig 5A). Basal area of trees and shrubs (R2=0.50) and (R2=0.78) showed strong positive relationship with elevation (Fig 5B). whereas diversity of trees and herbs and showed strong negative correlation with elevation, while shrub shows a strong positive correlation (Fig 5C).

Rank-abundance curves: The rank-abundance curves for tree and shrub species for different elevation shows highly skewed curves showing few species were having high density and most of the species having low densities (Fig. 6A). Shrub layers middle elevation were showing more balances shrub species composition compared to higher and lower elevation (Fig. 6B). In herb species higher elevation have high dominance of few species and lower and middle elevation having evenly distributed herb layer compared to higher elevation (Fig. 6C). The species distribution pattern showing external factor i.e. environment, climate and

Table 2. Summary of PCA

PC	Eigenvalue	% variance
1	6.40313	80.039
2	1.59687	19.961

Table 3. Score for all studied sites

Elevation	PC1	PC2
Higher Elevation	2.9208	0.039171
Middle Elevation	-1.3925	-1.2828

Table 1. Vegetation parameter of studied forest sites

Vegetation parameter	Higher elevation (1500-2500m)	Middle elevation (1000-1500m)	Lower elevation (400-1000m)
Tree density (individuals ha^{-1})	717	580	640
Tree basal area ($m^2 ha^{-1}$)	69.9	52.8	57.3
Tree diversity	2.1	2.2	2.4
Tree concentration of dominance	0.2	0.3	0.3
Tree evenness	0.5	0.6	0.6
Shrub density (individuals ha^{-1})	1654	966	982
Shrub basal area ($m^2 ha^{-1}$)	1.4	0.2	0.6
Shrub diversity	3.2	3.2	2.6
Shrub concentration of dominance	0.04	0.04	0.07
Shrub evenness	0.9	0.90	0.92
Herb density (individuals m^{-2})	75.7	39.4	27.6
Herb diversity	3.4	4.9	4.8
Herb concentration of dominance	0.03	0.03	0.03
Herb evenness	0.8	0.9	0.9

disturbance were highly influencing the species composition in this forest.

The quantitative profile of a forest is an important indicator that gives the existing data picture about the forest health and bio-production capacity of a forest. In this context, the study was carried out in Himalayan forests at three elevational ranges *i.e.*1500-2500m (at high elevation forest site), 1000-1500m (at middle elevation forest site) and 400-

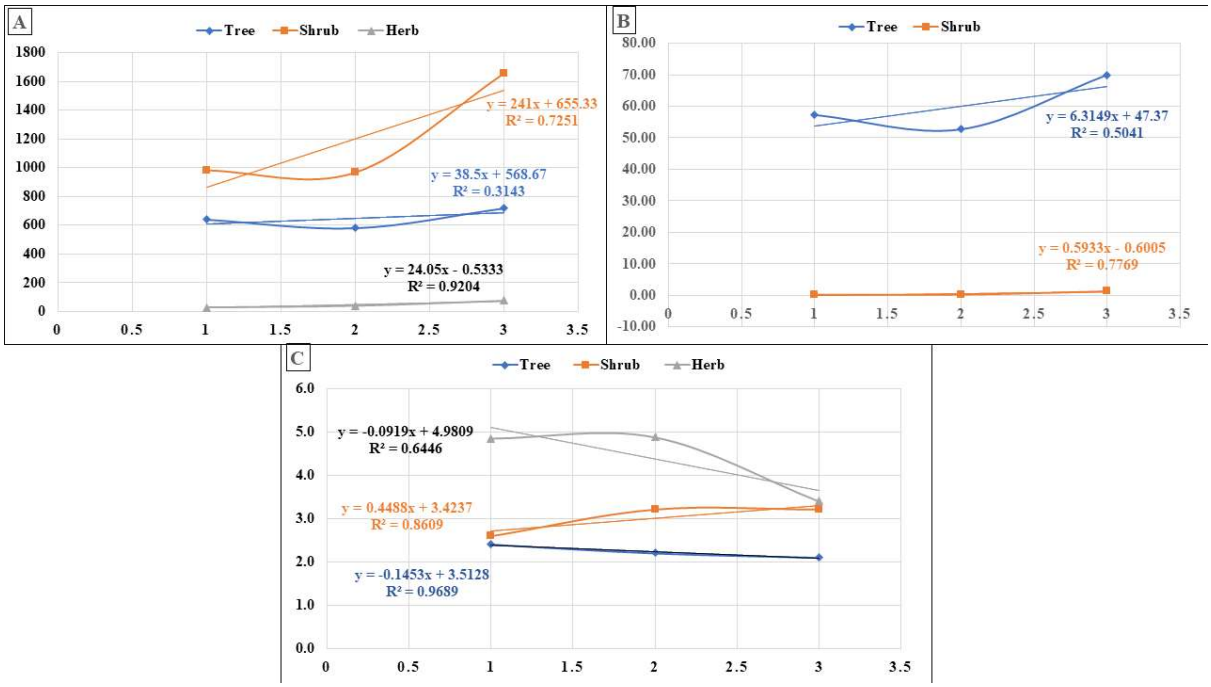


Fig. 5. Relationship of (A) tree, shrub, and herb density; (B) tree and shrub basal area; and (C) tree, shrub, and herb diversity along the elevational gradient

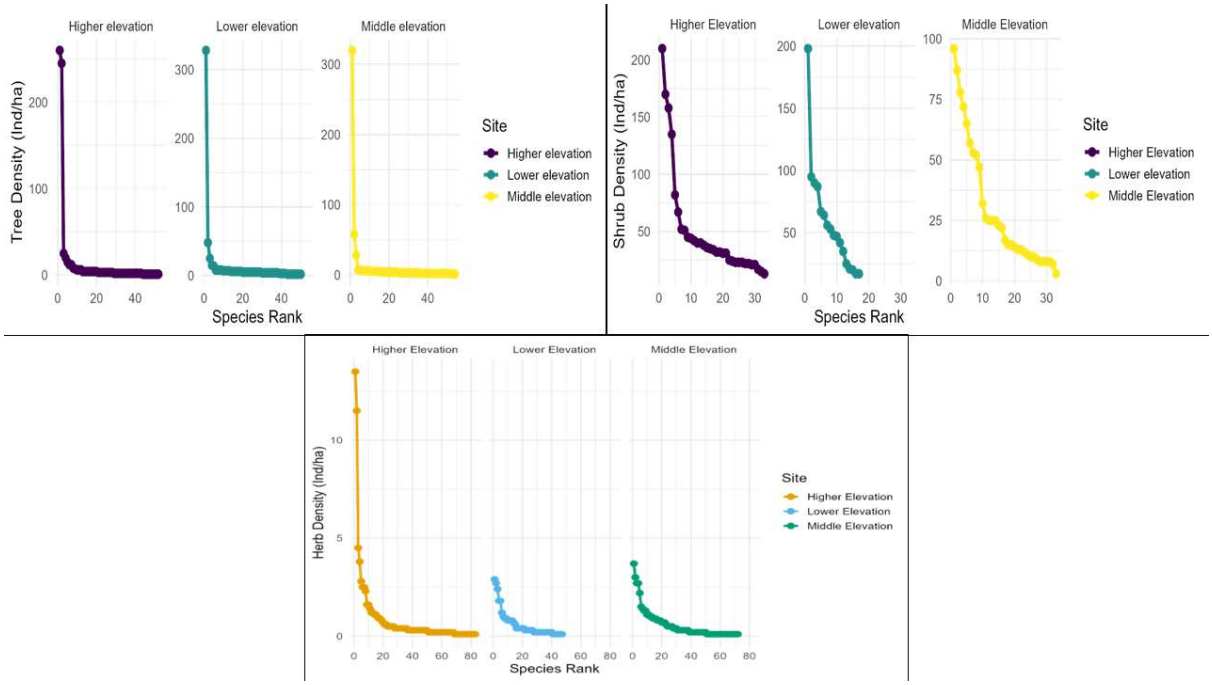


Fig. 6. Rank-abundance curves of tree, shrub, and herb species across different elevation gradient

1000m (at lower elevation forest site), these forests were fallen in the temperate subtropical and nearly tropical climate sites in the Nainital district of Uttarakhand, India.

The tree density was 717 individuals ha^{-1} recorded in the higher elevation forest site. Present value falls within the range 389-1197.5 individuals ha^{-1} reported for Indian Western and Kumaun Himalayan forests (Hussain 2008, Haq et al., 2024). The value is on the higher side than 56-490 individuals ha^{-1} reported for Central and Garhwal Himalayan Forests (Kharkwal et al., 2005, Rawat and Chandra, 2014, Ao et al., 2024), while lower side for reported for Kumaun Himalayan forests (832-2545 individuals ha^{-1}) (Bhatt and Bankoti, 2016, Bisht et al., 2025). The basal area of trees in the higher elevation forest site was 69.9 m^2 ha^{-1} which is almost like 63.6-67.7 m^2ha^{-1} reported for Kumaun Himalayan forests (Bhatt and Bankoti, 2016), but it is on the higher site 27.0-60.5 m^2 ha^{-1}reported for Eastern and Kumaun Himalayan forests (Ao et al., 2024, Bisht et al., 2025). The variation in basal area of forests studied by workers may be due to impacts of type of species, age group, tree girth, and disturbance regime and human activities in the forest sties. However, it can be stated that due to the presence of larger and older trees in the study forest site had been supported by good soil moisture and moisture conditions and rich nutrient availability and suitable climatic condition of forest site resulted the basal area on higher side comparted to the earlier study of other forests. The shrub density in the higher elevation was 1654 individuals ha^{-1}. Present value falls within the range of 1470-1840 individuals ha^{-1} reported for Kumaun Himalaya and Garhwal Himalayan Forests (Hussain, 2008, Rawat and Chandra, 2014). The present value is on higher side than 111-132 individuals ha^{-1} reported for central Himalayan forests (Kharkwal, et al., 2005), while the value is on lower side 2027.7-10,450 individuals ha^{-1} reported for Indian central Himalayan forests (Ao et al., 2024, Yadav et al., 2024, Bisht et al., 2025). The presence of high tree density and basal area of shrubs was due to adequate availability of sunlight, soil nutrients and microclimatic conditions in the forest site. The herb density (75.7 individuals m^{-2}) in the higher elevation was on the higher side than the value reported for Garhwal Himalayan Forest (Rawat and Chandra, 2014, Bisht et al., 2025), however, on the lower side than the value of 288-414 individuals m^{-2} reported for Central Himalayan Forests (Kharkwal, et al., 2005). The present value is on the higher side than 15.1 individuals m^{-2} reported for Indian Himalayan Forest (Ao et al., 2024). The difference in herb density was due to the variation in seasonal and climate change. In this forest site, the shrub layer was in a suppressed condition, resulting in a dominant position of herbs in the forests.

The tree density (580 individuals ha^{-1}) recorded in the middle elevation falls within the range of 373.3-633.3 individuals ha^{-1} reported for forests in Kumaun Himalaya (Dhar et al., 1997, Bisht et al., 2025). The present tree density is on the higher side than 122-403 individuals ha^{-1} was reported for Indian central and eastern Himalayan forests (Kharkwal et al., 2005, Ao et al., 2024), but is found on the lower side than 1673 individuals ha^{-1} reported for Kumaun Himalayan Forest (Ralhan et al., 1982). The variation in tree density and species composition occurred due to soil

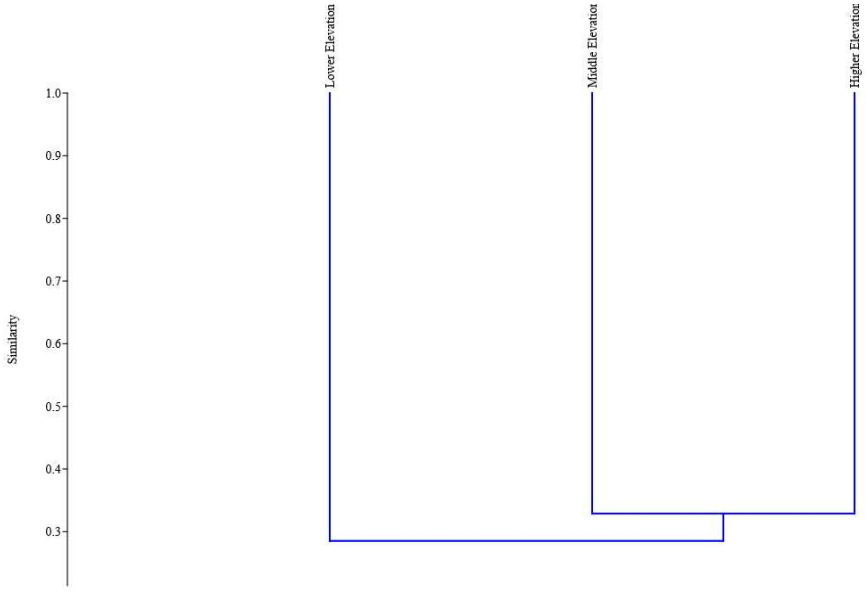


Fig. 7. Dendrogram showing clustering of plant species in forests along the elevational gradient

characteristics, nutrient status, topography, microclimate, and biotic disturbances in the forest site. The basal area of trees (52.8 $m^2 ha^{-1}$) in the middle elevation was on the higher side than the values (29.4-43.9 $m^2 ha^{-1}$) reported for the central and eastern Himalayan Forest by (, Ao et al., 2024, Bisht et al., 2025).. The shrub density in the middle elevation, 966 individuals ha^{-1}, was lower than the 2638.8-8100 individuals ha^{-1} reported for Kumaun Himalayan forests (Ao et al., 2024, Bisht et al., 2025), while the present value was higher than the 120-133 individuals ha^{-1} reported for Kumaun Himalayan Forest (Kharkwal et al., 2005). The variation occurred due to the dominant tree layer having high canopy

Table 4. Comparison of density (individual ha^{-1}), basal area ($m^2 ha^{-1}$), and diversity of higher elevation vegetation layers with other forest vegetation in Western Himalaya

Elevation	Tree density	Tree basal area	Shrub density	Shrub basal area	Herb density	Reference
1500-2500	717	69.9	1654	1.4	75.7	Present study
1500-1900m	1330-2545	63.6-135.5	-	-	-	(Bhatt and Bankoti 2016)
2050-2270	389 -832	27.0-60.5	-	-	-	(Ralhan et al 1982).
1700-2000	832-1100	35.3-67.7	8950-7850	-	-	(Dhar et al., 1997)
1710-2440	368-995	-	1470-28158	-	-	(Hussain 2008).
1600-2400	56-83	-	111-132	-	288-414	(Kharkwal et al., 2005)
2200-2500	490±30-350±20	-	1280±120-1840±80	-	6.4±0.3-8.9±0.4	(Rawat and Chandra 2014)
1800-3600	640±140.95-1197.5±199.56	-	-	-	-	(Haq et al., 2024)
1500-1900	333	30.29	10,450	-	15.1	(Ao et al., 2024)
1613-2149	1200	25.0	3120	0.2	11.9	(Bisht et al., 2025)

D-Density, BA-Basal area

Table 5. Comparison of density (individual ha^{-1}), basal area ($m^2 ha^{-1}$), and diversity of middle elevation vegetation layers with other forest vegetation in Western Himalaya

Elevation	Tree density	Tree basal area	Shrub density	Shrub basal area	Herb density	Reference
1000-1500	580	52.8	966	0.2	39.4	Present study
1300m	1673	35.3	-	-	-	(Ralhan et al., 1982).
1100-1200	586-616	29.9-43.9	5930-7800	-	-	(Dhar et al., 1997)
1000-1400	122-125	-	120-133	-	236-263	(Kharkwal et al., 2005)
1032-1053	-	-	-	-	146.6±0.14-328.40±0.33	(Thakur 2018).
1100-1500	403	36.59	8100	-	8.4	(Ao et al., 2024)
981-1282	373.3-633.3	29.4-31.9	1026.7-3789.7	0.1-0.4	9.2-14.6	(Bisht et al., 2025)

D-Density, BA-Basal area

Table 6. Comparison of density, basal area, and diversity of lower elevation vegetation layers with other forest vegetation in Western Himalaya

Elevation	Tree D (individuals ha^{-1})	Tre BA ($m^2 ha^{-1}$)	Shrub D (individuals ha^{-1})	Shrub BA ($m^2 ha^{-1}$)	Herb D (indi.m^2)	References
400-1000	640	57.3	982	0.6	27.6	Present study
400-1000	123-138	-	92-126	-	161-283	(Kharkwal et al., 2005)
809	-	-	-	-	96.40±0.96	(Thakur 2018)
710	457	38.60	-	-	-	(Kaushal and Baishya 2021)
600-900	600	-	-	-	-	(Bhardwaj et al., 2016)
450-600	462.5	-	-	-	-	(Sharma et al., 2010)
900-1000	1077-1309	-	-	-	-	(Soe and Takeda 2023)
300-1100	345-395	24.88-28.7	7350-9300	-	8.6-89000	(Ao et al., 2024)

D-Density, BA-Basal area

cover suppressing the shrub layer of the forest in the study sites. The herb density of 39.4 individuals m^{-2} in the middle elevation was higher than 146.6-328.40 individuals m^{-2} reported for the Himalayan Forest and tropical forest (Kharkwal et al., 2005, Thakur, 2018). At the same time, the value is higher than 8.4 individuals m^{-2} reported for Indian Himalayan forests (Ao et al., 2024, Bisht et al., 2025). The high density and basal area of dominance and co-dominance tree and shrub species, as well as their vegetation canopy impacts, resulted in the suppression of herbs, combined with less availability of sunlight and shading effects of the upper vegetation layer in the forest sites.

The tree density (640 individuals ha^{-1}) recorded in the lower elevation was somewhat similar to 600 individuals ha^{-1} reported for the Kumaun Himalaya forest (Bhardwaj et al., 2016). The tree density was on the higher side than (123-462.5 individuals ha^{-1}) as reported for the eastern and central Himalayan forests and the lakeside regions of Myanmar (Kaushal and Baishya, 2021, Bhardwaj et al., 2016, Sharma et al., 2010, Ao et al., 2024, Soe and Takeda 2023). The variation occurred due to differences in composition, age, and girth of tree species, as well as minimal human interference in the forest. The basal area of trees (57.3 m^2 ha^{-1}) recorded at lower elevations differs from the values (24.9-38.60 m^2 ha^{-1}) reported for eastern and Kumaun Himalayan forests (Kaushal and Baishya, 2021, Ao et al., 2024). The variation occurred due to the dominance of mature trees in the studied forest. The shrub density in the lower elevation was (982 individuals ha^{-1}), which was on the higher side than 92-126 individuals ha^{-1} for Kumaun Himalayan forests (Kharkwal, et al., 2005), while was on the lower side than (7350-9300 individuals ha^{-1}) reported for eastern Himalaya (Ao et al., 2024). The dominance of trees in the forest site had resulted in the suppressed condition of shrubs. The competition of trees for water and nutrients resulted in a lower value of shrubs. The herb density of lower elevation was 27.6 individuals m^{-2}, which was on the lower side than 96.40-283 individuals m^{-2} reported for Kumaun Himalayan Forest and tropical forest (Kharkwal et al., 2005, Thakur, 2018), however, the present value was on the higher side than 8.6-8.9 individuals m^{-2} reported for Eastern Himalayan forests (Ao et al., 2024). The deposition of forest floor biomass and the shading effects of upper-layer species resulted in a suppressed condition for herbs.

CONCLUSION

The results of the present study, conducted in the three elevational forests of the Nainital district in the western Himalayas, concluded that elevation plays a significant role in shaping the vegetation composition of these forests. Higher elevations have greater diversity of tree species, while lower elevations support more herbaceous plants. CA confirms that the tree layer dominates at higher elevations, whereas herbs are more prevalent at lower ones. Statistics show that higher elevations are structurally stable but less resilient due to lower plant biodiversity. Middle elevations are more resilient and ecologically stable because of their species richness and structural complexity. In contrast, lower elevations are more ecologically dynamic but less structurally stable due to reduced tree cover. Among all elevations, the lower zone is the most vulnerable and requires urgent conservation and management efforts, such as reforestation, strict protection, monitoring, conservation programs, and sustainable measures. The middle zone needs moderate and sustainable protection. Meanwhile, higher elevations should be preserved in their natural state to sustain plant biodiversity and ensure the longevity of the forest ecosystem.

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Woody Floral Diversity of College of Forestry, Sirsi Campus, Uttara Kannada, Karnataka, India

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***Abstract*:** This study provides a comprehensive assessment of woody flora diversity within the College of Forestry (COF), Sirsi, located in the ecologically rich Western Ghats of Karnataka, India. The complete enumeration method was used across six transects within 5.3 ha area. A total of 203 woody species from 56 families were recorded, comprising 1,863 individuals. The family Fabaceae was the most dominant, with 28 species and 515 individuals followed by Poaceae with 14 species and 18 individuals. Among the different species distributed the most predominant species is *Saraca asoca* (212) followed by *Tectona grandis* (149) and *Millettia pinnata* (70). With respect to proportion of woody flora in different growth stage trees were more predominant (35.00%) followed by poles (30.00%), saplings (27.00%) and seedlings (8.0%). Higher Shannon-Weaver species diversity index (4.309) and Simpson index (0.9699) indicates that College of Forestry, Sirsi campus is endowed with rich plant diversity. The findings underscore the ecological importance of academic landscapes in conserving native and rare species. Rich flora equipped in the campus serves as a vital resource for researchers, students, and forest managers involved in urban ecosystem conservation.

***Keywords*:** Woody flora, Western Ghats, Tree species diversity, Biodiversity conservation

Rapid urbanization in India is significantly reducing tree diversity, particularly in metropolitan areas, where habitat loss and the spread of non-native species are leading to ecological homogenization (Divakara et al., 2022).Urban expansion not only diminishes species richness but also alters the functional traits of remnant green spaces, further compromising biodiversity (Zheng and Yang 2023). This alarming trend highlights the urgent need for urban greening initiatives to mitigate biodiversity loss (Divakara et al., 2021, Pandey and Kumar 2018). Urban green spaces offer valuable opportunities for education and biodiversity enhancement, acting as learning hubs that foster environmental awareness. The taxonomic study of flora is very crucial to understand the richness of biodiversity. This goal can be achieved by carrying out floristic studies and it is the main pillar of assessing plant diversity conservation management and sustainable utilization (Jayanthi and Rajendran 2013). The survey of plants in a particular area helps in understanding the overall ecological conditions which can be deciphered by classifying the recorded plants into various biological life forms. Survey of plants and trees in a particular area gives us a profound understanding and appreciation of their medicinal and economic values. It provides the valuable information to the concerned authorities for formulation and implementing various strategies for the sustainable management and conservation of natural resources (Hanumantha et al., 2015, Poonia et al., 2020). Moreover, floristic investigations provide reliable information about the taxonomic classification, distribution, ecology and uses of such plants and trees (Thakur et al., 2005). Floristic surveys help in explaining the plant biodiversity providing information regarding the current status, new invasion, revision of the flora, ecosystem function and its conservation in a particular geographical area (Sasidharan, 2004, Bhusara et al., 2016).

Presently academic institutions have emerged as key contributors to biodiversity conservation through sustainable landscaping and native species preservation. This could be one of the best *ex-situ* conservation approaches practiced in the country (Hanumantha et al., 2015). For instance, Acharya Prafulla Chandra College and the University of Sumatera Utara have demonstrated how campuses can support significant tree diversity and promote ecological stewardship (Biswas et al., 2023, Susilowati et al., 2021). The Institute for Social and Economic Change further illustrate how educational campuses can conserve rare, endangered plant species and contribute meaningfully to biodiversity goals (Nautiyal 2010). The Western Ghats of Karnataka, recognized as a global biodiversity hotspot, harbour a remarkable variety of rare, endemic, and endangered species within diverse ecosystems ranging from tropical evergreen forests to montane grasslands. Nestled in this ecologically rich region, the College of Forestry (COF), Sirsi, has a unique role in documenting and conserving local tree diversity. The campus, serving as a living repository for students and researchers, is also home to >50 accessions of *Coscinium fenestratum*, Schedule III plant, *Nothapodytes nimmoniana*, *Salacia chinensis, Cinnamomum verum, etc*

and a critically endangered liana (*Entada phaseoloides*). Understanding the current tree species composition is essential for tracking ecological changes over time and for developing effective strategies to maintain and enhance the ecological integrity of both the campus and the broader Western Ghats, thereby supporting the long-term preservation of this invaluable natural heritage. At present establishment of baseline for on-going biodiversity monitoring and contributing to conservation, sustainable management, research, education, aimed at training future forestry professionals is very essential. With this backdrop the present study was carried out to comprehensively to document and analyze the woody flora diversity, composition, and regeneration patterns, different habit types of plants and also dominant species with dominant families within the College of Forestry (COF) campus, Sirsi.

MATERIAL AND METHODS

Study area: The present study was conducted within the campus of College of Forestry (COF), Sirsi, located in the Uttara Kannada district of Karnataka, India (14.61° N; 74.85°E), at an elevation of 611 meters above mean sea level. The region falls under the moist deciduous forest zone, with a mean annual temperature of 24°C and annual average rainfall ranges from 2500 mm to 3500 mm. Despite its compact size, the 5.70 ha area is recognized for its ecological richness, supporting a diverse range of flora and fauna, including several endemic and endangered species, making it an ideal site for woody component. To ensure systematic and complete enumeration of woody flora, the study area was divided into six well-defined transects (Hanumantha et al., 2015) *viz.* (1) Around the COF main building, (2) Nandini Parlour to the Dairy unit, (3) Nandini Parlour to the COF vehicle stand, (4) Library to the Basketball court cross, (5) Around the Sapota plantation and (6) Basketball court cross to the Dairy unit. These transects spanned both natural and planted vegetation zones. The aerial map illustrates the layout of these transects (Fig. 1), ensuring spatial clarity in sampling and enabling comprehensive documentation of the woody flora diversity across the campus.

Methodology: To facilitate the accurate documentation of woody flora, the entire 5.69 ha campus area was divided into six pre-defined transects (T1 to T6) (Fig. 1). The heterogeneous distribution of vegetation and the presence of physical barriers such as buildings and pathways made stratified sampling impractical. Therefore, a complete enumeration method was adopted to ensure maximum precision in data collection. For species identification, regionally relevant and scientifically validated field guides were used.

Data collection: Systematic field survey was carried out across all six transects for tree species identification and documentation. Each transect was surveyed independently, and a checklist of woody plants was prepared based on field observations. For every species encountered, key details such as scientific name, common name, and family were recorded, along with the number of individuals across different growth stages/habits - seedlings, saplings, poles, and mature trees. After individual transect data collection, the findings from all six transects were compiled, and the consolidated dataset was subjected to statistical analysis.

Diversity indices: For calculating diversity indices of the study area data pertaining to species recorded and number of individuals within species were used. The Shannon-

Fig. 1. Aerial view of COF Campus with selected transects for complete enumeration

Weaver species diversity index (H'), Simpson's index (D), Margalef index of species richness; dominance and evenness were calculated using Past 4 software.

RESULTS AND DISCUSSION

During the study a total of 203 woody plant species belonging to 56 families were documented in different transects of the campus. Check list of these species with different growth stages is presented in Table 1. Among the several species, *Saraca asoca* (212), *Tectona grandis* (149), *Millettia pinnata* (70), *Caryota urens* (62), *Nothapodytes nimmoniana* (61), *Delonix regia* (52), *Artocarpus heterohyllus* (47), *Syzygium cumini* (44), *Cinnamomum verum* (38), *Santalum album* (36) were the top species abundantly distributed and exhibited strong representation across all stages. Considering the natural regeneration of species *Saraca asoca* (84) reported maximum followed by *Millettia pinnata* (30) and *Delonix regia* (10) was found excellent. It could be due to regular seed-bearing nature of the species with good germination capacity of the seeds. Figure 2 illustrates the top 20 woody species reported based on total individuals across all growth stages.

Study showed that Fabaceae emerged as one of the dominant family, with 28 species and 515 individuals followed by Poaceae with 14 species and18 individuals (Table 2). This pattern reflects the ecological adaptability and widespread prevalence of Fabaceae, a family known for its nitrogen-fixing capability and tolerance to diverse habitat conditions. Its dominance not only reflects its ecological role in enhancing soil fertility and supporting forest dynamics but also aligns with patterns observed in other urban and semi-urban flora studies across the Western Ghats. The prominence of Fabaceae highlights its key role in maintaining ecological balance and sustaining biodiversity in managed green spaces like institutional areas. With respect to percent share of each family (Fig. 3), again Fabaceae, emerged as

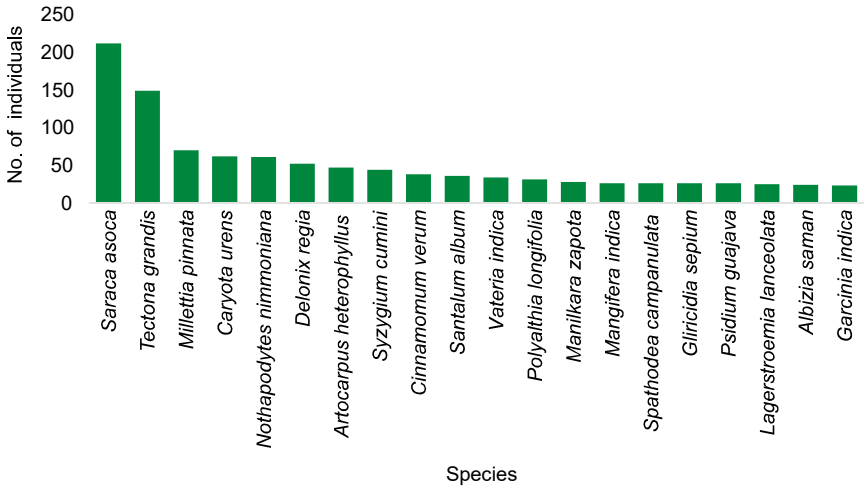

Fig. 2. Top 20 species with their abundance in the campus

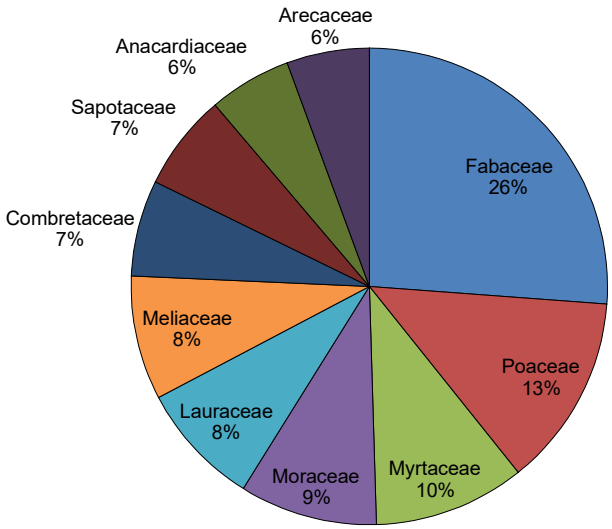

Fig. 3. Top 10 families contributing to total woody species diversity

Table 1. Woody flora diversity of COF Campus with their distribution in different growth stages/habits

Scientific name	Common name	Family	Trees	Poles	Saplings	Seedlings	Total
Acacia auriculiformis Benth.	Earleaf Acacia	Fabaceae	11	1	8		20
Acacia catechu (L.f.) Willd.	Khair	Fabaceae			1		1
Acacia mangium Willd.	Black Wattle	Fabaceae	2				2
Actinorhytis calapparia (Blume) H.Wendl. & Drude ex Scheff.	Ram Adike	Arecaceae			4		4
Adenanthera pavonina L.	Red Bead Tree	Fabaceae	1	1	2		4
Adina cordifolia (Roxb.) Brandis	Yellow Teak	Rubiaceae	1	2			3
Aegle marmelos (L.) Correa	Bael	Rutaceae	1				1
Ailanthus triphysa (Dennst.) Alston	Maddi Dhoopa	Simaroubaceae	1				1
Alangium salviifolium (L.f.) Wangerin	Ankole Tree	Cornaceae	1	1			2
Albizia lebbeck (L.)Benth.	Siris	Fabaceae	1	1			2
Albizia saman (Jacq.)Merr.	Rain Tree	Fabaceae	15	3	6		24
Alstonia scholaris (L.) R. Br.	Scholar Tree	Apocynaceae	4				4
Anacardium occidentale L.	Cashew	Anacardiaceae	8	3			11
Annona muricata L.	Lakshmanphal	Annonaceae		1	7		8
Annona reticulata L.	Ramphal	Annonaceae		1			1
Annona squamosa L.	Seetaphal	Annonaceae		1			1
Anogeissus latifolia (DC.) Wallich.ex Guill. & Perr.	Axlewood Tree	Combretaceae	2				2
Antiaris toxicaria Lesch.	Upas Tree	Moraceae	1				1
Aporosa lindleyana (Wight) Baill.	Salle	Phyllanthaceae		1			1
Aquilaria agallocha (Lour.) Roxb.	Agarwood	Thymelaeaceae			1		1
Araucaria araucana (Molina) K.Koch	Monkey Puzzle Tree	Araucariaceae	3	2	2		7
Artocarpus heterophyllus Lam.	Jackfruit	Moraceae	12	14	21		47
Artocarpus hirsutus Lam.	Wild Jack	Moraceae	3	6	5		14
Artocarpus lakoocha Roxb.	Monkey Jack	Moraceae	3	3	2		8
Azadirachta indica A. Juss.	Neem	Meliaceae		3			3
Bambusa aspera Schult. &Schult.f.	Rough Bamboo	Poaceae	1				1
Bambusa balcooa Roxb.	Balcoa Bamboo	Poaceae	2				2
Bambusa bambos (L.) Voss	Thorny Bamboo	Poaceae	1				1
Bambusa nutans Wall. exMunro	Nodding Bamboo	Poaceae	1				1
Bambusa polymorpha Munro	Burmese Bamboo	Poaceae	1				1
Bambusa tulda Roxb.	Bengal Bamboo	Poaceae	1				1
Bambusa ventricosa McClure	Buddha Bamboo	Poaceae	2				2
Bambusa vulgaris Schrad. ex J.C. Wendl.	Golden Bamboo	Poaceae	3				3
Barringtonia acutangula (L.) Gaertn.	Samudraphala	Lecythidaceae		4			4
Bauhinia malabarica Roxb.	Malabar Bauhinia	Fabaceae	1				1
Bauhinia purpurea L.	Purple Bauhinia	Fabaceae	5	8			13
Beilschmiedia wightii (Nees) Benth. ex Hook.fil.	Konkan Walnut	Lauraceae	1				1
Bischofia javanica Blume	Bishop Tree	Phyllanthaceae	1				1
Bixa orellana L.	Lipstick Tree	Bixaceae	1		4		5
Bombax ceiba L.	Red Silk Cotton Tree	Malvaceae	2				2
Boswellia serrata Roxb. ex Colebr.	Salai Guggul	Burseraceae				2	2
Broussonetia papyrifera (L.) Vent.	Paper Mulberry	Moraceae			2		2
Butea monosperma (Lam.)Taub.	Flame of the Forest	Fabaceae	4	2			6

Cont...

Table 1. Woody flora diversity of COF Campus with their distribution in different growth stages/habits

Scientific name	Common name	Family	Trees	Poles	Saplings	Seedlings	Total
Caesalpinia bonduc (L.)Roxb.	Fever Nut	Fabaceae			1		1
*Calliandra calothyrsus*Meisn.	Spiked Powder Puff	Fabaceae		1	1		2
Calliandra haematocephala Hassk.	Red Powder Puff	Fabaceae		3			3
Callistemon citrinus (Curtis) Skeels	Bottle Brush	Myrtaceae	2				2
Calophyllum apetalum Willd.	Bobbi	Calophyllaceae	1		1		2
Calophyllum inophyllum L.	Alexandrian Laurel	Calophyllaceae	1	2			3
Cananga odorata (Lam.) Hook.f. & Thomson	Ylang-Ylang	Annonaceae		2			2
Canarium strictum Roxb.	Black Dammar	Burseraceae	2	5			7
Canthium dicoccum (Gaertn.) Merr.	Ceylon Boxwood	Rubiaceae		1	1		2
Careya arborea Roxb.	Wild Guava	Lecythidaceae	2	1	4		7
Carica papaya L.	Papaya	Caricaceae		2			2
Caryota urens L.	Fishtail Palm	Arecaceae	12	8	41	1	62
Cassia fistula L.	Golden Shower Tree	Fabaceae	1				1
Casuarina equisetifolia L.	Beach She-Oak	Casuarinaceae	5	1			6
Ceiba pentandra (L.) Gaertn.	White Silk Cotton	Malvaceae		1			1
Cerberaodollam Gaertn.	Suicide Tree	Apocynaceae			1		1
Chionanthus mala-elengi (Dennst.) P.S.Green	Malabar Fringe Tree	Oleaceae		1			1
Chrysophyllum cainito L.	Star Apple	Sapotaceae			1		1
Chrysophyllum roxburghii G.Don	Hale Tree	Sapotaceae	1	1			2
Chukrasia tabularis A. Juss.	Indian Redwood	Meliaceae	3	3			6
Cinnamomum camphora (L.) J. Presl	Camphor Tree	Lauraceae	2				2
Cinnamomum heyneanum Nees	Cinnamon	Lauraceae		1			1
Cinnamomum malabatrum (Burm.f.) J.Presl	Wild Cinnamon	Lauraceae	1				1
Cinnamomum riparium Gamble	Cinnamon	Lauraceae		1			1
Cinnamomum tamala (Buch.-Ham.) T.Nees&C.H.Eberm.	Indian Bay Leaf	Lauraceae		2			2
Cinnamomum travancoricum Gamble	Cinnamon	Lauraceae		1			1
Cinnamomum verum J.S. Presl	Cinnamon	Lauraceae	6	9	17	6	38
Cocos nucifera L.	Coconut	Arecaceae	21				21
Cordia myxa L.	Clammy Cherry	Boraginaceae	1				1
Corypha umbraculifera L.	Talipot Palm	Arecaceae		1			1
Couroupita guianensis Aubl.	Cannon Ball Tree	Lecythidaceae	9		2		11
Dalbergia latifolia Roxb.	Indian Rosewood	Fabaceae	6	4	4		14
Delonix regia (Hook.)Raf.	Gulmohar	Fabaceae	16	6	20	10	52
Dendrocalamus brandisii (Munro) Kurz	Velvet Leaf Bamboo	Poaceae	1				1
Dendrocalamus stocksii (Munro)	Marihal Bamboo	Poaceae	1				1
Dendrocalamus strictus (Roxb.) Nees	Solid Bamboo	Poaceae	1				1
Dimocarpus longan Lour.	Dragon's eyes	Sapindaceae	1				1
Dinochloa compactiflora (Kurz) McClure	Dinochloa	Poaceae	1				1
Diospyros buxifolia (Blume) Hiern	Box Leaf Persimmon	Ebenaceae			1		1
Diospyros sylvatica Roxb.	Forest Ebony	Ebenaceae		1			1
Diospyros malabarica (Desr.) Kostel.	Malabar Ebony	Ebenaceae		12			12
Dipterocarpus bourdillonii Brandis	Dhuma	Dipterocarpaceae	2				2
Dipterocarpus indicus Bedd.	Gurjun	Dipterocarpaceae	4	3			7

Cont...

Table 1. Woody flora diversity of COF Campus with their distribution in different growth stages/habits

Scientific name	Common name	Family	Trees	Poles	Saplings	Seedlings	Total
Duabanga grandiflora (Roxb.exDC.) Walp.	Daubanga	Lythraceae	1				1
Dysoxylum binectariferum (Roxb.) Hook.f. ex Bedd.	KempuDevadari	Meliaceae	3		10		13
Dysoxylum malabaricum Bedd. ex C. DC.	Bili Devadari	Meliaceae	3	6			9
Elaeocarpus serratus L.	Rudraksh	Elaeocarpaceae			3		3
Emblica officinalis Gaertn.	Indian Gooseberry	Phyllanthaceae	2	3	1		6
Erythrina indica Lam.	Indian Coral Tree	Fabaceae	1	5			6
Eucalyptus globulus Labill.	Tasmanian Blue Gum	Myrtaceae	4	2			6
Eucalyptus tereticornis Sm.	Blue Gum	Myrtaceae	6				6
Ficus amplissima Sm.	Bat Fig	Moraceae	1				1
Ficus benghalensis L.	Banyan	Moraceae	1				1
Ficus elastica Roxb. ex Hornem.	Indian Rubber Tree	Moraceae	2				2
Ficus racemosa L.	Cluster Fig	Moraceae	4	4	2		10
Ficus religiosa L.	Sacred Fig	Moraceae	1	1			2
Flacourtia montana J. Graham	Mullu Sampige	Salicaceae	2				2
Garcinia gummi-gutta (L.) N. Robson	Malabar Tamarind	Clusiaceae		7	8		15
Garcinia indica (Thouars) Choisy.	Kokum	Clusiaceae	5	17	1		23
Garcinia morella (Gaertn.) Desr.	Indian Gamboge	Clusiaceae		3	6		9
Garcinia talbotii Raizada	Talbot Garcinia	Clusiaceae		1			1
*Garcinia xanthochymus*Hook.f.	Mysore Gamboge	Clusiaceae		4	1		5
Gliricidia sepium (Jacq.)Walp.	Gliricidia	Fabaceae	17	8	1		26
Gmelina arborea Roxb. ex Sm.	White Teak	Verbenaceae	3	1	1		5
Grevillea robusta A. Cunn. ex R. Br.	Silver Oak	Proteaceae	5	5	1		11
Grewia tiliifolia Vahl	Dhaman	Tiliaceae	4				4
Guadua angustifolia Kunth	Guadua Bamboo	Poaceae	1				1
Gymnacranthera canarica (Bedd. ex King) Warb.	Ondanki Mara	Myristicaceae		1			1
Hardwickia binata Roxb.	Anjan	Fabaceae			2		2
Holigarna arnottiana Wall. ex Hook. f.	Black Varnish Tree	Anacardiaceae	1	2	2		5
Holoptelea integrifolia Planch.	Indian Elm	Ulmaceae	5				5
Hydnocarpus pentandru (Buch.-Ham.) Oken	Chaulmugra	Achariaceae		1	2		3
Ixora brachiata Roxb.	Western Ghats Ixora	Rubiaceae			1		1
Knema attenuata (Hook.f. & Thoms.) Warb.	Wild Nutmeg	Myristicaceae			8		8
Kydia calycina Roxb.	Kadubende	Malvaceae		2			2
Lagerstroemia lanceolata Wall.	Ben Teak	Lythraceae	13	5	7		25
Lagerstroemia speciosa (L.) Pers.	Pride of India	Lythraceae	17		1		18
Lannea coromandelica (Houtt.) Merr.	Indian Ash Tree	Anacardiaceae		2			2
Lawsonia inermis L.	Henna	Lythraceae	1				1
Leucaena leucocephala (Lam.)de Wit	Subabul	Fabaceae	1	1			2
Lophopetalum wightianum Arn.	Banaate	Celastraceae	1	2			3
Macaranga peltata (Roxb.) Müll.Arg.	Chandakala	Euphorbiaceae	1	1			2
Madhuca bourdillonii (Gamble) H.J.Lam	Dodda Hippe	Sapotaceae			1		1
Madhuca longifolia var. latifolia (Roxb.) A.Chev.	Indian Butter Tree	Sapotaceae	1				1
Magnolia champaca (L.) Baill. ex Pierre	Champak	Magnoliaceae	9	6	2		17
Mallotus philippensis (Lam.) Müll.Arg.	Kumkum Tree	Euphorbiaceae	3	4	3		10

Cont...

Table 1. Woody flora diversity of COF Campus with their distribution in different growth stages/habits

Scientific name	Common name	Family	Trees	Poles	Saplings	Seedlings	Total
Mammea suriga (Buch.-Ham. ex Roxb.) Kosterm.	Ceylon Ironwood	Calophyllaceae		3	3		6
Mangifera indica L.	Mango	Anacardiaceae	10	9	7		26
Manilkara hexandra (Roxb.) Dubard	Milk Tree	Sapotaceae	2				2
Manilkara zapota (L.) P.Royen	Chikoo	Sapotaceae	27		1		28
Markhamia lutea (Benth.) K.Schum.	Markhamia	Bignoniaceae	5		1		6
Mastixia arborea (Wight) C.B.Clarke	Kumbala Tree	Nyssaceae		1			1
Melia dubia Cav.	Malabar Neem	Meliaceae	10	3	3		16
Mesua ferrea L.	Nagasampige	Calophyllaceae	4	2	4	4	14
Millettia pinnata (L.)Panigrahi	Indian Beech Tree	Fabaceae	14	13	13	30	70
Mimusops elengi L.	Bulletwood Tree	Sapotaceae		3	1		4
Mitragyna parvifolia (Roxb.) Korth.	Kalam	Rubiaceae	6	2			8
Morinda citrifolia L., nom. cons.	Noni	Rubiaceae	4		2		6
Moringa oleifera Lam.	Drumstick	Moringaceae	1	4			5
Muntingia calabura L.	Singapore Cherry	Muntingiaceae	11	1			12
Murraya koenigii (L.) Spreng.	Curry Leaf	Rutaceae		2	2		4
Myristica dactyloides Gaertn.	Giddapatre	Myristicaceae	1		1		2
Myristica fragrans Houtt.	Nutmeg	Myristicaceae			3		3
Myristica magnifica Bedd.	Dodda Ramapatre	Myristicaceae		2			2
Myristica malabarica Lam.	Ramapatre	Myristicaceae	3	3			6
Neolamarc kiacadamba (Roxb.) Bosser	Kadamba	Rubiaceae	3		4		7
Nothapodytes nimmoniana (J. Grah.) Mabb	Durvaasane Mara	Icacinaceae	1	11	47	2	61
Ochlandra rheedi (Steud.) Benth. &Hook.f. ex Gamble	VaateBidiru	Poaceae	1				1
Olea dioica Roxb.	Rose Sandalwood	Oleaceae		1			1
Oroxylum indicum (L.) Kurz	Broken Bones Tree	Bignoniaceae	1	2			3
Parkia biglandulosa Wight &Arn.	Badminton Ball Tree	Fabaceae	3	2	2		7
Peltophorum pterocarpum (DC.)K.Heyne	Copperpod Tree	Fabaceae	3	1			4
Perseam acrantha (Nees) Kosterm.	Gulamavu	Lauraceae			1		1
Pimenta dioica (L.) Merr.	All Spice	Myrtaceae	1				1
Pinanga dicksonii (Roxb.) Blume	PandavaraAdike	Arecaceae			4		4
Plumeria pudica Jacq.	Wild Plumeria	Apocynaceae		1			1
Polyalthia longifolia (Sonn.) Thwaites	False Ashoka	Annonaceae	28	1	2		31
Premna serratifolia L.	Agnimanth	Lamiaceae		2			2
Psidium guajava L.	Guava	Myrtaceae	9	14	3		26
Pterocarpus marsupium Roxb.	Indian Kino	Fabaceae	5	5	1		11
Pterocarpus santalinus L.f.	Red Sanders	Fabaceae		3	13	1	17
Roystonea regia (Kunth) O.F.Cook	Royal Palm	Arecaceae	4				4
Santalum album L.	Sandal	Santalaceae	4	26	6		36
Sapindus laurifolius Vahl	Soapnut	Sapindaceae	7	7			14
Saraca asoca (Roxb.)Willd.	Sita Ashoka	Fabaceae	11	69	48	84	212
Schleichera oleosa (Lour.) Oken	Ceylon Oak	Sapindaceae			3		3
Semecarpus kathalekanensis Dasappa & M.H. Swaminath	DoddeleHolegeru	Anacardiaceae		1			1
Senna siamea (Lam.) H.S. Irwin & Barneby	Siamese Cassia	Fabaceae	2	4			6

Cont...

Table 1. Woody flora diversity of COF Campus with their distribution in different growth stages/habits

Scientific name	Common name	Family	Trees	Poles	Saplings	Seedlings	Total
Senna spectabilis (DC.)H.S.Irwin& Barneby	Spectacular Cassia	Fabaceae	1				1
Shorea talura Roxb.	Jaalari	Dipterocarpaceae			1		1
Simarouba glauca DC.	Paradise tree	Simaroubaceae	4	7	4		15
Soymida febrifuga (Roxb.) A. Juss.	Indian Redwood	Meliaceae			1		1
Spathodea campanulata P. Beauv.	African Tulip Tree	Bignoniaceae	19	4	1	2	26
Spondias pinnata (L. f.) Kurz	Wild Mango	Anacardiaceae		2			2
Sterculia guttata Roxb.	Spotted Sterculia	Sterculiaceae			1		1
Swietenia macrophylla G. King	American Mahogany	Meliaceae			2		2
Swietenia mahagoni (L.) Jacq.	Mahogany	Meliaceae	2	8	8		18
Syzygium aromaticum (L.) Merr. & L.M. Perry	Clove	Myrtaceae			2		2
Syzygium caryophyllatum (L.) Alston	South Indian Plum	Myrtaceae		1			1
Syzygium cumini (L.) Skeels	Black Plum	Myrtaceae	10	13	21		44
Syzygium jambos (L.) Alston	Malabar Plum	Myrtaceae	1	4	5		10
Syzygium laetum (Buch.-Ham.) Gandhi	Panneralu	Myrtaceae		3			3
Syzygium travancoricum Gamble	KempuNerale	Myrtaceae		1			1
Tabebuia argentea (Bureau &K.Schum.) Britton	Silver Trumpet Tree	Bignoniaceae		1			1
Tabernaemontana heyneana Wall.	Maddarasa	Apocynaceae	1				1
Tamarindus indica L.	Tamarind	Fabaceae	1	3	1		5
Tectona grandis L.f.	Teak	Lamiaceae	81	54	13	1	149
Terminalia arjuna (Roxb.) Wight &Arn.	Arjuna	Combretaceae	1	5			6
Terminalia bellirica (Gaertn.) Roxb.	Bastard Myrobalan	Combretaceae	6	3	10		19
Terminalia catappa L.	Indian Almond	Combretaceae	2	1	1		4
*Terminalia mantaly*H. Perrier	Umbrella Tree	Combretaceae			1		1
Terminalia paniculata Roth	Kindal	Combretaceae	9	4	1		14
Terminalia tomentosa (Roxb. ex DC.) Wight &Arn.	Indian Laurel	Combretaceae	2				2
*Thuja orientalis*L.	Oriental Thuja	Cupressaceae		1			1
Toona ciliata M. Roem.	Red Cedar	Meliaceae	7	1	7		15
Trema orientalis (L.) Blume	Indian Charcoal Tree	Cannabaceae	4	4	4		12
Vateria indica L.	White Dammar	Dipterocarpaceae	8	9	17		34
Vitex altissima L.f.	Bharanagi	Lamiaceae	1	5			6
Xylia xylocarpa (Roxb.)Taub.	Burma Ironwood	Mimosaceae	1				1
Ziziphus rugosa Lam.	Wild Jujube	Rhamnaceae	1	1			2

the most species-rich family with 26 per cent to the total species diversity followed by Poaceae (13%), Myrtaceae (10%), Moraceae (9.0%), Lauraceae and Meliaceae (8.0%).This depiction confirms the dominance of certain plant families while offering insight into the broader taxonomic structure and floristic trends of the site. Photographs of important tree species found in campus of College of Forestry, Sirsi is shown in Plate 1.

Woody flora normally develops under four different growth stages *viz.,* seedlings, saplings, poles, and mature trees. Among different individuals of all the species, maximum number of individuals falls under the growth stage of trees (35%) followed by poles (30%), saplings (27%) and least was under seedlings (8%). Proportion of the woody flora under different growth stage is depicted in Figure 4. Study indicates that the natural regeneration of the species present in the campus is less except for few species; this may be due to the cleaning of campus continuously to avoid hindrance to students and also beautification of the campus; hence in order to increase the regeneration of rare and endangered species measures have to be initiated. Hanumantha et al. (2015) also reported 146 plant species belonging to 45

families' whereas Poonia et al. (2020) reported 93 tree species belonging to 93 genera and 47 families in same campus. Present study indicated that number of species and families were increased in the campus from 93 to 203 and 47 to 56 respectively during the span of 7-8 years.

Diversity of woody species: Species diversity is one of the most important measures of community structure and it has been related to various ecological factors. Shannon-Weaver"s Species Diversity Index (H") of woody species in the study area is noted as H' = 4.309, whereas the Simpson's Diversity Index is 0.9699 (Table 3). Mousumi Garai et al. (2013) reported Shannon index value of tree species ranges from 2.435 to 2.788 and also recorded Simpson's Diversity Index index (D) of tree species ranges from 0.072 to 0.115 in three study sites of Durgapur Government college campus. Neelamegam et al. (2016) reported lower Shannon index value (2.556) and with Simpson's Diversity Index index (0.124) at S.T. Hindu College campus, Kanyakumari, Tamil Nadu. Similar work carried out at GKVK campus, UAS, Bangalore by Sumanth and Prasanna (2022) reported lower

Table 3. Diversity indices for woody flora of the COF campus

Taxa (Species)	203
Individuals	1863
Dominance (D)	0.03005
Evenness (E)	0.3665
Shannon-Weaver species diversity index (H')	4.309
Simpson index (1-D)	0.9699
Margalef index of species richness	26.83

Table 2. Distribution of species and number of individuals in different families

Family	Number of species	Number of individuals	Family	Number of species	Number of individuals
Achariaceae	1	3	Lythraceae	4	45
Anacardiaceae	6	47	Magnoliaceae	1	17
Annonaceae	5	43	Malvaceae	3	5
Apocynaceae	4	7	Meliaceae	9	83
Araucariaceae	1	7	Mimosaceae	1	1
Arecaceae	6	96	Moraceae	10	88
Bignoniaceae	4	36	Moringaceae	1	5
Bixaceae	1	5	Muntingaceae	1	12
Boraginaceae	1	1	Myristicaceae	6	22
Burseraceae	2	9	Myrtaceae	11	102
Calophyllaceae	4	25	Nyssaceae	1	1
Cannabaceae	1	12	Oleaceae	2	2
Caricaceae	1	2	Phyllanthaceae	3	8
Casuarinaceae	1	6	Poaceae	14	18
Celastraceae	1	3	Proteaceae	1	11
Clusiaceae	5	53	Rhamnaceae	1	2
Combretaceae	7	48	Rubiaceae	6	27
Cornaceae	1	2	Rutaceae	2	5
Cupressaceae	1	1	Salicaceae	1	2
Dipterocarpaceae	4	44	Santalaceae	1	36
Ebenaceae	3	14	Sapindaceae	3	18
Elaeocarpaceae	1	3	Sapotaceae	7	39
Euphorbiaceae	2	12	Simaroubaceae	2	16
Fabaceae	28	515	Sterculiaceae	1	1
Icacinaceae	1	61	Thymelaeaceae	1	1
Lamiaceae	3	157	Tiliaceae	1	4
Lauraceae	9	48	Ulmaceae	1	5
Lecythidaceae	3	22	Verbenaceae	1	5

Plate 1. Photographs of important tree species distributed in College of Forestry, Sirsi

Shannon index value (3.53) and with Simpson's Diversity Index index (0.95). The higher diversity of the species in the COF campus indicates homogeneous distribution of species with rich diversity of species in the campus. The rich diversity could be due to higher rate of evolution and more diversified plant communities in the campus.

Morgalef index of species richness was 26.83 and evenness index is 0.3665; indicating more diversity and unequal distribution of individuals in different species. Mousumi Garai et al. (2013) recorded Margalef"s species richness index of tree species ranges from 3.795 to 4.991 in three study sites of Durgapur Government college campus. In the present study high diversity of species may be due favorable locality factors and complete protection of the

vegetation in the campus. Diversity of plant species is attributed by several factors such regeneration nature of the species, disturbances, anthropogenic factors and planting activities in an area. The saving and establishment of plant communities is an essential duty of human society for conservation and avail the immense benefits of biodiversity.

CONCLUSION

The findings of this study clearly demonstrate that the campus of College of Forestry (COF), Sirsi, serves as a model for biodiversity conservation. The high species richness and abundance recorded within a relatively small area is notable and highlights the ecological integrity of the campus, which mirrors the broader biodiversity of the Western Ghats.The dominance of families like Fabaceae, known for ecological functions such as nitrogen fixation, and the strong presence of native and regenerating species suggest that the campus provides suitable microhabitats and environmental conditions for woody flora to thrive. This study reinforces the role of educational institutions as biodiversity hotspots and conservation hubs, capable of supporting rare and endangered species. It underscores the potential of academic campuses to function as living repository for environmental education, biodiversity research, and ecological restoration. By establishing a detailed baseline, the study enables future ecological monitoring and provides a framework for integrating biodiversity conservation into urban and semi-urban land-use planning. The results advocate for replicating such initiatives across other institutions to combat the biodiversity loss driven by rapid urbanization. The present study would be helpful to derive conservation policies and make sustainable use of plant resources of campus.

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Population Density and Habitat of Indian Peafowl (*Pavo cristatus)* in Navsari Agricultural University, Navsari, Gujarat

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***Abstract*:** The Indian Peafowl (*Pavo cristatus*) plays various ecological roles, including seed dispersal, controlling venomous snake populations, and indirectly protecting human communities. This study estimated the population density and habitat use of Indian Peafowl at Navsari Agricultural University (NAU), Gujarat. Systematic line transects with distance sampling were conducted from March to May 2022, using seven transects ranging from 0.66 to 1.3 km in length, totalling 46.80 km. The estimated population density was 0.34 individuals per hectare (34 individuals/km²), with group densities of 0.18 and an average group size of 1.87. The best detection model was a uniform function with a simple polynomial adjustment, with an AIC of 289.55. Habitat-specific data showed that 79.41% of sightings occurred in farmed areas, 15.18% in mango orchards, and 7.59% in mixed habitats, indicating a preference for agricultural environments, likely due to greater food availability and suitable roosting sites. These results provide valuable baseline data for future research and conservation efforts.

***Keywords*:** Indian peafowl, Population density, Habitat use, Agroecosystems

The Indian Peafowl (*Pavo cristatus*), an iconic species of the Indian subcontinent, is deeply embedded in India's ecological and cultural fabric. Celebrated for its dazzling iridescent feathers, complex courtship displays, and high ecological adaptability, the species holds a special position at the intersection of biodiversity and human cultural identity (Ramesh et al., 2009, Gurjar et al., 2013). As India's national bird, the Indian Peafowl represents both aesthetic beauty and spiritual significance, frequently appearing in religious art, classical literature, and folklore. It is also strongly linked to seasonal phenomena, such as the monsoon (Ramesh and McGowan 2009).

Ecologically, *P. cristatus* is widespread across India, inhabiting a variety of environments including dry deciduous forests, scrublands, agricultural fields, temple grounds, and urban parks (Yasmin et al., 1996, Thaker 1963). The species exhibits impressive behavioral flexibility, enabling it to survive in human-dominated areas while fulfilling key ecological functions, such as insect predation and seed dispersal (Johansingh et al., 1980,Sathyanarayana, 2005). Its omnivorous diet of grains, seeds, insects, and small animals helps it adapt to different food conditions. However, living near farms sometimes results in conflicts over crop damage (Gurjar et al., 2013). Additionally, behaviours such as dust-bathing in open soil are essential for controlling parasites and maintaining healthy feathers.

Males (peacocks) are highly showy, with large, iridescent trains made of elongated tail coverts decorated with eye spots (ocelli), mainly used during courtship. Females (peahens), on the other hand, have cryptic plumage for effective camouflage during nesting (Sathyanarayana 2004). Vocal calls are crucial for group communication and predator detection, with loud calls often serving as early warning signals in diverse landscapes. Despite being widely distributed and culturally protected, the Indian Peafowl faces increasing threats from habitat loss, pesticide exposure, illegal hunting, and expanding human development (Divya and Sarita 2013). Although listed in Schedule I of the Indian Wildlife (Protection) Act, 1972, and in Appendix I of CITES, conservation efforts are often reactive rather than data-driven, mainly due to the lack of baseline ecological information in many areas (MoEFCC 2020). Gaining a deeper understanding of habitat preferences and population ecology is crucial for effective conservation, particularly in rapidly expanding urban areas. University campuses, which often feature semi-natural habitats and controlled human activity, can serve as vital refuges for wildlife and as models for studying species in human-altered environments.

This study examines the population density and habitat use of the Indian Peafowl on the Navsari Agricultural University (NAU) campus in South Gujarat. By providing basic ecological data, this research aims to enhance the understanding of *P. cristatus* ecology in semi-urban settings and offer practical insights for its conservation in human-modified landscapes.

MATERIAL AND METHODS

Study area: The study was conducted at Navsari Agricultural University (NAU), situated in the Navsari district of South Gujarat, India, within the biogeographic zone (Western

Ghats plains), at an elevation of 11.83 meters above sea level. NAU encompasses an expansive 400 hectares, accommodating faculties for Forestry, Agriculture, Horticulture, Veterinary Sciences, Animal Husbandry, Agribusiness Management, and Fisheries Science. The campus features a diverse range of habitats, including sugarcane fields, a Rice Research Centre, a Livestock Research Centre, mango and sapota orchards, woodlands, shrublands (Arboretum and Biodiversity Conservation Centre), a Floriculture farm, a KVK (Krishi Vigyan Kendra), nurseries, staff quarters, and student hostels. Navsari is characterized by substantial rainfall and experiences three distinct seasons: Summer (March-June), Monsoon (July-November), and Winter (December-February).

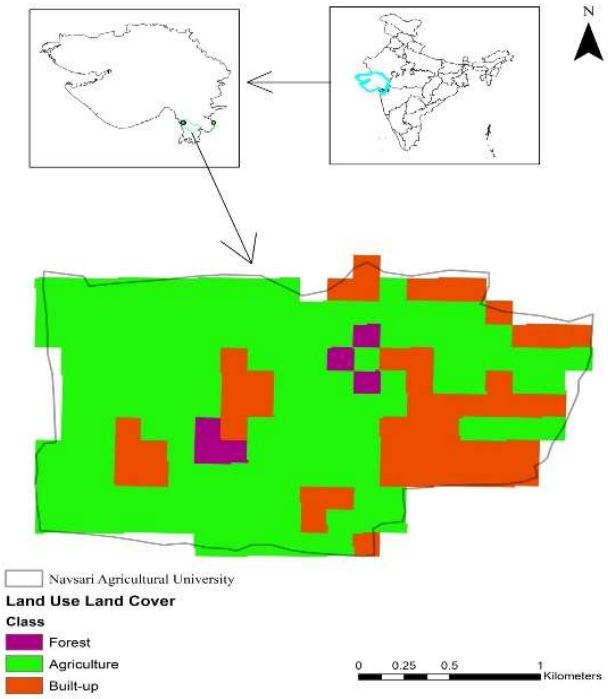

Fig. 1. Study area

Distance sampling involves a sophisticated set of techniques widely used to estimate the density or abundance of biological populations (Buckland et al., 2004). The primary methods within this framework are line transects and point transects. These approaches have proven effective across a variety of organisms, including trees, shrubs, herbs, insects, amphibians, reptiles, birds, fish, and both marine and terrestrial mammals. The core principle behind these methods remains consistently applicable. Our study aimed to estimate the population density of Indian peafowl within the NAU campus, and we used line transect sampling. In this method, an observer moves along a series of straight paths, known as track lines. We chose a walking transect approach within the distance sampling framework to assess the Indian peafowl population.

The NAU campus features a diverse range of habitats, leading us to conduct seven transect walks to evaluate the density and abundance of Indian peafowl. These transects were performed during the morning (8:30 to 9:30 AM) and evening (5:15 to 6:15 PM). Two observers carefully monitored each transect from both sides, systematically recording data on group size, perpendicular distance from the path, GPS coordinates of the groups, habitat features, and any additional behaviors exhibited by the species during the study period (21).

Statistical analysis: The analysis of distance sampling data was performed using DISTANCE software version 7.2 (Thomas et al., 2010), following standard procedures for

Table 1. List of transects monitored to assess Indian peafowl abundance at NAU

Transect No.	Transect name	Transect length (Km)	Replicates	Total length (Km)	Latitude	Longitude
1.	Rice Research Center – Farm No.3 – Livestock Research Center	1.3	7	9.1	20°92'723"	72°90'030"
2.	Regional Horticulture Research Station- Arboretum main road	1.2	7	8.4	20°92'425"	72°89'282"
3.	Research Farm of Genetics & Plant Breeding – Krishi Vigyan Kendra	1.1	7	7.7	20°93'057"	72°89'417"
4.	Bakery–Vice Chancellor Bungalow road–Agribusiness Management College- College of Forestry- Biodiversity –Bamboo Resource Center	1.1	7	7.7	20°92'697"	72°90'941"
5.	Canteen – Soil Management Unit – University Bhavan- Temple	0.633	5	3.1	20°92'411"	72°90'652"
6.	ASPEE College of Horticulture- Swami Vivekanand Boys Hostel – Gymnasium –Veterinary College – Agroforestry Farm	1.2	4	4.8	20°92'327"	72°90'585"
7.	Type D-1 Quarters – Mango Orchard – Helipad	1.0	6	6	20°92'812"	72°90'968"
Total				46.80		

estimating bird abundance and density. Initially, perpendicular distances of observations from transect lines were stratified into finer distance intervals. This stratification was intended to minimize detection bias due to evasive animal movement or increased detectability near roads (Buckland et al., 2001).

To meet the assumptions of conventional distance sampling, specifically, that detectability decreases with increasing distance from the line, perpendicular distances were subsequently binned into broader intervals, including the road shoulder zone, thereby accommodating detection heterogeneity. The appropriateness of distance class intervals was evaluated using Chi-square goodness of fit tests as proposed by Buckland and Turnock (1992).

Detection functions for species were modeled using a combination of main functions: Half-normal (HN), Hazard-rate (HR), and Uniform (UN). The HN function was combined with adjustment terms like cosine, simple polynomial, and Hermite polynomial functions to improve model flexibility. The best detection function was chosen based on the lowest Akaike Information Criterion (AIC), with the model having the lowest AIC being deemed the most parsimonious (Burnham et al., 2011).

RESULTS AND DISCUSSION

Seven transects were systematically laid across the NAU campus, with lengths ranging between 0.66 and 1.3 km, covering a total survey distance of 46.80 km. Transects included agricultural farms (sugarcane, rice, and crop research fields), orchards (mango and sapota), woodland patches (arboretum, bamboo resource centre, and biodiversity plots), shrublands, grass-dominated areas, and built-up zones (staff quarters, student hostels, academic blocks, and common areas). Latter stated transect distribution ensured adequate coverage of both natural and human-modified habitats to capture variation in Indian Peafowl detection and habitat use.

During the transect surveys, a total of 79 Indian peafowls were observed, yielding an encounter rate of 1.68 individuals/kilometer (Table 2). The majority of peafowl sightings (79.41%) occurred in agriculture habitats, followed by mango orchards (15.18%), mixed-use areas comprising agricultural and residential zones (7.59%), and areas in close proximity to human habitation (3.79%).

Distance sampling analysis indicated that the uniform model with a simple polynomial key provided the best fit and was therefore selected for density estimation (Table 2). Based on this model, the density of Indian peafowls in the NAU campus was estimated to be 0.34±0.16 (S.E.) individuals/hectare. The average group size of peafowl was 1.87±0.12, corresponding to a group density of 0.18±0.08 groups per hectare. The effective strip width (ESW) for the survey was estimated to be 46.27 meters, with a coefficient of variation (CV) of 48.01% (Table 2). The abundance of Indian peafowls in the NAU campus was estimated to be 136 ± 64 individuals.The Indian peafowl is renowned for its remarkable adaptability, a trait that underpins its enduring and treasured relationship with the people of India. The diverse cultures and religions of India have esteemed the sheer charisma of this unparalleled and exquisite avian species. The conservation of the Indian national bird is of paramount ecological and ethical significance.

The species' historical presence in urban environments, alongside human habitation, coupled with previous research conducted in this context, renders the Indian peafowl an exemplary subject for studies on population density and habitat at Navsari Agricultural University, Navsari, Gujarat. The line transect method proved to be the most effective, as the majority of birds were detected in proximity to the line, thereby facilitating detection and enumeration. Previous

Table 2. Different models run at different distances to assess the Indian Peafowl density

Model name	AIC	ΔAIC	Mean GS	GD	Densities ± SE	ESW	%CV
UN + SP	289.55	0.00	1.87 ± 0.12	0.18 ± 0.08	0.34 ± 0.16	46.27 ± 2.30	48.01
HN + SP	291.69	2.14	1.87 ± 0.12	0.18 ± 0.08	0.34 ± 0.16	45.95 ± 4.96	48.96
UN + COS	292.64	3.09	1.88 ± 0.13	0.19 ± 0.09	0.37 ± 0.18	42.31 ± 3.28	48.38
UN + HP	292.64	3.09	1.88 ± 0.13	0.19 ± 0.09	0.37 ± 0.18	42.31 ± 3.28	48.38
HR + HP	293.01	3.46	1.90 ± 0.13	0.20 ± 0.10	0.39 ± 0.20	40.99 ± 9.00	52.60
HR + COS	293.17	3.62	1.92 ± 0.13	0.20 ± 0.10	0.40 ± 0.20	40.32 ± 5.98	50.02
HR + HP	293.47	3.92	1.87 ± 0.12	0.18 ± 0.08	0.34 ± 0.16	45.99 ± 3.86	48.49
HN + COS	293.50	3.95	1.90 ± 0.13	0.21 ± 0.10	0.40 ± 0.19	40.11 ± 3.59	48.59
HN+ HP	293.90	3.95	1.90 ± 0.13	0.21 ± 0.10	0.40 ± 0.19	40.11 ± 3.59	48.59

(UN- Uniform, HN-Half Normal, SP- Simple Polynomial, COS- Cosine, HR- Hazard Rate, HP- Hermite Polynomial, AIC- Akaike Information Criterion, GS- Group Size, GD- Group Density, ESW- Effective Strip Width, CV%- Coefficient of Variation).

investigations have indicated that line transects yield more precise density estimates for bird species compared to point counts (Jarvinen, 1978, Verner 1985, Raman 2003). This method was previously employed to estimate the abundance of peafowl in Gir National Park (Trivedi 1993, Sankar et al., 2004). The current density findings align closely with those of other Indian peafowl populations. In Gir, the density was recorded at 39.6 ± 3.8 (mean ± S.E.) peafowl per km². The half-normal and cosine key models emerged as the most effective, with an effective strip width of 36.08 meters for Gir. The highest densities were observed in the eastern region of Gir, at 65.32 ±10 peafowl per km, followed by the central region at 42.60 ±7.6, and the western region at 31.06 ±3.5 peafowl per kilometer (Table 2).

We employed the line transect method to estimate the density of Indian peafowl (*Pavo cristatus*) at Navsari Agricultural University, Navsari, Gujarat, from March to May 2022. The present study reveals that the majority of peafowl were encountered in agricultural areas, with 79.41% within the NAU campus, followed by orchards (15.18%), mixed-use areas (7.59%), and human habitation (3.79%). This indicates a pronounced preference for agricultural fields within the campus. The elevated abundance of peafowl in these farm areas can be attributed to the availability of food and roosting sites. The observed low densities of peafowl may be discussed in the context of habitat unavailability and the myriad threats they face. Indian peafowl are omnivorous, consuming seeds, fruits, insects, worms, small rodents, and reptiles (including snakes and lizards). Their predation on snakes serves to mitigate the presence of these venomous creatures within human communities. Indian peafowl can pose both advantages and disadvantages to crops. On the one hand, they act as bio-control agents by preying on harmful pests.

On the other hand, they can become pests themselves. They have developed a reliance on the local human population for sustenance and protection, bolstered by various cultural and religious sentiments. Their preferred habitat consists of open meadows amidst scrub, mango, and coconut orchards. According to Bergmann (1980) and Johansgard (1986), Indian peafowl have been observed roosting in tall trees and nesting beneath dense bushes, with adjacent open areas serving as feeding grounds. It is imperative to protect these roosting trees and promote their plantation. The veracity of peafowl populations is threatened by habitat loss and destruction due to urban sprawl, which diminishes their natural environments. The university's substantial population of stray dogs poses an additional threat to peafowl populations, as these canines hunt adult peafowl residing near human settlements. Chicks, being more vulnerable, face a heightened risk of predation compared to adult birds. The Krishi Vigyan Kendra and its neighboring agricultural zones exhibited low populations of these birds, mainly due to the predation risk posed by stray dogs. NAU represents an area of significant agricultural potential, consequently increasing pressure on fallow lands to be cultivated. It has been documented that during mass roosting, peafowl disperse into smaller groups in the morning, with males forming harems of three to five females. After vacating the roosting sites, the birds forage in cultivated fields or other areas during the early morning. By midday, they seek refuge under shady trees, often near water sources, where they drink and preen extensively (Anwar et al., 2015). It has been observed that male peafowl frequent open areas for dust bathing, displaying, and feeding during early morning and late evening, rendering them more easily sighted. In the late afternoon, they forage once more and return for another drink at dusk before retiring to roost.

Brickle (2002) noted that areas adjacent to human habitation do not support substantial populations of peafowl. Furthermore, he stated that water sources are crucial for the species and significantly influence their population density. Dodia (2011) suggested that high tree density enhances the survival rate of Indian Peafowl, as roosting in trees with dense canopies mitigates the risk from predators such as cats, dogs, and mongooses. Anwar documented a decline in the population of Indian peafowl in cultivated areas, which is likely attributable to human activities and disturbances from livestock grazing, a phenomenon corroborated by our study. The conservation of Indian peafowl is intrinsically linked to their reliance on roosting trees; therefore, understanding their roost selection is vital for addressing their conservation requirements. The judicious selection of roosting sites enhances avian survival by reducing heat loss, facilitating information exchange, bolstering population accountability, and providing superior protection from predators. The current study investigates the population dynamics of Indian peafowl at Navsari Agricultural University, Navsari. It is recommended that long-term studies are essential for elucidating various impacts on wildlife.

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Patterns and Drivers of Wildlife Offenses in Nagarhole Tiger Reserve: A Socio-Spatial Assessment

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***Abstract*:** Nagarhole Tiger Reserve, a key component of the Nilgiri Biosphere Reserve in Karnataka, India, is a vital stronghold for wildlife, including tigers, elephants and several herbivore and carnivore species. However, the park faces persistent threats from wildlife and other forest-related crimes. This study investigates the patterns, trends and drivers of such offenses in Nagarhole between 2008–09 and 2017–18, based on Forest Offense Case (FOC) records maintained by the Karnataka Forest Department. A total of 617 such cases were reported during this period and it comprises 148 wildlife crimes and 469 other offenses. The analysis reveals a declining trend in crime numbers, although specific years showed spikes in wildlife crimes, indicating episodic surges possibly linked to poaching networks or enforcement drives. Spatial analysis showed significant variation across forest ranges, with DB Kuppe and Metikuppe reporting the highest number of cases. Temporal analysis highlighted increased crime incidence during monsoon months, though statistical tests showed no significant monthly or seasonal variation. Species most frequently targeted included spotted deer, elephants and tigers, along with 47 cases of illegal fishing. Demographic profiling of offenders revealed that most were male, in the 30–60 age group, poorly educated and economically vulnerable, primarily working as wage labourers. Nearly 94 per cent of crimes were intentional, suggesting organized or semi-organized involvement. The study emphasizes the need for improved legal processing, strengthened patrolling, community engagement and alternative livelihood opportunities to mitigate forest crimes. Targeted conservation interventions, informed by spatial and socio-economic data, can enhance the effectiveness of wildlife protection efforts in Nagarhole.

***Keywords*:** Biodiversity protection, Forest offense case, Temporal trends, Wildlife crime

India possesses an exceptional variety of flora and animals, a significant portion of which is safeguarded under its system of national parks, wildlife sanctuaries and conservation reserves. (Singh and Kushwaha 2008). Among these protected areas, Nagarhole National Park (Nagarhole hereafter) is also known as Rajiv Gandhi National Park stands out as a critical component of the Nilgiri Biosphere Reserve, located in the Western Ghats region of Karnataka. Nagarhole is characterized by moist deciduous and dry tropical forests and supports a wide array of wildlife species, including the Bengal tiger (*Panthera tigris*), Asian elephant (*Elephas maximus*), Indian leopard (*Panthera pardus*) and supporting a wild herbivore biomass density of 14,744 kg km^{-2} (Karanth and Sunquist 1992). While the Nagarhole serves as a vital habitat for wildlife and plays a key role in the conservation of range of threatened flora and fauna, however, Nagarhole is facing an increase in anthropogenic activities, particularly in the form of wildlife crimes and other forest-related offenses (Madhusudan and Karanth 2002).

These crimes include poaching of endangered species, illegal fishing, trapping of animals using snares, unauthorized collection of forest produce and other forms of environmental violations (Madhusudan and Karanth 2002, Rana and Kumar 2023, Haq 2023). Such activities not only threaten the survival of vulnerable and endangered species but also erode the integrity of ecosystems and undermine conservation efforts. Given the ecological and legal importance of wildlife protection, there is a pressing need to examine the nature, extent and patterns of such offenses. This study is based on the analysis of crime records reported in Nagarhole between 2008–09 and 2017–18 and focuses on developing a comprehensive profile of both wildlife and other crimes in the park by examining reported case data, including the number of cases, types of offenses, affected species and legal outcomes. Additionally, the study attempts to identify temporal trends in crime occurrences across different months and seasons. Understanding when crimes are most frequent can help managers allocate resources more effectively and plan surveillance accordingly.

Moreover, information on the species most frequently targeted by illegal activities has been compiled to highlight those at greatest risk. An overview of the demographic characteristics of individuals associated with reported crimes, such as age, gender, education level and occupation, offers additional context for understanding the socio-economic background of offenders. By systematically documenting these elements, the study lays the groundwork for more informed conservation strategies and policy planning.

MATERIAL AND METHODS

The present study was conducted in the Nagarhole Tiger Reserve, one of the five major reserves selected to understand the patterns and causes of wildlife crimes in Karnataka. Covering an area of approximately 643 km², Nagarhole is known for its diverse ecosystems and significant wildlife populations, including tigers, elephants and several herbivore and carnivore species. Data on wildlife and other forest-related crimes from 2008–09 to 2017–18 were collected from official Forest Offence Case (FOC) records maintained by the Karnataka Forest Department. This included details of the type of crime, affected species, location of the incident, legal status and seasonal occurrence.

In order to evaluate both temporal and spatial trends, reported cases were grouped by month (Table 3) and range (Table 2). The Kruskal-Wallis test and other statistical analysis were used to decide whether crime rates differed significantly between ranges and months. Also, structured interviews were used to gather demographic data about those who commit wildlife crimes, and the data was analysed to determine the socioeconomic characteristics that influence these kinds of crimes. The study's ability to document trends, pinpoint hotspots and evaluate the dynamics of wildlife crime at the local level in Nagarhole was made possible by its integrated approach.

RESULTS AND DISCUSSION

A total of 617 cases were recorded in Nagarhole over a ten-year span, comprising 148 wildlife crimes and 469 other forest-related offenses (Table 1). The data show a declining trend in both categories, with wildlife crimes dropping from 13 in 2008–09 to just 7 by 2017–18. A similar decline was observed in other forest offenses. However, two major spikes in wildlife crimes during 2012–13 (26 cases) and 2013–14 (25 cases) suggest episodic surges, possibly driven by increased enforcement or poaching pressure. These temporal variations align with findings from other protected areas in India, where local socio-economic changes and enforcement intensity influence wildlife crime trends (Rao et al 2010, Sharma et al 2019). The overall reduction may indicate successful interventions, though the persistently high baseline highlights ongoing challenges.

The distribution of crimes varied significantly across the eight ranges, with DB Kuppe (43 cases) and Metikuppe (38 cases) reporting the highest numbers (Table 2). In contrast, Hunsur and Kallahalla recorded the fewest cases (4 and 5, respectively). The Kruskal–Wallis test ($H = 38.58$, $p<0.001$) confirmed significant variation across ranges, suggesting unequal enforcement or differing access to forest areas. Such spatial heterogeneity is commonly influenced by proximity to human settlements, forest roads and resource abundance (Karanth et al., 2013). These findings emphasize the need for range-specific enforcement strategies and monitoring systems. Further, monthly analysis showed peak crime incidences in June and July (12.16% each), followed by September. The lowest incidences were noted in January (4.73%) and October (5.41%). The variation in wildlife crimes across months was not statistically significant, indicating relative uniformity across time. Nevertheless, higher crimes in the monsoon months may be linked to limited patrolling during rains or increased animal movement (Gubbi et al 2014). Seasonality in wildlife crime remains a critical consideration in resource planning and deployment (Table 3).

Seasonal comparison revealed that the majority of wildlife crimes occurred during the monsoon (64 cases, 43.2%), followed by post-monsoon (32), summer (30) and winter (17) (Table 4). Although the Kruskal–Wallis test did not show a statistically significant difference between seasons, the trend

Table 1. Profile of wildlife and other crimes reported in Nagarahole Tiger Reserve

Year	Wildlife	Others	Total cases
2008-09	13	100	113
2009-10	16	94	110
2010-11	12	61	73
2011-12	8	66	74
2012-13	26	40	66
2013-14	25	30	55
2014-15	17	20	37
2015-16	15	22	37
2016-17	9	18	27
2017-18	7	18	25
Total	148	469	617

Table 2. Comparison of different ranges across Nagarahole Tiger Reserve

Forest ranges	Cases
Hunsur	04
Veernahosahalli	14
Anechowkur	24
Nagarahole	09
Kallahalla	05
Metikuppe	38
Antharasanthe	11
DB Kuppe	43

Kruskal-Wallis test value $H= 38.58$, $p<0.001$

suggests there was a heightened risk during the monsoon, possibly due to lush vegetation cover aiding concealment of illegal activities. Studies in other reserves have reported similar trends, where monsoons enable easier snare setting and reduced detection (Madhusudan and Shankar Raman 2003).

The temporal analysis of wildlife crime in Nagarhole Tiger Reserve between 2008–09 and 2017–18 (Fig. 1) reveals notable monthly variations, with the highest incidences recorded in June and July (12.16% each), followed by September and August , while the lowest were observed in January (4.73%) and October (5.41%). This concentration of offences during the monsoon months suggests that dense vegetation cover may facilitate concealment of illegal activities, while reduced patrolling due to harsh weather conditions could further exacerbate the risk (Gubbi et al., 2014). The pattern aligns with findings from other Indian reserves where monsoon seasons see a surge in poaching and illegal forest use due to both ecological conditions and limited enforcement presence (Madhusudan and Shankar Raman 2003). Although the Kruskal–Wallis test indicated that these monthly differences were not statistically significant, the practical implications remain critical, necessitating enhanced surveillance and strategic deployment of forest staff during high-risk periods. These insights underscore the importance of integrating temporal risk factors into anti-poaching planning and wildlife protection strategies. The temporal dynamics of wildlife crimes across forest ranges in Nagarhole Tiger Reserve reveal varied patterns of monthly occurrence, influenced by range-specific factors such as terrain, accessibility, and enforcement presence (Table 5). Among the eight ranges analyzed, DB Kuppe (43 cases) and Metikuppe (38 cases) reported the highest number of wildlife crimes. In DB Kuppe, peak incidences occurred in January, June and July, while Metikuppe recorded the highest numbers during June, November and December, coinciding with monsoon and post-monsoon months. These patterns may be linked to thick vegetation during the rainy season, which facilitates concealment and limits patrolling efforts (Gubbi et al., 2014). In contrast, ranges like Hunsur (4 cases) and Kallahalla (5 cases) reported minimal activity, possibly due to stronger enforcement or lower accessibility for offenders.

The May, July and September recorded simultaneous spikes in multiple ranges, suggesting periods of increased vulnerability across the reserve. For example, May month was notably active in Veernahosahalli and Anechowkur, while July saw incidents in seven of the eight ranges. These simultaneous surges highlight the need for synchronized and intensive patrolling efforts during specific months. The presence of offenses even during winter months, although fewer, indicates that illegal activities are not entirely seasonal

Table 3. Temporal patterns in Wildlife Crime across months in Nagarahole Tiger Reserve

Month	Number	Per cent
January	7	4.73
February	10	6.76
March	8	5.41
April	11	7.43
May	11	7.43
June	18	12.16
July	18	12.16
August	13	8.78
September	15	10.14
October	8	5.41
November	12	8.11
December	12	8.11
Data NA	5	3.38

Kruskal-Wallis test value (H): 34.2, p<0.001 [Between Reserves comparison]

Table 4. Seasonal distribution of Wildlife Crimes

Season/Reserves	Nagarahole
Winter	17
Summer	30
Monsoon	64
Post Monsoon	32

Kruskal Wallis test value is H= 4.52, p=0.24 (Non-significant)

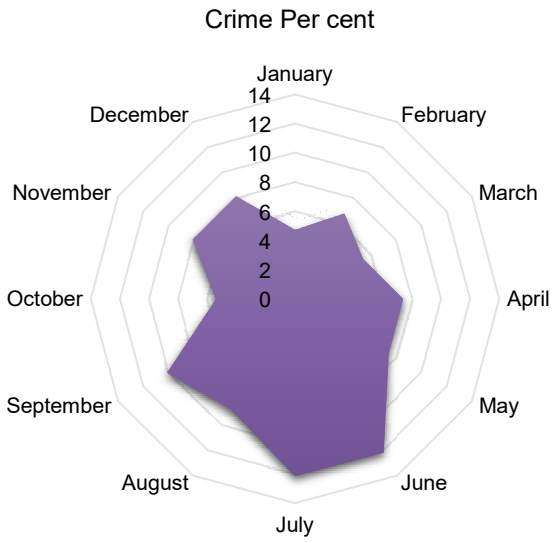

Fig. 1. Temporal dynamics of wildlife crime reported in Nagarahole Tiger Reserve

Table 5. Temporal dynamics of wildlife crime reported across forest ranges in Nagarahole Tiger Reserve

Month	HNS		VHH		ANK		NGH		KLH		MKP		ATS		DBK		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
January	0	0.0	0	0.00	0	0.00	0	0.00	1	20.00	1	2.63	0	0.00	5	11.63	7	4.73
February	1	25.0	1	7.14	0	0.00	1	11.11	0	0.00	3	7.89	1	9.09	3	6.98	10	6.76
March	0	0.0	0	0.00	1	4.17	1	11.11	0	0.00	2	5.26	1	9.09	3	6.98	8	5.41
April	0	0.0	0	0.00	1	4.17	0	0.00	0	0.00	5	13.16	1	9.09	4	9.30	11	7.43
May	0	0.0	2	14.29	5	20.83	0	0.00	0	0.00	0	0.00	1	9.09	3	6.98	11	7.43
June	0	0.0	1	7.14	1	4.17	0	0.00	0	0.00	8	21.05	0	0.00	8	18.60	18	12.16
July	1	25.0	2	14.29	4	16.67	1	11.11	0	0.00	2	5.26	1	9.09	7	16.28	18	12.16
August	0	0.0	2	14.29	2	8.33	1	11.11	1	20.00	3	7.89	2	18.18	2	4.65	13	8.78
September	1	25.0	3	21.43	4	16.67	2	22.22	0	0.00	4	10.53	0	0.00	1	2.33	15	10.14
October	0	0.0	0	0.00	3	12.50	0	0.00	1	20.00	3	7.89	1	9.09	0	0.00	8	5.41
November	0	0.0	0	0.00	1	4.17	3	33.33	0	0.00	4	10.53	1	9.09	3	6.98	12	8.11
December	1	25.0	0	0.00	1	4.17	0	0.00	2	40.00	3	7.89	2	18.18	3	6.98	12	8.11
Data NA	0	0.0	3	21.43	1	4.17	0	0.00	0	0.00	0	0.00	0	0.00	1	2.33	5	3.38
Total	4	100.0	14	100.00	24	100.00	9	100.00	5	100.00	38	100.00	11	100.00	43	100.00	148	100.00

Forest Ranges of NTR = HNS=Hunsur; VHH=Veernahosahalli; ANK=Anechowkur; NGH=Nagarahole; KLH=Kallahalla; MKP=Metikuppe; ATS=Antharasanthe; DBK=DB Kuppe

and can occur year-round when opportunities arise. Similar spatial-temporal crime clustering has been reported in other protected areas, where landscape structure, community proximity and resource availability shape criminal behaviour (Karanth et al., 2013, Raza et al., 2012, Madhusudan and Shankar Raman 2003). Thus, localized intelligence, community surveillance, and adaptive patrolling schedules based on seasonal risk can enhance conservation outcomes across forest ranges.

The most frequently targeted species were spotted deer (*Axis*, 26 cases), elephants (*Elephas maximus*, 18) and tigers (*Panthera tigris*, 8). Additionally, 47 cases of illegal fishing were recorded (Table 6). Lesser-known species such as monitor lizards, langurs, foxes and dholes were also affected. This wide taxonomic impact reflects diverse motivations behind poaching, ranging from commercial gain (Ivory, Skins) to subsistence and cultural use (Meijaard et al., 2011). The species profile underscores the need for awareness campaigns and strict enforcement even for non-charismatic species.

The majority of wildlife crimes (93.9%) were intentional, with only 6.1 per cent deemed unintentional (Table 7). About half the offenders were identified (74 out of 148 cases), while the rest remained unidentified. This finding is consistent with patterns reported in wildlife crime literature where intentionality is often linked to organized or semi-organized efforts (Anonymous 2020). Improving intelligence networks and community informant systems can aid in increasing offender identification rates. Of the 30 respondents from Nagarhole, 83.3 per cent were male and they mostly fell in the 30–60 age group. The majority were wage labourers (80%) with low education levels, 50 per cent illiterate and 40 per cent educated only up to primary school (Table 8). Most respondents belonged to nuclear families. These socio-demographic factors suggest a link between economic vulnerability and involvement in forest crimes (Karanth 2008, Dutta 2020, Nikhil et al., 2023). Interventions aimed at livelihood generation, environmental education and local participation in conservation may reduce future crime incidence.

CONCLUSION

The comprehensive analysis of wildlife and other forest-related crimes in Nagarhole Tiger Reserve from 2008–09 to 2017–18 reveals critical insights into the spatial, temporal and socio-economic dynamics, which influence the illegal activities in the region. Despite an overall declining trend in reported offenses, episodic spikes and persistent hotspots particularly in DB Kuppe and Metikuppe ranges, highlight the need for sustained and range-specific enforcement strategies. Temporal patterns show elevated crime incidence during monsoon months, though these variations are not statistically significant across months or seasons. The high proportion of intentional crimes and the predominance of cases involving economically vulnerable individuals underscore the complex interplay between poverty,

Table 6. Profile of species affected by wildlife crime in the study area

Species	Scientific name	Numbers
Tiger	*Panthera tigris*	8
Leopard	*Panthera pardus*	7
Elephant	*Elephas maximus*	18
Wild boar	*Sus Scrofa*	4
Spotted deer	*Axis*	26
Sambar deer	*Rusa unicolor*	4
Barking deer	*Muntiacus muntjack*	2
Indian gaur	*Bos gaurus*	3
Hare	*Lepus nigricollis*	1
Fishing	-	47
Langur	*Semnopithecus entellus*	2
Jackal	*Canis aureus*	0
Tortoise	*Geochelone elegans*	0
Pangolin	*Manis crassicaudata*	0
Monkey	*Macaca radiata*	1
Birds	-	1
Snake case	-	1
Teasing	-	0
Honey	-	1
Mouse deer	*Moschiola indica*	0
Civet cat	*Viverricula indica*	0
Monitor lizard	*Varanus bengalensis*	2
Bat	*Pteropus giganteus*	0
Otter	*Lutrogale perspicillata*	0
Porcupine	*Hystrix indica*	0
Gaint squirrel	*Ratufa indica*	1
Fox	*Vulpes bengalensis*	2
Dhole	*Cuon alpinus*	1
Snare and hunting intension	-	16
Data NA	-	0
Total	133	148

Table 7. Classification and intentionality of Wildlife crimes in Nagarhole Tiger reserve

Particulars	Number
Identified	74
Unidentified	69
NA	5
Total	148
Intentional	139
Un-intentional	9
Data NA	0
Total	148

Table 8. Demographic characteristics of respondents in Nagarhole Tiger reserve

Particular	Categories	Frequency	Per cent
Gender	Male	25	83.3
	Female	5	16.7
Age	<30	5	16.7
	30-45	11	36.7
	45-60	11	36.7
	>60	3	10.0
Family Type	Nuclear	22	73.3
	Joint	8	26.7
Education	Illiterates	15	50.0
	Primary	12	40.0
	High School	3	10.0
	Plus 2	0	0.0
	Graduation and Above	0	0.0
Occupation	Farmer	1	3.3
	Private	2	6.7
	Wage Labour	24	80.0
	Dependent	3	10.0
	Others	0	0.0
Working days/Month	Low	7	23.3
	Average	18	60.0
	High	5	16.7
Total Number of cases Recorded		148	

awareness and opportunity in driving such offenses. The targeting of both charismatic megafauna and lesser-known species indicates the breadth of threats facing the reserve's biodiversity. In response, there is a pressing need to enhance patrolling, invest in community engagement and promote alternative livelihoods for forest-dependent populations. Strengthening institutional mechanisms, combined with local participation and environmental education, will be key to ensuring long-term conservation success in Nagarhole and similar protected landscapes across India.

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Ecosystem Restoration in the Indian Context: Strategies, Challenges and Case Studies

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***Abstract*:** Ecosystem restoration is essential for reversing land degradation and achieving the United Nations Sustainable Development Goals, particularly SDG 15 (Life on Land). India, with over 96 million hectares of degraded land, faces ecological stress from climate change, deforestation, and biodiversity loss. This review examines global and national restoration frameworks with a focus on India's major initiatives such as the Green India Mission (GIA) and the National Action Plan on Climate Change (NAPCC). Case studies from Kerala demonstrate successful community-based interventions in forest, wetland and watershed ecosystems. Emerging scientific approaches such as biochar application and soil biotechnological recovery are also discussed. Despite these efforts, challenges remain due to fragmented policies, lack of ecological assessment tools, and insufficient monitoring. The study advocates for participatory, ecosystem-based restoration approach that blends scientific planning with traditional knowledge and social equity. Recommendations include building local capacity, developing region-specific ecological benchmarks, and strengthening policy coherence. Aligning with the goals of the UN Decade on Ecosystem Restoration, this review highlights opportunities for India to promote biodiversity, enhance climate resilience, and improve rural livelihoods through inclusive restoration strategies.

Keywords: Biodiversity conservation, Community-based restoration, Ecological restoration, Environmental governance, Nature based solutions

Healthy, stable, and biodiverse ecosystems are the foundation of well-being for both human and non-human species. They regulate essential ecological processes such as climate moderation, pest and disease control, and support basic life needs including water, food, raw materials, and space for living and recreation. However, ecosystems across the globe are being degraded at an alarming rate; in fact, humanity is not separate from nature but an integral part of it (IBPES 2019). Ecosystem degradation is driven by a combination of factors including climate change, pollution, invasive species, unsustainable food production, and large-scale land and ocean use changes. This degradation paradoxically supports economic growth, thereby placing long-term ecological security at risk. Ecosystem restoration is the process of assisting the recovery of degraded, damaged, or destroyed ecosystems to a healthier and more functional state (SER 2004). This process supports biodiversity, climate resilience, food security, and human well-being. In India, integration of restoration with traditional knowledge and community participation is gaining traction (Kumar et al., 2022).

According to the Global Footprint Network (GFN) (2021), sustaining current consumption levels would require 1.6 rarths, placing future ecological and economic systems in jeopardy. Land degradation not only undermines development goals but also increases the cost of meeting international environmental commitments. Restoration of damaged ecosystems has thus, emerged as a necessary complement to conservation strategies (Choudhary et al., 2022). Although restoration alone cannot resolve all environmental problems, but it serves as a key strategy under Sustainable Development Goal 15 (Life on Land) and offers multiple co-benefits for climate mitigation, disaster risk reduction, and sustainable livelihoods (Kumar et al., 2020).

Eco-Restoration in India: Indian Space Research Organisation (ISRO) in 2016, estimated that approximately 96.3 million hectares (Mha) or 29.32 per cent of India's total geographical area have been degraded or classified as wastelands (ISRO 2016). Most forest ecosystems in India, whether protected or not, are experiencing severe degradation due to anthropogenic pressures, biological invasions, and unsustainable logging practices (Ravindranath et al., 2012, Ghosh and Maiti 2021). India's ecological degradation is closely tied to socioeconomic marginalization. Many rural communities, particularly in ecologically fragile zones, face persistent exclusion from formal development processes. Limited access to education, healthcare, and infrastructure further compounds their vulnerability. Moreover, caste, gender, and religious discrimination continue to hinder equitable participation in restoration planning and policy decisions (Parthasarathy 2018, Bhattacharya 2020). Despite the presence of numerous policies in India that intersect with environmental governance such as Green India Mission, Compensatory Afforestation Fund Management and Planning Authority (CAMPA), Mahatma Gandhi National Rural Employment

Guarantee Act (MGNREA) and the National Action Plan on climate Change (NAPCC) the country still lacks a dedicated, coherent ecological restoration policy. Often, initiatives are reduced to shallow afforestation efforts rather than being guided by ecological science and restoration principles (Menz et al., 2013, Suding et al., 2015, Chazdon and Brancalion 2019, Holl and Brancalion 2020). For example, state monitoring reports document low survival and design gaps in CAMPA plantations (e.g., Uttarakhand state average ≈33%, division values as low as 16–26%, with use of exotics and limited soil–water conservation), and the national audit highlights systemic compliance and oversight failures (CAGI 2013, UK-CAMPA/FRI 2021).

For restoration to be effective in India, it must be embedded within a multidisciplinary and participatory framework that draws from ecological science, local knowledge, and socioeconomic development goals (Chazdon and Brancalion 2019, Pascual et al., 2023). A major opportunity lies in integrating ecological restoration objectives into existing national programs and leveraging international finance mechanisms such as the Global Environment Facility (GEF) and carbon markets (Dickson 2021, Mansourian and Stephenson 2023). Ecological restoration paves way for a cost-effective, long-term solution to India's overlapping crises of climate change, biodiversity loss, and rural poverty. United Nations Environment Programme (UNEP) (2021) reports that each dollar invested in ecosystem restoration yields up to $9 in ecosystem services, including carbon sequestration, flood regulation, and public health benefits. Restoration efforts can also reduce zoonotic disease risk by mitigating habitat fragmentation, a key driver of emerging pandemics (Díaz et al., 2019, Dobson et al., 2020, Keesing and Ostfeld 2021). Given that India accounts for 27.5 per cent of the world's degraded land, the country holds a strategic position in the global restoration agenda. With strong institutional coordination, scientific support, and inclusive governance, India can emerge as a leader in the UN Decade on Ecosystem Restoration (2021-2030).

Eco-Restoration in Kerala: Kerala, situated in the biodiversity-rich western ghats, faces complex ecological restoration challenges despite its comparatively high forest cover and progressive conservation framework. Ecological degradation in the state stems from multiple interacting drivers. These include the spread of invasive species (*Senna spectabilis*, *Prosopis juliflora, Lantana camara, Ageratina adenophora, Parthenium hysterophorus, etc*.; Anusree and Rajendran 2022, Prakash et al., 2022), hydrological disruptions due to unregulated land use changes, over-extraction of natural resources, unsustainable tourism expansion and the conversion of natural forests into monoculture plantations (Ravindranath et al., 2012, Ghosh and Maiti 2021). Moreover, state-led interventions in Kerala have occasionally prioritized aesthetic objectives over ecological functionality. For instance, tree-planting campaigns have sometimes favoured fast-growing exotics or monocultures, neglecting the importance of restoring native biodiversity and ecological processes (Suding et al., 2015, Holl 2017). These actions, though visually appealing, do not always lead to resilient or self-sustaining ecosystems.

The situation is exacerbated by socio-political marginalization. Tribal and rural communities inhabiting ecologically sensitive areas frequently lack formal access to infrastructure and policy processes. Structural barriers based on caste, gender, and class inhibit inclusive participation in environmental governance (Bhattacharya 2020). Consequently, restoration strategies often fail to engage these stakeholders meaningfully, undermining both ecological outcomes and social equity. Despite these challenges, Kerala has pioneered several successful community-based restoration initiatives that offer replicable models. One such example is the targeted removal of *Senna spectabilis* in Wayanad district, where tribal cooperatives collaborated with forest departments to control invasive spread through manual clearing and native species reintroduction. Another example is the Vembanad Lake restoration effort, coordinated by the Ashoka Trust for Research in Ecology and the Environment (ATREE), which leveraged local fisher's ecological knowledge to restore hydrological flow and enhance wetland biodiversity (ATREE, n.d). In the Attappadi hills, participatory watershed management combined with agroforestry practices has enabled landscape-level ecological recovery while improving livelihoods for tribal communities (Kumar et al., 2014, 2015).

Going forward, ecological restoration in Kerala must be anchored in scientific diagnostics such as biodiversity baselines, soil quality assessment, and hydrological profiling. Restoration strategies should move beyond tourism to adopt long-term, adaptive management plans that emphasize ecological processes. Additionally, scaling up nature-based solutions including mangrove regeneration, riparian buffer creation, and agroforestry diversification, which can help Kerala simultaneously meet its biodiversity conservation, climate adaptation, and sustainable development goals (Seddon et al., 2020). At the policy level, Kerala adopted the Eco restoration Policy (2021), a first of its kind state initiative, where Kerala has committed to phase out ~27,000 ha of exotic monoculture plantations (e.g., Eucalyptus, Acacia, Wattle), prioritise invasive-species removal, replace exotics with native species and restore

wetlands, riverbanks, sacred groves, and coastal 'bio-shields' (mangroves) through participatory approaches with forest-dependent communities (KFD 2021). Kerala's State Action Plan on Climate Change (SAPCC) 2.0 (2023-2030) likewise foregrounds nature-based solutions, including ecosystem-based coastal protection such as mangrove afforestation and bio-shields, as part of climate adaptation (DECC 2022). Finally, aligning state-level efforts with international initiatives, the Bonn Challenge and the UN Decade on Ecosystem Restoration can unlock technical cooperation and climate finance, strengthening the institutional foundation for restoration success (IUCN n.d., UNEP and FAO n.d.).

Complexities of eco-restoration process: Ecological restoration is fundamentally a design and governance challenge, interventions must balance biophysical feasibility with social legitimacy across heterogeneous landscapes and a non-stationary climate (Chazdon and Brancalion 2019, Gann et al., 2019). Selecting appropriate reference models is particularly difficult in systems shaped by path dependence (past land uses leave long lasting legacies that push the site along certain recovery paths), altered disturbance regimes (pattern of fires, floods, grazing, *etc*), and novel species assemblages (new mix of species compared with the past due to invasions, extinctions, climate driven shifts *etc*.), in many cases, strict historical fidelity is neither achievable nor desirable. Because of these legacies trying to build the ecosystem exactly as it was historically is often impossible so the restoration programmes should make explicit trade-offs among the core objectives: biodiversity recovery, eco-hydrological stability, carbon storage and livelihood benefits and thereby choose between natural regeneration and assisted approaches based on the recovery potential and context (Holl and Aide 2011, Suding et al., 2015, Seddon et al., 2020). Operationally, this choice follows a degradation–intervention gradient (Fig. 1): when the state of degradation is high, projects begin with reclamation/ rehabilitation (rebuilding basic soil function and stability), sometimes *via* commercial reforestation/agroforestry as a transitional step; at moderate degradation, reforestation with native trees or Assisted Natural Regeneration (ANR) becomes feasible once barriers (e.g., grazing, fire, invasive pressure) are removed; where degradation is low, natural regeneration can deliver the highest biodiversity and ecosystem-service gains. Consistent with the figure axes, biodiversity/services increase up the staircase, while time and cost decline towards ANR and natural regeneration. Rigorous evaluation requires a clearly defined baseline, an explicit counterfactual (e.g., control plots or a Before–After, Control–Impact design), and process-based indicators (e.g., natural recruitment, soil function, hydrological connectivity) in addition to simple survival percentages (Palmer et al., 2005, Ruiz-Jaen and Aide 2005).

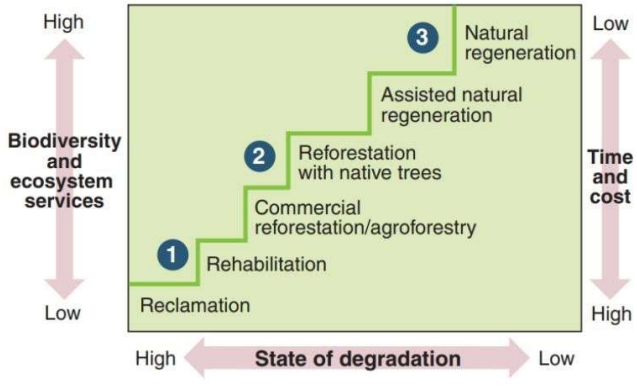

Fig. 1. Complexities of eco-restoration process (Rai 2022)

Implementation often falters because of supply-side and institutional constraints. On the supply side, ecological fit is weakened by poor provenance/seed-source matching, variable nursery quality, insufficient genetic and functional diversity in plantings, neglect of soil biota, and under-resourced after-care; moreover, the persistence of riparian, wetland, and floodplain interventions depends on hydrological management specifically, appropriate flows, groundwater regimes, and barrier operations like dams, barrages and embankments (Palmer et al., 2005, Menz et al., 2013, Gann et al., 2019). Correctly placing a site on the Fig. 1 gradient hinges on these diagnostics: misclassifying a severely degraded site as "ready for assisted natural regeneration," or a lightly degraded site as needing heavy planting, wastes resources and depresses outcomes (Rai 2022). On the institutional side, recognized tenure, equitable benefit-sharing, and Free, Prior and Informed Consent (FPIC) enable co-design and long-term stewardship, while effective cross-agency coordination, ring-fenced maintenance finance, and performance-linked contracts (payments tied to verified outcomes) help avoid short-term, tokenistic plantings (Suding et al., 2015, Chazdon and Brancalion 2019). Finally, robust Measurement, Reporting and Verification (MRV), transparent open-data frameworks that integrate ecological and social indicators and acknowledge climate uncertainty, underpins adaptive management and facilitates access to finance (Gann et al., 2019, Seddon et al., 2020).

Various Eco-restoration initiatives in India: India has implemented a diverse array of ecological restoration strategies across its varied biogeographic regions. These initiatives span from low-intervention, passive natural recovery to scientifically intensive techniques involving

biotechnology and soil engineering. Together, they illustrate the country's growing portfolio of context-specific, evidence-based approaches. One striking example of passive restoration emerged during the COVID-19 lockdown, when decreased industrial activity led to a temporary reduction in environmental stressors. The Damodar River in eastern India exhibited substantial improvements in water quality due to a sharp decline in effluent discharge. Water parameters neared the Bureau of Indian Standards (BIS 2012) norms for drinking water, as reported by Chakraborty et al. (2021). Similar patterns were observed in the Yamuna and Ganga rivers, where decreased anthropogenic pressure led to higher dissolved oxygen levels and reduced biochemical oxygen demand (Kumar et al., 2020, Varma and Jha 2023). These events underscored the latent regenerative capacity of ecosystems when disturbances are minimized.

At the other end of the spectrum are biochar-assisted soil restoration methods, which are gaining prominence for their multifaceted benefits. Biochar, a stable, carbon-rich byproduct of pyrolysis has been shown to improve soil structure, enhance microbial activity, and increase carbon sequestration. Ghosh and Maiti (2021) demonstrated that biochar produced from invasive weeds especially *Lantana camara* and *Calotropis procera* improved soil texture, pH balance, and nutrient content in degraded lands. Irfan and Mirara (2024) showed that biochar supports arbuscular mycorrhizal fungi and reduces the mobility of heavy metals in contaminated mining soils. These results highlight biochar's utility in restoring degraded soils and stabilizing toxic landscapes.

Biotechnology-integrated restoration approaches have also proven effective, particularly in post-mining landscapes. For example, Jambhulkar and Kumar (2019) successfully rehabilitated ~20 ha coal mine spoils in Maharashtra's Dhandrapur district using an integrated biotechnology approach that combined biofertilizers (e.g., *Azotobacter*, *Rhizobium*, VAM fungi) and industrial effluent treatment plant (ETP) sludge (such as organic amendments). Their results showed notable gains in vegetation biomass, canopy structure, and heavy metal immobilization. Complementing this, Juwarkar and Jambhulkar (2008) demonstrated, in a 10-ha coal-spoil field trial, that ETP sludge @ 50 t ha^{-1} along with biofertilizers markedly increased native microbial groups (previously near-absent) and immobilised heavy metals (e.g., Cr 41%, Zn 43%, Cu 37%) thereby accelerating soil functional recovery and enabling vegetation establishment. On other hand, species composition and planting strategy are also critical to the success of restoration efforts. Singh et al. (2012) found that mixed-species plantations significantly improved soil microbial diversity, enzymatic activity, and ecological stability in sodic lands compared to monocultures. More recently, Mandal et al. (2024) reported that polyculture restoration in riparian zones of Odisha led to enhanced groundwater recharge, biodiversity, and erosion control. Community-based initiatives have also demonstrated substantial success. Pattnaik (2014) documented the restoration of wetlands through the integration of local ecological knowledge and hydrological interventions. Similarly, Cao et al. (2022) applied watershed-based restoration models in semi-arid zones, which led to improvements in vegetation cover, groundwater levels, and agricultural productivity. These examples underscore the importance of participatory governance and social ownership in achieving long-term restoration goals. Collectively, these case studies illustrate that India's ecological restoration landscape is evolving toward a more diversified, science-based, and community-inclusive model. Scaling up such approaches will require capacity building, interdepartmental coordination, and policy support to embed restoration within broader environmental and developmental planning.

Tools for assessing progress of ecological restoration: Measuring the success of ecological restoration is inherently complex due to the long timescales involved and the variability of ecological responses across regions and ecosystems. Restoration does not necessarily aim to return an ecosystem to a pristine or historical state, but rather to initiate or accelerate recovery along a trajectory that increases ecological integrity, functionality, and resilience (Clewell and Aronson 2012, Gann et al., 2019). To provide structure and consistency in evaluating outcomes, the Society for Ecological Restoration (SER) introduced the *International Standards for the Practice of Ecological Restoration* (McDonald et al., 2016). Central to these standards is the Five-Star Recovery System, which assesses how closely a recovering site resembles a reference ecosystem across key ecological parameters such as species composition, structural complexity, and ecosystem functions. A score ranging from one to five stars reflects a continuum of recovery, with five stars indicating a high degree of ecological integrity.

Complementing this system is the Recovery Wheel (Fig. 2), a diagnostic and visualization tool designed to track progress across multiple attributes including biodiversity, ecosystem functionality, resilience to disturbance, and landscape connectivity (McDonald et al., 2016). This wheel enables restoration practitioners to identify underperforming components and prioritize interventions. It also supports adaptive management by allowing repeated assessments over time (McDonald et al., 2016, Gann et al., 2019). Both tools are grounded in the principle that restoration is a

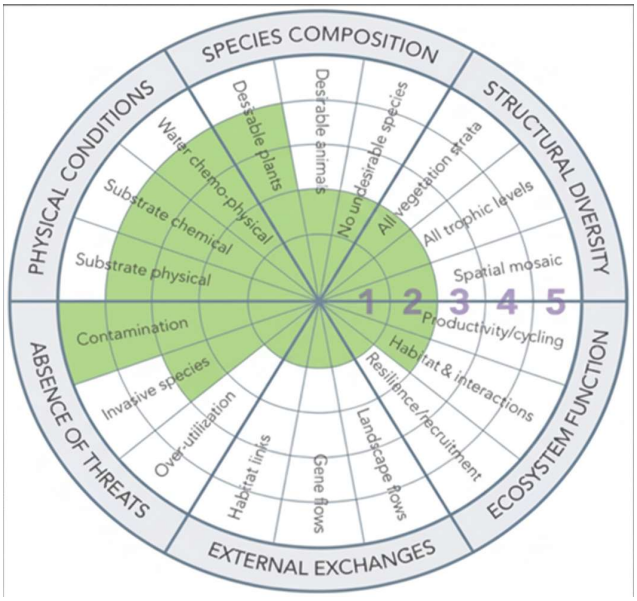

Fig. 2. Progress evaluation "recovery wheel" (McDonald et al., 2016)

dynamic and iterative process. Practitioners are encouraged to adopt a *trajectory-based approach* rather than relying on fixed endpoints, recognizing that partial or alternate forms of recovery can still yield meaningful ecological and societal benefits (Holl and Brancalion 2020). While these frameworks are increasingly used in global restoration programs, their application in India remains limited, often due to a lack of baseline data, insufficient training, or institutional fragmentation. Even so, several programmes are beginning to operationalise these frameworks in practice. In Uttarakhand, biodiversity offset projects attached to roads and hydropower, now set a "no net loss" type of target. Developers finance assisted natural regeneration and enrichment of oak-broadleaf forests on Van Panchayat and reserve forest lands. Sites are chosen using straight forward habitat condition scores alongside slopes and landslide risk maps. Monitoring revisits permanent plots, tracks seedlings through to recruitment and uses indicator fauna such as pheasants and ungulates. Independent audits check progress at agreed milestones (Tambe et al., 2022).

In the Western Ghats, Eco-development Committees (EDCs) and partner non-governmental organisations implement standardised, community-based monitoring using resource-efficient protocols. Field teams employ participatory maps and fixed photo-points, maintain mobile-based patrol records and fire-incidence logs, and conduct rapid line-transects and habitat assessments to track regeneration and invasive-species pressure. These observations are supplemented by low-cost hydrological and soil measurements including spring discharge, baseflow, and infiltration to link interventions with water-security outcomes (ATREE, n.d.). Taken together, these pilots demonstrate that standard baselines, control/counterfactual plots, and process-based indicators can be integrated into routine operations, generating evidence that is trusted by communities and verifiable by funders (Tambe et al., 2022). To scale up implementation, Indian policymakers and environmental agencies must invest in- a) Training programs for local practitioners and forest staff, b) Integration of monitoring tools into project management protocols, and c) Development of region-specific reference ecosystems based on historical data, local knowledge, and current site potential. Moreover, as per Mansourian and Stephenson (2023) the use of remote sensing, GIS-based modelling, and citizen science platforms can greatly enhance data collection and monitoring efficiency, making these frameworks more accessible and scalable.

CONCLUSION

Ecological restoration in India holds transformative potential, not only to reverse decades of environmental degradation but also to catalyse sustainable development, strengthen climate resilience, and empower marginalized communities. However, realizing this potential requires a shift from symbolic actions to scientifically grounded, context-specific, and participatory approaches. Before initiating restoration interventions, it is imperative to conduct comprehensive ecological assessments. These should evaluate site-specific degradation drivers, biodiversity baselines, soil characteristics, hydrological conditions, and socio-economic factors. Restoration strategies must be designed based on such diagnostics, adhering to internationally accepted principles like those outlined by the Society for Ecological Restoration. Multidisciplinary approaches are also essential, for instance, effective restoration should integrate actions such as invasive species control, nutrient cycling enhancement, water resource management, and livelihood support. Projects that combine ecological goals with human well-being through agroforestry, wetland restoration, or urban green infrastructure tend to be more sustainable and socially accepted. Equally critical is the establishment of robust monitoring and evaluation frameworks. The five-star recovery system and the recovery wheel provide adaptable, science-based tools to assess restoration progress over time. When tailored to local contexts, these tools can help guide adaptive management and promote transparency, accountability, and learning. Aligning restoration with national development goals and global frameworks—such as the UN Decade on Ecosystem Restoration, the Bonn Challenge, and India's NDCs under

the Paris Agreement—can unlock technical and financial resources. Furthermore, integrating restoration metrics into programs like CAMPA, MGNREGA, and the GIM can institutionalize restoration within existing policy structures. Ultimately, the long-term success of ecological restoration in India will depend not only on sound science and policy alignment, but also on inclusive governance, local stewardship, and cross-sectoral collaboration. Restoration must move beyond project-based interventions to become a core principle of land management and national planning. Embracing emerging tools, participatory models, and transdisciplinary knowledge systems will ensure that restoration is not just ecologically effective but also socially equitable and resilient in the face of future challenges.

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Incidence of *Cuscuta* Species on Angiosperm Dicotyledons in Nirmal District in Telangana State, India

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***Abstract*:** The incidence of parasitic *Cuscuta* spp. was observed on 4 angiosperm dicotyledonous host plants species belonging to 30 genera of 22 families were observed with infection of parasitic *Cuscuta* spp. from in the Nirmal district of Telangana State, India. Dominant infection was to Fabaceae family (07 species) followed by Rhamnaceae (03 species) and families Moraceae, Euphorbiaceae, Rutaceae and Verbenaceae, (02 species each). Dominant infected plants belonging to tree categories with 50% (17 species), shrubs infected with 44% (15 species) and least attack on herbs with 6% (02 species).

Keywords: Parasite, *Cuscuta*, Dicotyledonous, Angiosperm, Host plant

Cuscuta L. species commonly parasitic plants known as dodder and this a genus contains over 201 species of yellow, orange, green or red colour. Dodders are holoparasitic plants that enwind stems of host plants and penetrate those by haustoria to connect to the vascular bundles. Having a broad host plant spectrum., *Cuscuta* spp infect nearly all dicot plants, formerly treated as the only genus in the family Cuscutaceae and now is accepted as genus of family Convolvulaceae on the basis of the work of the phylogeny group of angiosperms. The genus is found throughout the world, with the greatest species diversity in tropical and subtropical regions, the genus becomes rare in cool temperate climates. The life cycle of *Cuscuta* parasite include, seed germination, early development of the seedling, and search for a host plant, haustorium induction and invasion of the host, haustorium maturation and interaction with the host plant (Yoder 1999). Parasite plants have diversified, and the evolution of *Cuscuta* appears to be completely different from other root parasite plants (Heide-Jørgensen 2008). Epiparasitic myco-heterotrophic plants appear to be evolved from mutualistic myco-heterotrophic plants (Merckx et al., 2009). Sakshi et al. (2024) provided detailed review on *Cuscuta reflexa* Roxb. In India, *Cuscuta* spp. poses a serious problem in oilseed niger (*Guizotia abyssinica*), linseed (*Linum usitatissimum*) and blackgram (*Vigna mungo*), greengram (*Vigna radiata*), chickpea (*Cicer arietinum*) and fodder crops lucerne (*Medicago sativa*)and berseem (*Trifolium* spp.) under rainfed as well as in irrigated conditions. Legislation in 25 countries lists the dodder as "declared noxious weed" with seeds and plant material denied entrance. In the, *Cuscuta* spp is the only weed seed whose movement in prohibited in United States. The wide geographical distribution of dodder species and wide host range, listed among the most damaging parasites. In present study the incidence of *Cuscuta* L. on angiosperm dicotyledons in Nirmal District in Telangana State, India was recorded.

MATERIAL AND METHODS

The Nirmal district situated in at latitude 19.096413° N and longitude 78.342972° E, on east Manchiryal district north by Adilabad. and Utnoor divisions on the south by Jagithyal and Nizamabad districts and on the west by Nanded district of Maharashtra State (Fig. 1). The most important river that drains the divisions is Godavari, which is the largest river in peninsular India. The Kadam vagu is tributary of the Godavari. Besides these Swarna vagu, and Sudda vagu drain the division. The average annual normal rain fall of the Nirmal district is 1107.2 mm and average number of rainy days in the year is 55 – 63 days. The forest of this district falls under tropical dry deciduous and tropical thorn forest type's consisting of mixed teak. From June 2022 to March 2025, a comprehensive survey was conducted throughout the Nirmal district, covering locations such as Timmapur, Dehagam, Bhainsa, Valegam, Ranapur, Mamada, Pichara, Thandra, Jam, Kadama, and the surrounding forest region. The study explores a list of 34 plants belong to 22 different families of dicot plants and include trees, shrubs and herbs. The identification was done according to Bentham & Hooker (1862-1883) classification.

RESULTS AND DISCUSSION

The incidence of *Cuscuta* spp. was observed on 34 angiospermic dicotyledonous host plants belonging to 30 genera of 22 families (Table 1). The incidence of *Cuscuta* spp. was more on Fabaceae family (affecting seven species

belonging to six genera), followed by Rhamnaceae (03 species belonging to single genus *Zizyphus*) and Moraceae, Euphorbiaceae, Rutaceae and Verbenaceae, (02 species each). Remaining 16 families viz. Acanthaceae, Apocynaceae, Asclepiadaceae, Bignoniaceae, Capparidaceae, Combretacae, Lythraceae, Malvaceae, Meliaceae, Moringaceae, Myrtaceae, Nyctaginaceae, Oleaceae, Plumbaginaceae, Sapindaceae and Tiliaceae infested with single plant species each (Fig. 2). Predominantly, incidence was severe on the genus *Ziziphus* (Family Rhamnaceae*)* with three species namely *Z. mauritiana* Lam., *Z. oenoplia* (L.) Mill. *Z. xylopyrus* (Retz.) Willd. and genera *Ficus* (Moraceae) and *Vachellia* (Fabaceae) with two species each namely *F. benghalensis* L., *F. virens* L. *V. nilotica* (L.) P.J.H.Hurter & Mabb. and *V. leucophloea* (Roxb.) Maslin, Seigler & Ebinger respectively. Seven species of Fabaceae family infected with *Cuscuta* are *Albizia lebbeck* (L.) Willd, *Butea monosperma* (Lam.) Taub.,

Table 1. Angiosperm dicotyledonous plant species infected with parasitic *Cuscuta* plant

Scientific name	Family	Local name	Categories of plants
Albizia lebbeck (L.) Willd	Fabaceae	Dirisena	Tree
Aegle marmelos (L) Corr.	Rutaceae	Maredu	Tree
Azadirachta indica Juss.	Meliaceae	Vepa	Tree
Bougainvillea spectabilis Willd.	Nyctaginaceae	Kagithampulu	Climbing Shrub
Butea monosperma (Lam.) Taub.	Fabaceae	Modugu	Tree
Calotropis procera (Ait.) R.Br.	Asclepiadaceae	Jilledu	Shrub
Capparis zeylanica L.	Capparidaceae	Uppi teega	Climbing Shrub
Corchorus trilocularis L.	Tiliaceae	Parinta Koora	Herb
Dalbergia sissoo Rxob.	Fabaceae	Shisham	Tree
Ficus benghalensis L.	Moraceae	Marri Chettu	Tree
Ficus virens L.	Moraceae	Juvvi Chettu	Tree
Hibiscus rosa-sinensis L.	Malvaceae	Mandara	Shrub
Lantana camara L.	Verbenaceae	Parasu Kampa	Shrub
Millingtonia hortensis L.	Bignoniaceae	Sadac malle	Tree
Moringa olifera Lam.	Moringaceae	Munaga Chettu	Tree
Murraya paniculata (L.) Jack.	Rutaceae	Nagagolungu	Perennial shrub
Nerium oleander (L.)	Apocynaceae	Ganneru	Shrub
Nyctanthes arbor-tristis L.	Oleaceae	Parijatham	Shrub
Phyllanthus reticulatus Poir.	Euphorbiaceae	Puli Chettu	Shrub
Pithecellobium dulce (Roxb.) Benth.	Fabaceae	Seema Chintha	Tree
Plumbago zeylanica L	Plumbaginaceae	Chitra Mooolam	Shrub
Punica granatum L.	Lythraceae	Danimma	Shrub
Ricinus communis L.	Euphorbiaceae	Amudamu	Shrub
Ruellia tuberosa L.	Acanthaceae	Chitapata Kayala chettu	Herb
Sapindus emarginatus Vahl	Sapindaceae	Kunkudu Kayalu	Tree
Syzygium cumini (L.) Skeels	Myrtaceae	Alla neredu	Tree
Tamarindus indica L.	Fabaceae	Chinta	Tree
Terminalia tomentosa Wight & Arn.	Combretacae	Nallamaddi	Tree
Vachellia nilotica (L.) P.J.H.Hurter & Mabb.	Fabaceae	NallaTumma	Tree
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	Fabaceae	Tella tumma	Tree
Vitex negundo L.	Verbenaceae	Vavili	Shrub
Ziziphus mauritiana Lam.-	Rhamnaceae	Jitti Nerachettu	Evergreen Shrub
Ziziphus oenoplia (L.) Mill.	Rhamnaceae	Pariki	Shrub
Ziziphus xylopyrus (Retz.) Willd.	Rhamnaceae	Gotti Chettu	Tree

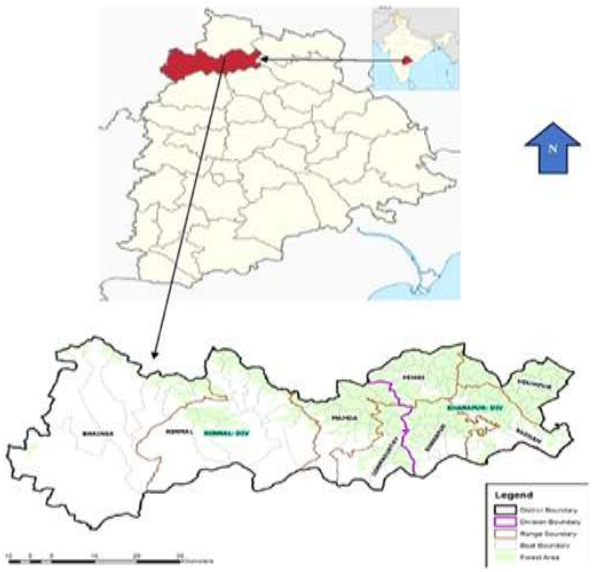

Fig. 1. Location of study area map

Dalbergia sissoo Rxob., *Pithecellobium dulce* (Roxb.) Benth., *Tamarindus indica* L., *Vachellia nilotica* (L.) P.J.H.Hurter & Mabb. and *V. leucophloea* (Roxb.) Maslin, Seigler & Ebinger (Fig. 2). Dominant infected plants belonging to tree categories (50%) followed by shrubs (44%) and herbs (6%).

Abubacker et al. (2005) observed that *Cuscuta* spp. have unique glandular cells that help the parasite adhere to the host and this explains why primarily observed on *Z. mauritiana* Lamk's rough bark. After dividing and spreading outward like a collar around the host plant, these cells pierce the phloem. Sarma et. al. (2008) also observed the same trend. *The* invasion is facilitated by habitat disturbance and climate change, which produce favorable conditions in new locations. In many regions of the world, at least a few species of *Cuscuta* are regarded as a major invasive danger due to their aggressive behavior, ability to disturb local ecosystems, and potential to reduce agricultural production (Parker 2012)

Fig. 2. Host plant attacked by *Cuscuta* spp. (A) *Vitex negundo* L.,(B) *Ziziphus mauritiana* Lam.

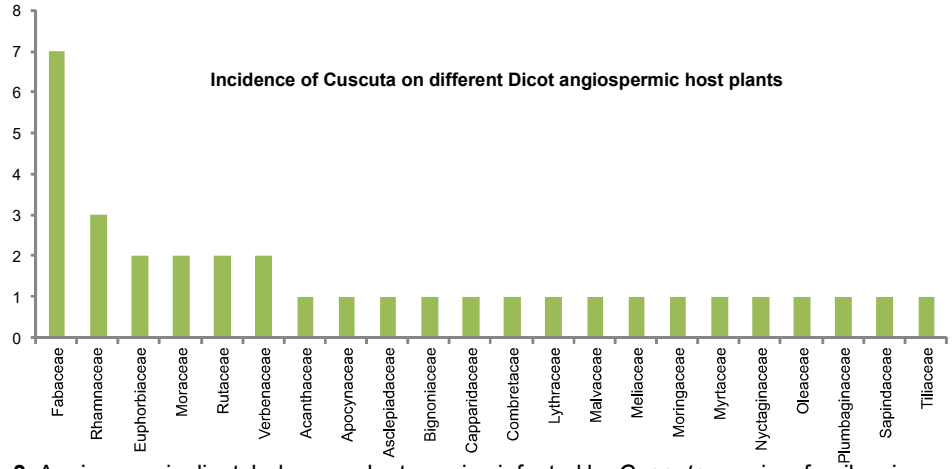

Fig. 3. Angiospermic dicotyledonous plant species infected by *Cuscuta* spp. in a family-wise manner in Nirmal district

CONCLUSION

Cuscuta species do not have a specific host and can even flourish by consuming the least quantity of nutrients and water from the host. It impairs or hinders the host's ability to grow and develop normally. The Fabaceae host plants ensured a very quick attachment and short lag phase of the parasite, likely because of the family's presumably higher nitrogen content and the high nitrogen requirements of *Cuscuta* genus members. *Cuscuta* spp. management is challenging in agriculture and the environment because of their parasitic nature. Phytosanitary management and prevention appears to be the most crucial step in preventing future infestations.

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Natural Regeneration and Population Assessment of *Berberis aristata*: A Endangered High Value Medicinal Shrub of Western Himalayas

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Abstract: The present study was undertaken to assess the natural regeneration and population status of *Berberis aristata* DC. in the Sindh Forest Range of Ganderbal district, Jammu & Kashmir, India. Twelve sampling plots (20 × 20 m), 96 sub-plots (5 × 5 m), and 864 sub-sub plots (1 × 1 m) were randomly established along both north and south aspects of the Sindh River at three elevation ranges: E1 (1500–2000 m AMSL), E2 (2000–2500 m AMSL), and E3 (>2500 m AMSL). The regeneration per cent was highest (16.7%) at mid-altitude (2000–2500 m AMSL). The northern aspect exhibited fair regeneration up to 2500 m AMSL, whereas the southern aspect showed poor regeneration at similar elevations. Population attributes *viz*., mean density (12.9 m²), frequency (14.8%) and basal area (3.51 m²) were highest at mid-altitude on the southern aspect. However, these parameters increased up to mid-altitude and thereafter declined. The study concluded that mean regeneration status of *B. aristata* was very poor (16.7%), indicating that the species faces a high risk of extinction.

Keywords: *Berberis aristata*, Conservation, Kashmir Himalaya, Natural regeneration

There are numerous shrub species which co-exist with other tree and grass-based land use systems (Thakur et al., 2005), contributing towards economics, health wellbeing and environment conservation and carbon sequestration. Among these the genus *Berberis contribute these aforesaid important attributes* (Thakur et al., 2011, Thakur et al., 2017). Globally, this genus comprises of 500 species, of which nearly 60 are reported from the Indian Himalayas (Hashmi et al., 2024). The family Berberidaceae comprises 16 genera, with *Berberis* being the largest, accounting for about 70–80% of total species. Among them, *Berberis aristata* DC., is an important medicinal shrub distributed from the western Himalayas to Sri Lanka, Bhutan, and Nepal, and sporadically in the Nilgiri hills of South India (Sharma et al., 2018). It generally occurs at altitudes of 1800–2800 m AMSL, but in rare and scattered populations (Thakur et al., 2011). Pharmacological studies have confirmed a broad spectrum of properties including antibacterial, antiviral, antifungal, anticancer, and antidiabetic activities, largely attributed to **berberine**, a quaternary is quinoline alkaloid concentrated in the roots and stems (Sharma et al., 2024). Despite its importance, *B. aristata* faces severe threats due to overharvesting of roots for berberine extraction, habitat degradation and lack of propagation protocols. Consequently, it has been listed as an endangered species in the Indian Himalayan Region by the IUCN (Malik et al., 2024). Natural regeneration in this species is poor due to low germination, irregular fruiting and seed predation, resulting in declining wild populations (Malik et al., 2024). Parallel ecological studies have shown that regeneration dynamics of forest species vary markedly along altitudinal gradients (Joshi 2023). *Berberis aristata* and *B. jaeschkeana* attained the highest density in Sangla valley, Northwest Himalayas, reflecting their strong adaptability to extreme climates (Mohapatra 2019). Diversity of *B. lycium* was also higher on drier (southern aspects) along Neeru stream (J&K) (Sharma et al., 2017). Aspect-driven variation in community composition was further confirmed (Sinha and Sinha 2013) in the Balandi watershed, Chhattisgarh, India where species dominance differed significantly between aspects. Despite the ecological and medicinal importance of *B. aristata*, no detailed study on its regeneration status and phytosociology has been reported from Sindh Forest Division, Ganderbal (J&K), or elsewhere in Kashmir Himalaya, particularly across aspects. Therefore, the present study was undertaken to analyze its community structure and regeneration dynamics.

MATERIAL AND METHODS

The regeneration and population assessment of *B. aristata* was conducted during the year 2021 to 2022 in Sindh Forest Range of Ganderbal district (J&K) located at 34°7'0" to 34°28'0"N and 74°42'0" to 74°26'0" E (Fig. 1). The study range was divided into three altitudes *viz*., E1 (1500–2000 m AMSL), E2 (2000–2500 m AMSL), and E3 (>2500 m AMSL) with two aspects *viz*., northern and southern aspects. To assess the population and regeneration status of *Berberis*

aristata, four sampling plots (20 × 20 m) were established at each of altitudinal range and aspect. Each main plot was subdivided into eight sub-plots (5 × 5 m) for population assessment. However, each sub-plot was further divided into nine quadrats (1 × 1 m) for regeneration survey. In total, 12 main plots, 96 sub-plots and 864 regeneration quadrats were laid along three altitudinal gradients along two aspects of the study area to understand the natural regeneration potential of the species. The occurrence of *B. aristata* was used as an indicator for laying the sampling plots to study its natural population status of the species.

Regeneration assessment: The survey was conducted for counting number of recruits (r), which may be defined as the current year seedlings, established regeneration (u) seedlings other than recruits which has not yet established and with height less than 2 meter and established regeneration (e) plants with more than 2 meter height (Chacko 1965).

$$\text{Recruits= (r)/ha= } 2500 \sum \frac{\text{total number of recruits in each quadrant}}{\text{Total number of recording units (plots or blocks) laid in a stratum}}$$

$$\text{Unestablished regneration=(u)/ha= } 2500 \sum \frac{\text{total no. of un-established plants in each quadrant}}{\text{total number of (plots or blocks) laid in a stratum}}$$

$$\text{Established regeneration=(e)/ha= } 2500 \sum \frac{\text{total number of established plants in each quadrant}}{\text{total number of (plots or blocks) laid in a stratum}}$$

$$\text{Weighted average height (cm)=} \frac{\text{Total height of un-established regeneration + (Number of established plants × establishment height)}}{\text{Total un-established plants + Total established plants}}$$

$$\text{Establishment index (I)=} \frac{\text{Weighted average height}}{\text{Establishment height}}$$

$$\text{Stocking Index (II)=} \frac{1}{2500} \times \frac{\text{(u) regeneration/ha}}{2} + \text{(e) regeneration/ha}$$

Established stocking per cent=100 (Establishment Index × Stocking Index)

Regeneration success (%)=Stocking Index (I) × 100 (Malik et al., 2012).

The regeneration status of *B. aristata* in the area was also evaluated by comparing seedling with sapling and sapling with matured shrub data (Shankar, 2001) in the following categories; G good, fair, poor, none and new regeneration

Population assessment: For population assessment the following quantitative parameters were taken into consideration;

$$\text{Density=} \frac{\text{Total number of individuals of a species in all quadrants}}{\text{Total number of quadrants studied}} \times 100$$

$$\text{Frequency=} \frac{\text{Number of quadrants in which the species occurred}}{\text{Total number of quadrants studied}} \times 100$$

$$\text{Basal area=} \frac{\pi D^2}{4}$$

RESULTS AND DISCUSSION

The maximum mean number of mature shrubs were recorded on the southern aspect at 2000–2500 m AMSL(3.5), while the minimum occurred above 2500 m on the northern aspect (0.5) (Table 1). Mature shrub density increased up to mid-altitude before declining with elevation. Saplings were highest (1.0) at 2000–2500 m AMSL on both aspects, whereas seedlings were maximum (1.5) on the northern aspect at the same elevation, indicating better regeneration potential under northern microclimatic conditions. Regeneration was absent at 1500–2000 m AMSL on both aspects, while above 2500 m AMSL only poor regeneration was observed . Regeneration density and stocking patterns vary significantly with altitude and slope aspect in Himalayan forests, with seedling and sapling densities often peaking at mid-altitudes and differing between northern and southern aspects (Sharma et al., 2018, Negi et al., 2024). Studies in the Garhwal Himalaya revealed that overall regeneration status of forest species was fair to good at mid-altitude zones, correlating with optimal microclimatic conditions and reduced anthropogenic disturbance, while regeneration declined at higher elevations due to harsher climatic constraints (Sharma et al., 2018). Similarly, biological diversity and regeneration in North-Western Himalayan agroforestry varied with altitude, aspect, and habitat. Mid-altitude sites supported greater diversity and regeneration of woody species like *B. aristata*. Replicated, plot-based sampling facilitates accurate assessment of population and regeneration, underscoring the ecological influence on species conservation in Himalayan agroforestry systems (Thakur et al., 2005).

At lower altitude (1500–2000 m AMSL), the maximum number of recruits were recorded on the southern aspect

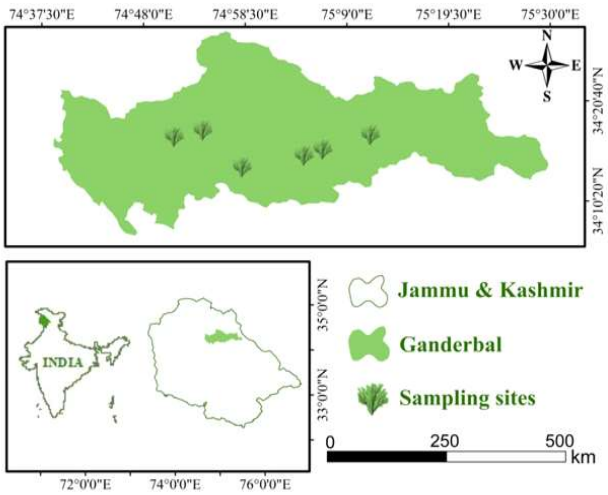

Fig. 1. Ganderbal district distribution zone of *B. aristata*

(414.66 recruits ha^{-1}), whereas the minimum (277.77 recruits ha^{-1}) on the northern aspect. In contrast, un-established regeneration peaked at mid-altitude (2000–2500 m AMSL) on the northern aspect (555.56 ha^{-1}) and was lowest (138.89 ha^{-1}) at higher altitude (>2500 m AMSL) on the same aspect. Established regeneration followed a similar trend, with the highest value (277.78 ha^{-1}) observed at mid-altitude on the southern aspect and the lowest (138.89 ha^{-1}) at both lower and higher altitudes of the southern aspect and at higher altitudes of the northern aspect. The stocking index (I_1) also varied across altitudes and aspects, with the highest at mid-altitude (2000–2500 m AMSL) (0.167) on the northern aspect, followed by 0.112 on the southern aspect, while the lowest (0.083) occurred at lower altitude on the southern aspect. Shrub species diversity in the Indian Himalayas generally shows a hump-shaped pattern along elevation, with peak diversity at mid-altitudes and decline at higher elevations due to colder temperatures and harsher conditions (Boscutti et al., 2018). Aspect influences shrub distribution, as southern slopes often support higher species diversity owing to greater sunlight exposure, while northern slopes tend to support moisture-retentive but less diverse shrub communities (Wani et al., 2023). These vegetation patterns reflect strong altitudinal and aspect-driven ecological gradients documented in cold desert and temperate Himalayan zones, underscoring their importance in biodiversity conservation planning (Negi et al., 2024). Regeneration per cent exhibited marked variation across altitudes and aspects (Fig. 3). The highest regeneration per cent (16.7%) was at mid-altitude (2000-2500m AMSL) on the northern aspect, followed by 11.2% at lower altitude (1500-2000m AMSL) on the northern aspect and 2.78% (the lowest figure) at higher elevation on the southern aspect . According to the methodology of Chacko (1965), the overall maximum regeneration potential (recruits: 277.78 ha^{-1}, un-established: 555.56 ha^{-1}, established: 277.77 ha^{-1}, establishment stocking: 7.47%) was also concentrated at mid-altitude on the northern aspect. These findings clearly indicate that regeneration of *B. aristata* is more successful on the northern aspect, particularly at mid-altitudes, where favorable

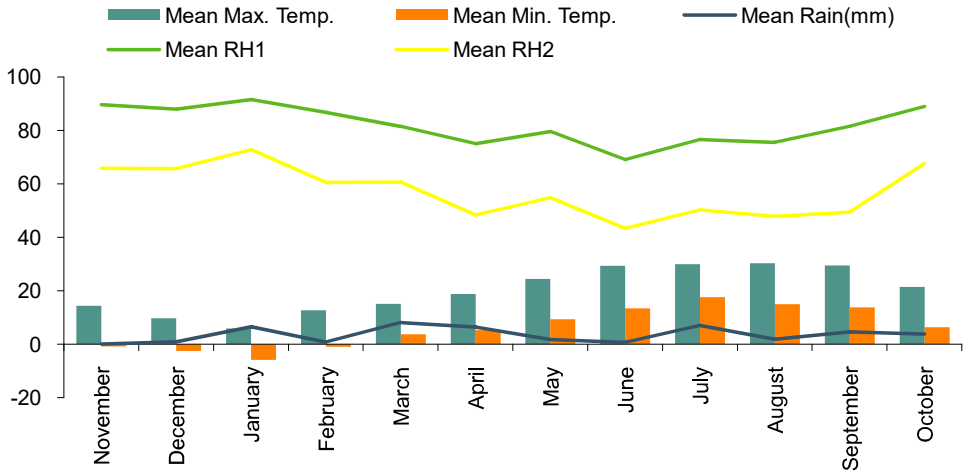

Fig. 2. Meteorological data of Sindh forest range (November 2021 to October 2022)

Table 1. Regeneration status of *B. aristata* along the altitudinal gradient and aspect in Sindh Forest range of district Ganderbal

Elevation (m AMSL)	Average no. of mature shrubs		Average no. of saplings		Average no. of seedlings		Regeneration status	
	NA	SA	NA	SA	NA	SA	NA	SA
E_1	1.0	2.0	-	-	-	-	N	N
E_2	1.50	3.50	1.0	1.0	1.50	-	F	P
E_3	0.50	1.0	0.50	0.50	-	-	P	P
Mean	1.0	2.10	0.50	0.50	0.50	-		
CV (%)	50.0	59.50	100.0	100.0	172.0			
C.I.	U.L	2.35	5.11	1.37	1.37	1.66		
	L.L	1.56	3.11	0.58	0.58	0.29		

NA-north aspect; SA- south aspect; E1= (1500-2000); E2= (2000-2500); E3= (Above 2500); N-no regeneration, F-fair regeneration, P-poor regeneration, C.I-Confidence interval, UL-upper limit, LL-lower limit

moisture regimes, nutrient availability and reduced anthropogenic disturbances likely create optimal conditions for establishment. The trend is consistent with previous studies, where higher regeneration on northern aspects was reported for *Pinus gerardiana* (Malik et al., 2012), *Pinus ponderosa* (Busse et al., 1996), and fir–spruce communities in Shimla (Yashpal, 2006). The overall regeneration status indicated fair regeneration on the northern aspect at mid-altitude and poor regeneration on the southern aspect, while both aspects lacked regeneration at lower elevations.

Phytosociological parameters also followed a mid-altitude dominance trend. The maximum density (22.22 m²/ha), basal area (6.93 m²), and frequency (22.22%) were at 2000–2500 m AMSL on the southern aspect (Table 3). In

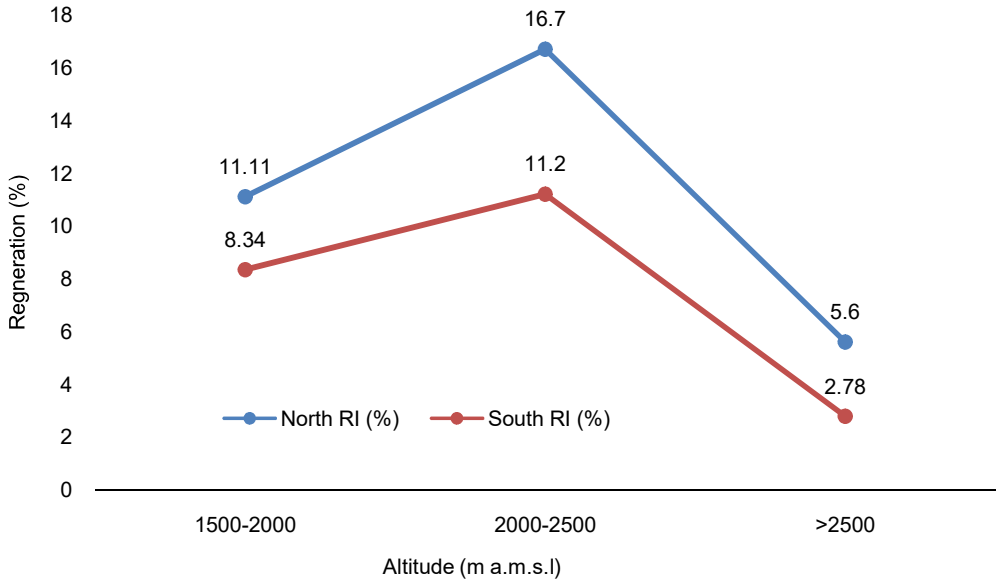

Fig. 3. Regeneration index (%) of *B. aristata* across altitudinal gradients under north and south aspects in the Sindh Forest Range

Table 2. Natural regeneration status of *B. aristata* at different elevations and aspects of Sindh forest range of district Ganderbal

Aspect	E	RC/ha	U/ha	Ht. U (cm)	Est./ha	WAH (cm)	EI (I_1)	SI (I_2)	ES (%)
North aspect	E_1	277.77	555.55	155.00	0.00	0.38	0.19	0.11	2.14
	E_2	277.78	555.56	150.00	277.77	0.89	0.44	0.16	7.47
	E_3	0.00	138.89	190.00	138.89	1.95	0.97	0.05	5.46
South aspect	E_1	414.66	277.78	160.00	138.89	1.05	0.52	0.08	4.37
	E_2	0.00	277.78	155.00	277.78	1.18	0.53	0.11	6.64
	E_3	0.00	0.00	0.00	138.89	1.70	0.85	0.02	2.36

See Table 2 for treatments details

Table 3. Phytosociology of *B. aristata* along altitudinal gradient and aspects in Sindh Forest Range of district Ganderbal

Elevation (m AMSL)	Density/plot (m^2)		Frequency (%)		Basal area (m^2)	
	North aspect	South aspect	North aspect	South aspect	North aspect	South aspect
E_1	6.25	11.11	5.60	11.11	2.0	2.20
E_2	9.37	22.22	16.70	22.22	3.20	6.93
E_3	3.12	5.60	5.60	11.11	1.10	1.40
Mean	6.24	12.90	9.30	14.80	2.10	3.51
CV (%)	67.60	65.11	68.8	43.30	48.0	82.6
CI UL	9.87	19.64	16.76	19.93	2.90	5.83
LL	3.12	6.15	1.83	9.66	1.29	1.18

See Table 2 for treatments details

contrast, the northern aspect reported lower density (6.24 m²/ha) and basal area (2.1 m²). Bhandari et al. (2000) observed highest density of shrubs on southern aspect may be related to the lower density and less developed canopy of trees, which may have allowed enough light to reach the ground and encouraged the growth of shrubs. In contrast, the deep, well-developed canopy in the northern aspect prevents enough sunlight from reaching the shrub vegetation to support it. The basal area is directly correlated with density of the species. Similar trends were observed in Kashmir Valley agroforestry systems, where shrub and herb densities declined with increasing canopy cover, highlighting the role of light availability in understory growth (Rather et al., 2025). Rawat and Chandra (2014) also reported that while trees and herbs attained maximum diversity, richness, and density along moist stream banks in Garhwal Himalayas, shrubs thrived better on drier sites—supporting the present observation of *B. aristata* exhibiting higher density on southern (drier) aspects and better regeneration on northern (moister) aspects. Sharma et al. (2017) observed higher density and diversity of *B. lycium* in drier zones (Z-II) on both banks of Neeru stream (J&K). Sharma et al. (2014) documented the highest density of *B. aristata* and *B. jaeschkeana* in Sangla Valley, attributing this to their strong adaptive capacity to extreme Western Himalayan climates. The phytosociological study in Gomarda Wildlife Sanctuary, Chhattisgarh, recorded 66 herb species across 52 genera and 25 families, reflecting moderate to high herbaceous diversity linked to habitat heterogeneity and microenvironmental variation indicated by IVI differences among sites (Patel et al., 2024). The present findings also align with Kumar (2017) indicating higher density and basal area of shrubs on southern aspects, likely due to increased solar radiation. Bhardwaj et al. (2021) reported that the community characters differ among aspect, slope, and altitude even in the same vegetation type. These findings are consistent with reports indicating that shrub diversity attains its peak on drier sites, reflecting niche differentiation driven by microhabitat conditions.

The population structure, characterized by low seedling and sapling density, indicates regeneration challenges, largely attributed to anthropogenic pressure, fuelwood collection, and poor agricultural practices of *B. aristata* (Srivastava et al., 2006; Ali et al., 2008). Given the species' endangered status (Amira, 2021), these findings provide baseline data essential for its conservation and sustainable management.

CONCLUSION

Maximum regeneration percentage of *B. aristata* occurred at mid-altitudes (2000-2500 m AMSL) across northern and southern aspects, with the northern aspect exhibiting relatively better regeneration compared to the southern aspect. The overall regeneration status of the species was extremely poor, with only 16.7% regeneration and 7.4 % establishment stocking, indicating the poor natural regeneration in the study area. This poor regeneration can be attributed to multiple anthrogenic pressures such as overharvesting, intensive grazing and habitat disturbance, coupled with species biological constraints. Given that *B. aristata* has already been categorized as “endangered” by the IUCN, the observed regeneration failure underscores the urgent need for immediate protection measures. For the implementation of successful conservation strategies and for understanding the status of *B. aristata* in the area, this information is crucial for further ex-situ and in-situ conservation of the species.

AUTHOR'S CONTRIBUTION

Nisha Tariq: Conceptualization, field investigation, data collection, data analysis and manuscript writing (original draft preparation) ,A.R. Malik: Conceptualization, Supervision, study design, project administration and critical manuscript review and editing, S.A. Gangoo: Methodology development and guidance on experimental design, P. A. Sofi: Data analysis, interpretation and statistical validation, Tahir Mushtaq: Assistance in field sampling and data compilation, Amerjeet Singh: Support in data management and preparation of figures/ tables, Peerzada Ishtiyak Ahmad: Review and editing of the manuscript, Mehvish Mushtaq: Literature survey and preparation of reference materials, N. A. Pala: Assistance in data interpretation and manuscript editing, S. N. Zafar: Administrative support and coordination with field authorities.

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Seed Source Variation in Seed Traits, Germination and Seedling Growth Attributes of Sandalwood (*Santalum album* L.)

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Abstract: *Santalum album* is indigenous to peninsular India and popularly known as Indian Sandalwood. In this study, we evaluated total six different sandalwood seed sources under nursery condition including seed morphology at College of Forestry, NAU, Navsari, Gujarat. There was a significant variation in seed morphological attributes, seed germination and other attributes *viz.,* Mean daily germination, Peak value of germination, Germination value and Germination rate index and Mean germination time. Seedling growth measured at 90 days after transplanting also resulted in significant variation among the seed sources under nursery. Idukki (Kerala) and Bengaluru (Karnataka) sources showed superiority for seed size, germination and seedling growth attributes under Navsari climatic conditions; conversely, Surat and Dharwad sources showed poor germination. Therefore, Idukki and Bengaluru sources can be used for large scale seedling production as well as for further selection and evaluation at field condition.

Keywords: Hemiparasite, Nursery attributes, Sandalwood, Seed morphology, Seed source

Sandalwood, a generic term used for species of Genus *Santalum,* is a hemi-parasitic genus renowned for its fragrant wood. It includes 15 extant species and 14 varieties and one extinct species *i.e., Santalum fernandezianum* (Harbaugh and Baldwin 2007). Among several species of *Santalum*, *S. album* (Indian Sandalwood), *S. spicatum, S. austrocaledonicum, S. insulare, S. lanceolatum, S. macgregorii* and *S. yasi* are commercially important ones (Durai 2021). *S. album* is indigenous to peninsular India distributed from Nasik to Northern Circars (Madras Presidency) downwards, and occurs in the dry deciduous forest of Deccan plateau at the edge of Western Ghats and Kalrayan and Shevaroy Hills of Tamil Nadu. *S. album* stands out from other sandalwood species for its highly valued oil and wood making. It is the second most expensive wood in the world after *Dalbergia melanoxylon* (African blackwood). The most economical parts of a sandalwood tree are heartwood of root and stem; therefore is most valued for its fragrant heartwood. Santanol content is most responsible for its aroma. Sandalwood oil is commonly used in the perfumery industries and pharmaceutical uses in medicines (Arunkumar et al., 2012, Arunkumar et al., 2016) and there is great global and domestic demand for sandalwood oil.

Thus, farmers, private agencies, state forest departments started growing sandalwood plantations in large scale across India including non-traditional sandalwood areas *viz.,* Andhra Pradesh, Telangana, Gujarat, Madhya Pradesh, Maharashtra, Rajasthan and other parts. Currently, the area under sandalwood in farmlands has grown dramatically to an estimated 30,000 ha in 2019, with the majority of the plantings taken place in Gujarat and Karnataka (Pallavi 2015). Considering the future financial benefits of growing sandalwood, farmers have started cultivation of Sandalwood from the last 10 years. With the help of Gujarat Forest Department, more than 670 farmers raised about 3.3 lakhs Sandalwood seedlings under Agroforestry and Vrukshkheti schemes (Singh 2021, Rathore et al., 2021). Hence, there was a demand for quality planting materials for large scale plantation programs. Then, identification of good seed source is very crucial and screening of good seed sources provides information on nature and magnitude of variability present in planting material (Suma and Balasundaran 2007, Gunaga et al., 2015, Arunkumar et al., 2012, Bhuva et al., 2024). With this context, a study comprising six distant seed sources including Gujarat was started to understand the seed trait variability and its performance on germinability and growth under nursery condition in the Navsari climatic situation of southern Gujarat.

MATERIAL AND METHODS

The present study was carried out at Navsari Agricultural University (NAU), Navsari, Gujarat [20° 55' 21.18'' N and 72° 54' 29.24'' E with an altitude of 9 meter above the mean sea level during 2023-24. Seeds were collected from six different seed sources- one from Kerala, three from Karnataka and two from Gujarat (Table 1). Since species is under IUCN threat category (Arunkumar et al., 2016), the geo co-ordinates of selected locations are not given. Collected seeds were cleaned and characterized for seed morphological observations in the laboratory.

Further, all these seed lots were used for assessing seed germination and seedling growth at Nursery in the NAU Campus. Study site belongs to typical tropical warm climate characterized by fairly hot summer, moderately cold winter and warm humid monsoon. Generally, monsoon commences in the second week of Jun and ends in Sept with mean annual rainfall from 1200 to 1500 mm. During experimental period from Apr 2023 to Mar 2024, maximum rainfall occurred during July with 1030 mm, followed by Jun (306 mm) and Sept (289mm); while, maximum temperature ranged from 29.5 to 36.0 ºC and minimum temperature ranged from 14 to 26.9 ºC. The minimum and maximum relative humidity recorded was 62 and 93 per cent, respectively. These data were collected from the Agricultural Meteorological Cell, Department of Agricultural Engineering, N.M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat.

Morphometric variation in seed traits such as seed length, seed thickness, seed weight and test weight (hundred seed weight) was measured using all the six seed sources in the laboratory. For each seed source, total two hundred fifty seeds *i.e.,* five sample containing fifty seeds each were used. For germination study, five repetitions containing 100 seeds each (N= 500 per source) for six seed sources were sown on nursery bed by following completely randomized design by maintaining uniform growing condition under mini-polytunnel in the nursery. Prior to sowing, seed were subjected to common pre-sowing treatment with GA_3 @ 500 ppm for 24 hours uniformly for all the seed sources. Seed beds were drenched with Carbendazim (Bavistin), before seed sowing (Lekshmi 2024). The numbers of seeds germinated on each day were counted. Emergence of plumule above the soil was taken as germinated. Based on daily germination count, day of first germination and day of last germination was recorded. Further, daily germination count was used to determine the germination percentage and other germination parameters such as mean daily germination (MDG), Peak Value (PV), germination value (GV), germination rate index (GRI) and mean germination time (MGT) using standard formulae (Czabator 1962, Orchard 1977, Esechie 1994, Thakur et al., 2017).

To assess the seedling growth, germinated seeds from germination experiment (different seed sources wise) were transplanted into polybags of size 4x8cm containing potting mixture of soil, sand and FYM (well decomposed) in the ratio 2:1:1. Pigeon pea (*Cajanus cajan* L.) was grown as a host plant (Lekshmi 2024). Total five repetitions, each containing 25 seedlings, were used and then seedlings were arranged in completely randomized design under shade net condition. Growth observation such as plant height, collar diameter and number of leaves per plant was recorded and growth at 90 days after transplanting was reported.

Statistical analysis: All the data were subjected to CRD and DMRT analysis was also performed by following Gopinath et al. (2020).

RESULTS AND DISCUSSION

Variation in seed traits: There was a significant variation among six seed sources for seed length (7.18 to 7.87 mm), seed width (6.56 to 7.01 mm), seed weight (0.15 to 0.19 g) and 100 seed weight (14.24 to 18.69 g). Seed width was slightly lesser than seed length indicating oval shape. Among all the seed sources, seeds collected from Idukki, Bengaluru and Dharwad sources recorded to be bigger in size having more length, width and weight, while seeds collected from local sources *viz.,* Surat and Junagadh showed smaller seeds (Table 1). Similar to the present study, Madhuvanthi et al. (2024) reported variability in seed weight between individuals as well as populations of *S. album*, where the Idukki population recorded maximum seed weight and was minimum in Mysore population. Earlier studies on *S. album* showed that seed length varied 6.02 to 7.9 mm, seed width from 6.00 to 8.42 mm seed weight from 0.16 to 0.19 g. (Manonmani and Vanangamudi 2002, Annapurna et al., 2005, Shwetha et al., 2024)

Variation in seed germination: Seeds collected from Surat source resulted in poor and irregular seed germination (1 to 3%); hence, this source was dropped from germination and growth studies. Germination experiment shows that seed source influenced the seed germination and its attributes in Sandalwood. Seeds started germinating 21 days after sowing and completed within 52 days. Shwetha et al. (2024) and Annapurna et al., (2005) also reported variation in initiation of seed germination and time of seed germination varied from 16 to 31 days and 15 to 28 days, respectively. Periodic germination showed a significant variation among five seed sources (Table 2) and it varied from 1.40 to 24.20 per cent at 30 days and 7.20 to 45.00 per cent at 70 days after sowing. Similarly, other germination attributes such as germination rate index also showed significant variation among seed sources (Table 3). Mean germination time show the average days to achieve maximum germination ranged from 33 (Mysore) to 43 (Dharwad). Such information is ideal for selection of better seed source(s). Shwetha et al. (2024) observed variation in germination among seven seed sources from Karnataka and one from Kerala (Marayoor). Out of these, Marayoor (Idduki, Kerala), Gungaraghatti (Dharwad, Karnataka) and Gottipura (Bengaluru, Karnataka) performed better than other sources. In present study Idukki and Bengaluru sources proved better germination; in contrast, Dharwad and Junagadh sources resulted in lower germination. Better performance of seed sources could be

due to greater genetic diversity and nature of adaptability (Suma and Balasundaran 2007). It is also evident that provenances and individual genotypes behave differently for germination and attributes including seedling growth. Erstwhile studies confirm that variation in germination traits can be attributed by seed sources. As per review, the germination varied from 4.00 to 80.33 per cent (Manonmani and Vanangamudi 2002, Annapurna et al., 2005, Batabyal et al., 2014, Madhuvanthi et al., 2024 and Shwetha et al., 2024). Interestingly, the range of germination (7.20 to 45.00%) recorded in the present study also falls under this range. Apart from genetic factors, seed germination is also influenced by

Table 1. Variation in seed traits among six seed sources of Sandalwood

Seed sources	Seed length (mm)	Seed width (mm)	Seed weight (g)	Test weight (g)
Idukki (Kerala)	7.87^{a}	6.96^{ab}	0.19^{a}	18.69^{a}
Mysore (Karnataka)	7.18^{c}	6.56^{d}	0.16^{d}	15.88^{c}
Bengaluru (Karnataka)	7.60^{b}	7.01^{a}	0.17^{cd}	16.69^{bc}
Dharwad (Karnataka)	7.87^{a}	6.83^{bc}	0.18^{ab}	17.58^{ab}
Junagadh (Saurashtra, Gujarat)	7.47^{b}	6.91^{abc}	0.17^{bc}	16.10^{c}
Surat (South Gujarat)	7.61^{b}	6.78^{c}	0.16^{d}	14.21^{d}
Mean	7.60	6.84	0.17	16.53
CD (P<0.05)	0.17	0.16	0.016	1.37
CV (%)	1.67	1.74	6.95	6.35

Treatments with same letters are not significantly different

Table 2. Variation in seed germination at different time intervals among six seed sources of Sandalwood

Seed sources	Seed germination (%)				
	30 DAS (G30)	40 DAS (G40)	50 DAS (G50)	60 DAS (G60)	70 DAS (G70)
Idukki (Kerala)	13.60^{b} (21.62^{b})	20.60^{bc} (26.98^{bc})	27.80^{b} (31.75^{b})	30.20^{b} (33.30^{b})	31.60^{b} (34.18^{b})
Mysore (Karnataka)	16.80^{b} (24.08^{b})	25.40^{bc} (30.17^{b})	27.80^{b} (31.76^{b})	28.40^{b} (32.15^{b})	31.40^{b} (34.03^{b})
Bengaluru (Karnataka)	24.20^{a} (29.36^{a})	36.40^{a} (37.08^{a})	39.20^{a} (38.74^{a})	41.40^{a} (10.03^{a})	45.00^{a} (42.12^{a})
Dharwad (Karnataka)	1.40^{d} (6.58^{d})	3.80^{d} (10.78^{d})	5.40^{d} (13.14^{d})	6.60^{d} (14.64^{d})	7.20^{d} (15.33^{d})
Junagadh (Saurashtra, Gujarat)	8.60^{c} (16.40^{c})	16.40^{c} (23.59^{c})	21.20^{c} (27.29^{c})	22.20^{c} (28.40^{c})	22.60^{c} (28.33^{c})
Mean	12.92	20.52	24.28	25.76	27.56
CD (P<0.05)	4.41	4.49	3.91	3.41	3.44
CV (%)	17.05	13.32	10.38	8.82	8.46

Note: Values in the parenthesis are arc-sine transformed; DAS = Days After Sowing; Treatments with same letters are not significantly different

Table 3. Variation in seed germination attributes among five seed sources of Sandalwood

Seed sources	MDG	PV	GV	GRI	MGT
Idukki (Kerala)	0.51^{b}	0.17^{b}	0.09^{b}	0.98^{b}	35.94^{b}
Mysore (Karnataka)	0.50^{bc}	0.19^{b}	0.10^{b}	1.07^{b}	33.03^{b}
Bengaluru (Karnataka)	0.77^{a}	0.29^{a}	0.22^{a}	1.53^{a}	33.08^{b}
Dharwad (Karnataka)	0.12^{d}	0.06^{c}	0.01^{c}	0.19^{d}	43.22^{a}
Junagadh (Saurashtra, Gujarat)	0.40^{c}	0.16^{b}	0.07^{bc}	0.69^{c}	35.99^{b}
CD (P<0.05)	0.11	0.08	0.06	0.18	4.74
CV (%)	18.13	34.80	49.41	15.69	9.91

Note: MDG = Mean daily germination; PV= Peak value of germination; GV= Germination value; GRI = Germination rate index and MGT = Mean germination time; Treatments with same letters are not significantly different

Table 4. Variation in seedling growth at 90 days after transplanting across five seed sources of Sandalwood

Seed sources	Shoot height (cm)	Basal diameter (mm)	Number of leaves
Idukki (Kerala)	20.44[a]	1.82[a]	11.42
Mysore (Karnataka)	14.82[b]	1.43[b]	8.76
Bengaluru (Karnataka)	19.97[a]	1.85[a]	11.01
Dharwad (Karnataka)	17.34[ab]	1.74[a]	12.98
Junagadh (Saurashtra, Gujarat)	15.75[b]	1.76[a]	11.34
Mean	17.66	1.72	11.10
CD (P<0.05)	3.30	0.28	NS
CV (%)	12.42	10.80	16.78

several factors like viability, dormancy, season of seeding, seed maturation, tree age, and other extrinsic factors (Schmidt 2000, Gunaga et al., 2007, Gunaga and Vasudeva 2009).

Variation in seedling growth: Seedling growth attributes recorded at 90 days after transplanting showed significant variation among five seed sources, where Idukki and Bengaluru seed sources showed superiority over Mysore source. Plant height varied significantly from 14.82 to 20.44 cm, whereas collar diameter varied from 1.43 to 1.85 mm (Table 4), however, seed source did not influence on the number of leaves at 90 days of growth in the nursery. This result is compliance with the investigation of Shwetha et al., (2024) on Sandalwood, where superior performance of Marayur (Kerala) and Gottipura (Karnataka) sources on seedling growth and biomass was observed. Variation attributed for growth among seed sources is mainly due to genetic factors, followed by physiological functions and local environment (Schmidt 2000, Gunaga et al., 2007, Gunaga and Vasudeva 2009). Alike other studies, both Idukki and Bengaluru seed source also showed superiority under south Gujarat condition. Hence, these sources can be used for large scale seedling production as well as further tree improvement work.

CONCLUSION

Study concludes that different seed sources of Sandalwood used in the experiment resulted in significant variation for seed traits, germination and seedling growth attributes. Idukki (Kerala) and Bengaluru (Karnataka) seed sources showed superiority for seed size, germination and seedling growth attributes under Navsari climatic conditions. Therefore, these sources can be used for large scale seedling production as well as for further selection and evaluation at field condition. Further investigation may be required to address the problem of poor germination in local seed sources.

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AUTHOR'S CONTRIBUTION

Ms. Lekshmi as a master's student, she collected, analyzed the data, and prepared the thesis, Dr. Gunaga as a major guide, planned, designed, executed the experiment and synthesized the manuscript, Dr. Thakur and Dr. Huse helped in the nursery experiments as well as in the draft manuscript, and Dr. Garde helped in statistical analysis.

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Provenance-based Variation in Seed Traits of *Quercus leucotrichophora* A. Camus in Western Himalayas

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***Abstract*:** The present study investigated provenance variation in seed characteristics of *Quercus leucotrichophora* A. Camus (Ban Oak) across fifteen distinct locations in Western Himalayas of Himachal Pradesh. Mature acorns were collected from phenotypically superior trees representing altitudinal gradients ranging from 1220 m to 2206 m above mean sea level. Key seed traits such as acorn length, width, moisture content, and 100-seed weight were analyzed. Significant variation was observed among provenances and seed size categories. These traits are important for improving the planting stock material in hand. The largest acorn size (2.28 cm length, 1.21 cm width), highest moisture content (63.87%), and maximum 100-seed weight (239.15 g) was at Haripurdhar (P_9), the highest elevation site. Seed size grading revealed that large seeds (S_3) consistently showed superior physical attributes, including the highest acorn weight (2.82 g) and moisture content (64.88%). The variation in seed traits suggests a strong influence of altitudinal and environmental gradients on seed development, which could have significant implications for seedling vigor, natural regeneration, and conservation strategies. This study provides valuable insights into seed quality parameters useful for selecting optimal seed sources for afforestation and restoration programs in Himalayan ecosystems.

***Keywords*:** *Quercus leucotrichophora*, Seed traits, Provenance, Elevation, Seed size, Ban oak

The genus *Quercus* includes more than 400 species, and *Quercus leucotrichohora* A. Camus (Ban Oak) is one of the most important tree species in temperate and subtropical plant communities. *Q. leucotrichophora* is the commonest oak of the Western Himalayas, extending eastward to Nepal, within an altitude range from 1000 to 2400 m asl (above sea level) but occasionally descending lower in moist situations (Saklani et al., 2012). Ban oak is a dominant broadleaved species in the mid-elevation zones of the Western Himalayas, and is a major forest-forming tree species in Himachal Pradesh, playing a crucial role in maintaining ecological stability, supporting biodiversity, and sustaining rural livelihoods through fodder, fuelwood, and soil conservation functions (Barman et al., 2023). It is challenging for the species to regenerate because of the ongoing anthropogenic disturbances, such as lopping, which alter stand structure and species composition in oak forests (Amare and Bhardwaj 2016), coupled with climate variability, both of which have negatively impacted its natural regeneration capacity (Bhatt and Ram 2015). The ban oak forest is a crucial part of the Himalayan ecosystem from the perspective of biodiversity preservation and locals typically associate oaks with water and soil conservation and the maintenance of rural livelihoods (Tamta 2016). Due to its numerous uses as fodder, fuel wood, tiny lumber, and charcoal, the species is under significant biotic pressure. Its regeneration is very poor, partly due to over-exploitation and partly due to damage to seed populations by the insect (*Calandra sculpturata*) and the Himalayan langoor (*Presbytis entellus*). Mast seed year in *Q. leucotrichophora* takes place in intervals of every 2-3 years, which may be another reason for its poor regeneration.

The ripening of seeds plays a significant role in the life cycle of forest trees. Earlier studies have shown that seed traits vary considerably across geographical and altitudinal gradients, reflecting local adaptations and environmental influences (Pandit et al., 2002, Bhuva et al., 2024). In Himalayan oak species, these variations are often linked with seed maturation timing, nutrient allocation, and microclimatic factors, which ultimately govern regeneration patterns (Bhatt and Ram 2015). Among the key factors influencing regeneration potential, seed characteristics such as size, weight, and moisture content are considered critical determinants of seed viability, germination success, and seedling vigor (Tewari et al., 2019, Chauhan et al., 2021, Fox et al., 1994, Joshi et al., 2022). Khera (2010) observed that variations in seed maturation times reflect climatic influences on forest tree species, affecting stand structure, regeneration, and development; thus, identifying precise seed maturation periods is essential for effective seed collection and regeneration (Murali and Sukumar 1994). However, limited comprehensive studies have been conducted to quantify such variations in *Q. leucotrichophora* across diverse provenances in Himachal Pradesh.

Establishment of plantations of this native multipurpose tree species is recommended as a suitable conservation

strategy. In this Himalayan region, the lack of quality planting material could be improved by selecting a more suitable provenance. Therefore, this study aimed to assess provenance-wise variation in key seed traits of *Q. leucotrichophora* to identify potential seed sources with superior physiological attributes, thereby contributing to more effective conservation and afforestation strategies in the region.

MATERIAL AND METHODS

Seed collection: Seeds were collected from 15 provenances of Himachal Pradesh, including Banikhet, Bharmour, Banjor, Manali, Palampur, Dharamshala, Shoghi, Rampur, Haripurdhar, Sarahan, Kandaghat, Rajgarh, Oachghat, Joginder Nagar, and Rewalsar, which provided fully grown acorns of *Q. leucotrichophora* (Fig. 1). The study sites were located between 30°58'-32°24′ N Latitude and 75°94′-77°63 E Longitude along an elevational transect of 1220 to 2206 m in Himachal Pradesh, India. At each provenance, five mature *Q. leucotrichophora* trees that were phenotypically superior and had a well-developed crown were chosen at random and marked for seed collection (Table 1). Using measuring tapes and a Ravi multimeter, the height and DBH (1.37 m) of each chosen tree were calculated. Each tree was 100 m apart from the other to avoid narrowing down the variation sampled due to relatedness (Schmidt 2000). From the first week of October to the last week of December, the collection of *Q. leucotrichophora* acorns (with involucre) began at all provenances. From each provenance bulk seed sample was collected and brought to the laboratory, and allowed to dry in shade for 24 h. The sample collected from each provenance was then placed in a cotton bag, allotted an accession number, and a name of place, and stored in a cooling incubator for further experiments.

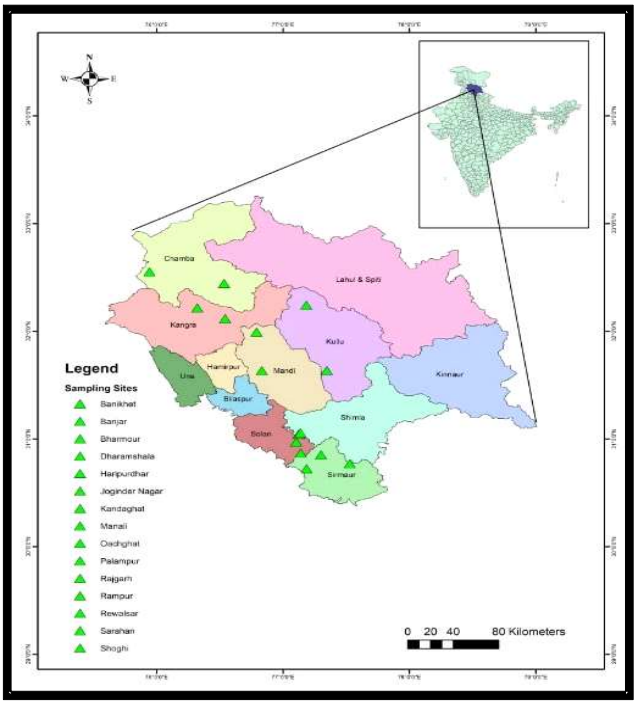

Fig. 1. Map of the study area

Acorns were visually classified as small, medium, and large-sized, and seed length, seed width were measured by using a digital vernier calliper, whereas seed weight was measured by using a digital electronic balance. To identify the seed properties, the involucre (outer seed-based cap) was removed. To create a composite seed sample, the seeds were gathered from the chosen trees at each provenance. The seed lot's five replicated batches of 25 seeds each were utilised to calculate various seed properties.

Seed morphology: The moisture percentage of each seed sample was determined on a fresh weight basis by drying the seeds at 103 ± 2°C as per ISTA (1999) rules (Table 2). Seed length and breadth (in the middle portion of the seed) were measured (using a digital vernier calliper) on five replicate samples, each consisting of 100 seeds randomly drawn from each seed lot. Seed weight (g/100 seed) was recorded by choosing eight random samples of each population, *i.e.*, 100 seeds per seed lot (ISTA 1999). Five samples (each of 100 seeds) were drawn from the seed lot of each provenance, and the number of seeds damaged due to insect attack and healthy seeds was separated. Number of seeds per 100 g were calculated (Tewari et al., 2017).

Seed biochemical parameters: The freshly harvested acorns were washed with distilled water, and the excess water was absorbed by keeping the seeds between the folds of blotting paper. After that, the seeds were dried for 24 hours in an oven at 70℃. The dried seeds were crushed to a coarse powder using metallic mortar and pestle to estimate various biochemical parameters. The total sugar, starch, total phenols, and soluble proteins in the seeds were estimated with respect to the dry weight of the seeds (Bewley and Black 1994, Mahadevan and Shridhar 1982).

Statistical analysis: Descriptive statistics was made directly from a spreadsheet in Windows Excel 2017. Analysis of variance was assessed by using the Statistical Package for Social Sciences (SPSS) version 20.0 software.

RESULTS AND DISCUSSION

Acorn physical and biochemical characters: To understand how different provenances and seed sizes influence the *Q. leucotrichophora* seed morphological traits, various physical traits (such as acorn length, width, moisture content, and 100-seed weight) and biochemical properties

(including total sugar, phenol, starch, and soluble protein content) were carefully studied.

Acorn length (cm): Significant variations in *Q. leucotrichophora* acorn length among provenances and seed sizes reflected inherent genetic diversity and environmental influences (Table 3). Provenance P_9 (Haripurdhar) recorded the maximum acorn length (2.28 cm), consistent with observations that higher altitudes can enhance seed morphological attributes due to adaptive selection (Ginwal et al., 2005). The significantly greater acorn length in larger seeds (S_3: 2.37 cm) supports previous findings that seed size is positively correlated with embryo development and reserve accumulation (Deb and Sundriyal 2017). The non-significant P × S interaction suggests consistent size trends across geographic regions.

Acorn width (cm): The provenance and seed size significantly influenced the acorn width of *Q. leucotrichophora* (Table 4). The acorn width followed a similar pattern, with larger seed size classes (S_3: 1.28 cm) displaying significantly greater width, likely due to enhanced pericarp development and nutrient accumulation. Haripurdhar and Sarahan provenances displayed superior width, suggesting eco-geographical influence, especially under cooler climates and fertile soils (Rawat et al., 2022). The uniform increase in width with seed size across provenances implies a strong genetic control over radial seed traits. The study highlight the importance of selecting both suitable provenances and larger seed sizes to enhance initial seedling traits, which is often linked to seed vigor and subsequent nursery performance.

Acorn moisture content (%): The significant influence of provenance and seed size on *Quercus leucotrichophora* acorn moisture content was observed (Table 5). Larger seeds exhibited higher moisture retention (S_3: 64.88%), aligning with the hypothesis that bigger seeds contain more hydrophilic storage tissues (Harrington and Kozlowski 1972). Provenance P_9 again led with the highest mean moisture, reinforcing its potential for superior seed physiology. Differences in microclimate, especially relative humidity and soil moisture regimes, likely contributed to these variations. This indicates a direct positive correlation between seed size and moisture content, likely due to the greater volume and capacity of larger seeds to retain water. However, the interaction between provenance and seed size was non-significant, suggesting that the trend of increasing moisture content with seed size was consistent across different geographic origins. These findings underscore the importance of selecting not only optimal seed sizes but also superior provenances for maximizing seed moisture content-an essential parameter for seed vigor, storage viability, and germination performance in nursery practices.

Table 2. Seed size categories

Seed grade	Seed category	Average acorn weight (g)
S_1	Small	1.78
S_2	Medium	2.56
S_3	Large	2.82

Table 1. Geographical origin of *Q. leucotrichophora* seed sampling locations and soil pH value

Provenance	Districts	Code	Elevation (m amsl)	Latitude (°N)	Longitude (°E)	Rainfall (mm)	Soil pH
Banikhet	Chamba	P_1	1700	32° 55′	75° 94′	1600 mm	6.0
Bharmour	Chamba	P_2	2133	32° 44′	76° 53′	1550 mm	5.6
Banjar	Kullu	P_3	1356	31° 63′	77° 34′	1360 mm	6.3
Manali	Kullu	P_4	2050	32° 24′	77° 19′	1363 mm	6.0
Palampur	Kangra	P_5	1300	32° 11′	76° 53′	1750 mm	6.2
Dharamshala	Kangra	P_6	1457	32° 22′	76° 32′	1800 mm	6.0
Shoghi	Shimla	P_7	1712	31° 04′	77° 12′	1520 mm	6.0
Rampur	Shimla	P_8	1675	31° 45′	77° 63′	1480 mm	5.8
Haripurdhar	Sirmaur	P_9	2206	30° 77′	77° 53′	1420 mm	5.5
Sarahan	Sirmaur	P_{10}	1668	30° 73′	77° 19′	1500 mm	5.8
Rajgarh	Sirmaur	P_{11}	1586	30° 58′	77° 30′	1400 mm	6.0
Oachghat	Solan	P_{12}	1472	30° 87′	77° 14′	1380 mm	6.1
Kandaghat	Solan	P_{13}	1425	30° 97′	77° 11′	1350 mm	6.0
Joginder Nagar	Mandi	P_{14}	1220	31° 99′	76° 79′	1850 mm	6.3
Rewalsar	Mandi	P_{15}	1360	31° 63′	76° 83′	1820 mm	6.2

100 Seed weight (g): Both provenance and seed size significantly influenced the 100 seed weight of *Q. leucotrichophora* acorns. Seed weight is a direct measure of seed vigor and resource availability (Table 6). A progressive increase in 100-seed weight from S_1 to S_3 reflects the metabolic advantage of larger seeds in developing heavier cotyledons (Moles and Westoby 2006). Haripurdhar provenance (P_9) again emerged as the best performer

Table 3. Effect of provenances, seed size, and their interaction on acorn length (cm)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	1.95	2.12	2.29	2.12
P_2 (Bharmour)	1.98	2.13	2.3	2.14
P_3 (Banjar)	1.99	2.14	2.3	2.14
P_4 (Manali)	2.0	2.14	2.3	2.15
P_5 (Palampur)	2.0	2.15	2.33	2.16
P_6 (Dharamshala)	2.0	2.15	2.34	2.16
P_7 (Shoghi)	2.05	2.23	2.47	2.25
P_8 (Rampur)	2.04	2.23	2.42	2.23
P_9 (Haripurdhar)	2.08	2.26	2.52	2.28
P_{10} (Sarahan)	2.07	2.25	2.48	2.27
P_{11} (Rajgarh)	2.06	2.23	2.44	2.24
P_{12} (Oachghat)	2.03	2.21	2.36	2.20
P_{13} (Kandaghat)	2.03	2.21	2.4	2.21
P_{14} (Joginder Nagar)	1.89	2.09	2.27	2.09
P_{15} (Rewalsar)	1.95	2.1	2.28	2.11
Mean	2.01	2.18	2.37	

CD (p-0.05) :P =0.07 , S = 0.03, P × S =N.S.

Table 4. Effect of provenances, seed size, and their interaction on acorn width (cm)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	0.99	1.09	1.24	1.11
P_2 (Bharmour)	0.99	1.10	1.25	1.11
P_3 (Banjar)	1.00	1.13	1.26	1.13
P_4 (Manali)	1.00	1.13	1.27	1.14
P_5 (Palampur)	1.00	1.15	1.27	1.14
P_6 (Dharamshala)	1.01	1.15	1.28	1.15
P_7 (Shoghi)	1.05	1.19	1.31	1.18
P_8 (Rampur)	1.03	1.17	1.3	1.16
P_9 (Haripurdhar)	1.07	1.21	1.37	1.21
P_{10} (Sarahan)	1.06	1.21	1.35	1.21
P_{11} (Rajgarh)	1.05	1.20	1.33	1.19
P_{12} (Oachghat)	1.02	1.15	1.29	1.15
P_{13} (Kandaghat)	1.03	1.17	1.30	1.17
P_{14} (Joginder Nagar)	0.95	1.07	1.22	1.08
P_{15} (Rewalsar)	0.96	1.07	1.23	1.09
Mean	1.01	1.15	1.28	

CD (p-0.05) :P =0.03 , S = 0.01, P × S =N.S.

(242.25 g), consistent with reports that higher altitude provenances often produce denser seeds due to prolonged developmental periods and adaptive nutrient allocation (Tewari et al., 2019). This suggests that selecting large seeds from superior provenances could be a viable strategy for nursery propagation and reforestation programs aimed at enhancing early seedling performance.

Total sugar (%): The total sugar content of *Q.*

Table 5. Effect of provenances, seed size, and their interaction on acorn moisture content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	58.09	60.32	63.6	60.67
P_2 (Bharmour)	56.59	60.35	63.73	60.22
P_3 (Banjar)	56.52	60.61	64.07	60.4
P_4 (Manali)	58.32	60.6	64.39	61.11
P_5 (Palampur)	58.38	60.66	64.48	61.18
P_6 (Dharamshala)	58.74	60.88	64.56	61.39
P_7 (Shoghi)	59.5	62.25	65.66	62.47
P_8 (Rampur)	59.5	61.72	65.63	62.28
P_9 (Haripurdhar)	59.61	63.1	68.92	63.87
P_{10} (Sarahan)	59.6	62.58	66.16	62.78
P_{11} (Rajgarh)	59.57	62.39	65.57	62.51
P_{12} (Oachghat)	59.1	61.3	64.67	61.69
P_{13} (Kandaghat)	59.31	61.39	64.86	61.85
P_{14} (Joginder Nagar)	56.6	59.76	63.33	59.89
P_{15} (Rewalsar)	57.51	60.14	63.53	60.39
Mean	58.46	61.2	64.88	

CD (p=0.05)- P-2.20, S -0.10, P × S - N.S.

Table 6. Effect of provenances, seed size, and interaction on acorn 100 seed weight (g)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	174.51	244.94	281.45	233.64
P_2 (Bharmour)	175.21	245.90	280.59	233.90
P_3 (Banjar)	178.66	242.72	278.87	233.42
P_4 (Manali)	176.20	243.00	280.56	233.25
P_5 (Palampur)	183.26	246.41	283.74	237.71
P_6 (Dharamshala)	177.13	245.86	281.37	234.79
P_7 (Shoghi)	182.36	247.85	280.40	236.87
P_8 (Rampur)	178.66	247.35	283.66	236.56
P_9 (Haripurdhar)	186.32	248.48	291.47	242.25
P_{10} (Sarahan)	177.06	248.10	283.04	239.06
P_{11} (Rajgarh)	186.57	247.88	282.76	239.07
P_{12} (Oachghat)	177.80	248.91	283.46	236.72
P_{13} (Kandaghat)	179.18	244.18	283.89	235.75
P_{14} (Joginder Nagar)	172.03	243.91	278.66	231.54
P_{15} (Rewalsar)	175.51	250.53	278.70	234.91
Mean	178.70	246.43	282.16	

CD (p=0.05)- P - 4.0, -S - 1.80. P × S -N.S.

leucotrichophora acorns varied across different provenances and seed sizes, though the differences were statistically non-significant (Table 7). Although not statistically significant, trends in total sugar content showed that larger seeds (S_3: 1.63%) and certain provenances (e.g., P_9: 1.68%) tend to accumulate more carbohydrates. This aligns with previous observations that high sugar levels in seeds enhance early metabolic activity during germination. While provenance

Table 7. Effect of provenances, seed size, and their interaction on acorn total sugar content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	1.53	1.56	1.58	1.56
P_2 (Bharmour)	1.55	1.57	1.59	1.57
P_3 (Banjar)	1.57	1.59	1.6	1.59
P_4 (Manali)	1.55	1.59	1.6	1.58
P_5 (Palampur)	1.56	1.62	1.61	1.6
P_6 (Dharamshala)	1.56	1.63	1.62	1.6
P_7 (Shoghi)	1.6	1.64	1.65	1.63
P_8 (Rampur)	1.59	1.64	1.65	1.63
P_9 (Haripurdhar)	1.66	1.67	1.69	1.68
P_{10} (Sarahan)	1.65	1.66	1.68	1.67
P_{11} (Rajgarh)	1.62	1.64	1.66	1.64
P_{12} (Oachghat)	1.58	1.63	1.64	1.61
P_{13} (Kandaghat)	1.58	1.63	1.64	1.62
P_{14} (Joginder Nagar)	1.51	1.54	1.57	1.54
P_{15} (Rewalsar)	1.52	1.55	1.58	1.55
Mean	1.58	1.61	1.63	

CD (p=0.05)-P -NS , S = NS , P × S - NS

Table 8. Effect of provenances, seed size, and their interaction on acorn total phenol content (mg/g)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	39.7	41.26	44.97	41.98
P_2 (Bharmour)	39.11	42.64	44.68	42.14
P_3 (Banjar)	39.24	42.99	45.53	42.59
P_4 (Manali)	39.78	43.36	45.86	43.0
P_5 (Palampur)	42.12	42.88	46.15	43.72
P_6 (Dharamshala)	41.24	43.98	47.06	44.09
P_7 (Shoghi)	45.08	46.82	49.06	46.99
P_8 (Rampur)	43.88	46.62	48.46	46.32
P_9 (Haripurdhar)	45.97	49.26	50.69	48.64
P_{10} (Sarahan)	45.44	48.37	49.61	47.81
P_{11} (Rajgarh)	45.31	47.91	49.51	47.58
P_{12} (Oachghat)	42.0	44.71	47.17	44.62
P_{13} (Kandaghat)	43.16	45.57	47.71	45.48
P_{14} (Joginder Nagar)	38.23	40.38	43.5	40.7
P_{15} (Rewalsar)	38.45	40.7	44.11	41.08
Mean	41.91	44.5	46.94	

CD (p=0.05) P -NS, S -2.66, P × S- NS.

influence was subtle, environmental cues like light and canopy exposure could modulate carbohydrate biosynthesis in developing acorns, which may have implications for seedling vigor and nursery performance.

Total phenol (mg/g): The total phenol content in *Q. leucotrichophora* acorns showed considerable variation across different provenances and seed sizes (Table 8). Phenolic compounds serve as biochemical defence markers

Table 9. Effect of provenances, seed size, and their interaction on a corn starch content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	48.76	49.6	51.83	50.06
P_2 (Bharmour)	48.53	50.0	52.17	50.23
P_3 (Banjar)	48.71	50.5	53.17	50.79
P_4 (Manali)	48.74	50.65	53.34	50.91
P_5 (Palampur)	48.59	50.67	53.47	50.91
P_6 (Dharamshala)	49.62	50.76	53.57	51.31
P_7 (Shoghi)	51.15	53.18	55.4	53.24
P_8 (Rampur)	50.07	52.81	55.03	52.64
P_9 (Haripurdhar)	51.44	54.23	57.68	54.45
P_{10} (Sarahan)	51.32	53.45	56.48	53.75
P_{11} (Rajgarh)	51.54	53.33	55.54	53.47
P_{12} (Oachghat)	49.82	50.9	53.66	51.46
P_{13} (Kandaghat)	50.09	50.95	54.03	51.69
P_{14} (Joginder Nagar)	47.1	48.63	50.93	48.89
P_{15} (Rewalsar)	48.06	48.73	50.97	49.25
Mean	49.57	51.23	53.82	

CD (p-0.05) - P- 2.57, S -2.15. P × S - NS.

Table 10. Effect of provenances, seed size, and their interaction on acorn soluble protein content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	40.83	41.12	45.66	42.54
P_2 (Bharmour)	41.52	41.62	47.42	43.52
P_3 (Banjar)	42.25	43.38	48.09	44.57
P_4 (Manali)	44.38	45.65	50.48	46.84
P_5 (Palampur)	46.23	47.56	51.43	48.41
P_6 (Dharamshala)	48.9	49.6	52.46	50.32
P_7 (Shoghi)	52.53	52.69	57.88	54.37
P_8 (Rampur)	50.54	50.57	56.95	52.68
P_9 (Haripurdhar)	57.16	58.72	60.79	58.89
P_{10} (Sarahan)	55.39	56.93	59.68	57.34
P_{11} (Rajgarh)	53.56	54.69	58.74	55.66
P_{12} (Oachghat)	51.34	51.43	54.69	52.49
P_{13} (Kandaghat)	51.83	51.9	55.78	53.17
P_{14} (Joginder Nagar)	39.53	39.57	45.0	41.37
P_{15} (Rewalsar)	39.61	39.89	45.3	41.6
Mean	47.71	48.36	52.69	

CD (p-0.05) - P -1.24 , S- 0.56, P × S -NS.

and antioxidant agents. Seed size significantly influenced total phenol concentration, with S_3 recording the highest (46.94 mg/g), implying a higher investment in protective secondary metabolites. Although not statistically significant, the consistent superiority of P_9, P_{10}, and P_{11} suggests a localized selection for phenolic richness under biotic stress or high UV conditions (Sytar and Hajihashemi 2024).

Starch (%): The acorn starch content (%), a primary energy reserve for germination, was significantly influenced by provenance and seed size, whereas the interaction between provenance and seed size was non-significant (Table 9). S_3 acorns showed the highest starch concentration (53.82%), supporting literature linking large seeds with enhanced energy reserves (Leishman et al., 2000). The high-starch provenances (Haripurdhar and Sarahan) may thus be considered for nursery use in low-input environments where endogenous reserves are critical for establishment.

Soluble protein (%): Both provenance and seed size have a significant influence on the soluble protein content of acorns (Table 10). Soluble protein content was highest in large seeds (S_3: 52.69%) and in provenances like Haripurdhar (58.89%), suggesting that both genetic and size-based factors contribute to storage protein accumulation. Proteins in seeds play a vital role in enzyme function and nitrogen availability during seedling establishment (Shewry and Halford 2002). The observed pattern suggests selection of large-seeded genotypes from superior provenances could be an effective strategy to enhance soluble protein content in acorns and thus enhance early growth potential.

CONCLUSION

The present study highlighted significant variation in the physical and biochemical characteristics of *Q. leucotrichophora* acorns as influenced by seed size and provenance. Larger seeds consistently exhibited superior values for key parameters such as acorn length, width, moisture content, and 100-seed weight, indicating their potential for better germination and seedling vigor. Biochemical analyses revealed that larger seeds also contained higher concentrations of total sugars, phenolics, starch, and soluble proteins, underscoring their enhanced nutritional and physiological quality. Provenance-level comparisons demonstrated that local environmental factors substantially influence trait expression, reaffirming the role of genotype × environment interactions. These findings provide a vital basis for selecting superior seed sources and seed sizes for conservation, afforestation, and nursery management practices aimed at improving forest productivity and regeneration success in Himalayan oak ecosystems.

AUTHOR's CONTRIBUTION

Jayashree Behera: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing-original draft, Writing-review & editing. CL Thakur: Conceptualization, Investigation, Supervision, Validation. DR Bhardwaj: Formal analysis, Methodology, Resources, Supervision. Saurabh Sharma: Data curation, Visualization, Writing-review & editing.

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Principal Component based Dissection of Growth and Leaf Trait Variation in River Red Gum (*Eucalyptus camaldulensis*) Accessions

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***Abstract*:** This study investigated the morphological and growth variation among 21 accessions of *Eucalyptus camaldulensis* (River Red Gum) using multivariate statistical techniques under tropical conditions in South Gujarat, India. Eleven morphometric descriptors were assessed following the DUS (Distinctness, Uniformity and Stability) testing guidelines. Principal Component Analysis (PCA) revealed that the first three principal components accounted for 84.57% of the total variation. PC1, explaining 49.64% of the variance, was primarily influenced by leaf elongation traits such as leaf length, blade ratio, roundness and petiole length along with tree volume. PC2 (18.50%) captured variation related to clear bole height and broader leaf size parameters, while PC3 contributed 16.42%. The analysis highlights significant phenotypic diversity among the accessions, with implications for biomass selection, breeding programs, and the refinement of descriptors for varietal registration. These findings demonstrate the utility of PCA in trait prioritization and support the strategic selection of superior genotypes for tree improvement initiatives.

***Keywords*:** Principal component analysis, Morphological variation, Growth traits, Leaf traits, River Red Gum, *Eucalyptus camaldulensis*, Tree improvement, DUS testing

Eucalyptus camaldulensis Dehnh., commonly known as River Red Gum, is one of the most extensively planted *Eucalyptus* species due to its fast growth, adaptability and multiple utility as fuelwood, timber, pole, pulp and plywood raw material. *E. camaldulensis* is native to Australia and has been widely introduced across diverse ecological regions of India, particularly in semi-arid and tropical zones, where its robust nature supports afforestation, agroforestry and industrial plantation programs. Apart from other species like Poplar, *Melia dubia*, *Leucaena* spp. *etc*., (Luna et al., 2011, Thakur et al., 2023), *Eucalyptus* is in growing demand as a raw material for pulp and particle board industries, further emphasizing its importance as an industrial species in many Indian states (Luna et al., 2009) including Gujarat (Huse et al., 2024). Since it is highly used for pole production by the construction industries, especially in South Gujarat, there is a great demand for good genotypes that provide high strength as poles (Huse et al., 2024).

Despite its ecological and economic significance, limited attention has been given to the characterization of intra-specific morphological variation among accessions maintained for breeding and clonal deployment. Understanding morphological and growth variability among genotypes is essential for effective selection and improvement programs. In long-lived tree species the evaluation of both qualitative and quantitative traits, particularly those related to leaf structure and growth form, branching pattern and bark features, provides a foundation for identifying superior and distinct genotypes. Moreover, under the framework of Distinctness, Uniformity and Stability (DUS) testing, prescribed by the Protection of Plant Varieties and Farmers' Rights Authority (PPVFRA), New Delhi, morphological descriptors form the basis for varietal registration, intellectual property protection and germplasm conservation. Recent studies have demonstrated the utility of multivariate statistical techniques such as Principal Component Analysis (PCA) in identifying trait combinations that account for the majority of variability among genotypes. Sharma et al. (2018), Kumar et al. (2020) and Lakshmi et al. (2020) highlighted the PCA as a multivariate analysis tool for characterization of crops. In this context, the present investigation was undertaken during 2024–2025 at Navsari Agricultural University (NAU), Navsari, Gujarat, India to evaluate the phenotypic variability among 21, five-year-old *Eucalyptus camaldulensis* accessions using multivariate analysis – PCA to identify the most influential traits contributing to variability and to support DUS characterization and thereby identifying the superior genotypes for tree improvement and varietal registration of the University. The present study aims to assess the morphological variation among selected superior individuals of *Eucalyptus camaldulensis*, selected from a broader base population, with the long-term goal of supporting breeding and genetic improvement programs.

MATERIAL AND METHODS

Study area and environmental conditions: The present investigation was conducted during 2024-2025 at the

Forestry Farm, Navsari Agricultural University (NAU), Navsari, Gujarat, India. The study site is geographically located at 20°55′19″ N latitude and 72°53′11″ E longitude, with an elevation of 11.98 meters above mean sea level. The region falls under a tropical climate zone characterized by hot summers, humid monsoons and mild winters. The site receives an average annual rainfall of 1500–1600 mm, primarily during the southwest monsoon (June to September).

Plant material, experimental design and selection strategy: The study was conducted on a population of 128 individual trees, representing 36 families of *Eucalyptus camaldulensis* Dehnh, established at the Department of Forest Biology and Tree Improvement, NAU, Navsari during 2020. These families were raised from the germplasm collected from ICFRE – Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore and the trees were spaced at 2 x 2 m and maintained under identical silvicultural practices, thereby minimizing environmental variability and allowing phenotypic differences to reflect underlying genetic variation. Initial assessments were conducted on all 128 individuals for growth and morphological traits. Based on family level performance, 21 families showing superior growth and vigour were shortlisted. From each selected family, one phenotypically superior tree was chosen, resulting in a total of 21 accessions for detailed morphological characterization. This corresponds to a selection intensity of approximately 16%. The selective sampling was designed to identify superior genotypes for tree improvement, it is acknowledged that it does not represent the full genetic variability within the entire population. This has been taken into consideration when interpreting the results.

Morphological and growth trait assessment: Comprehensive set of 11 morphological descriptors (identified as in the DUS test guidelines for *E. camaldulensis* and *E. tereticornis*, prescribed by the PPVFRA (2013) including growth and leaf traits were used to evaluate the different accessions. The growth traits include tree height (m), clear bole height (CBH, m), diameter at breast height (DBH, cm at 1.37 m) and stem volume (m^3), whereas the leaf morphometric traits *viz*., leaf length (LL, cm), leaf breadth (LB, cm), leaf area (LA, cm^2), leaf perimeter (LP, cm), leaf blade ratio (LBR), leaf roundness (LR) and petiole length (LPL, cm).

Height and mid diameter measurements were performed using dendrometers, digital callipers were used to estimate the DBH. The data were recorded following the standard procedures. For leaf morphometric parameters, 25 fully grown leaves were collected from the middle of the canopy and were scanned along with a reference scale using common scanner. The images were then analysed using the *Image J* software (Schneider et al 2012).

Statistical and multivariate analysis: All quantitative traits were subjected to descriptive statistical analysis, including calculation of means, standard deviations and coefficients of variation to assess the extent of phenotypic diversity among accessions. To investigate the underlying structure of trait variation, Principal Component Analysis (PCA) was performed using the correlation matrix, thus standardizing the influence of measurement units across traits (Jackson 2003). PCA was conducted using KAU Grape software (Gopinath et al., 2020). Only components with eigenvalues greater than 1.0 were retained in accordance with Kaiser's criterion (Kaiser 1960). Trait loadings with absolute values ≥ 0.30 were considered significant contributors to the respective components. The percentage of variance explained by each principal component was used to identify the dominant axes of phenotypic variation. Visualization tools such as scree plots, loading plots and biplots were generated to interpret the clustering of accessions and relative importance of traits across components. The PCA results were then integrated with phenotypic profiles to identify key traits relevant to DUS characterization and potential selection criteria for tree improvement programs.

RESULTS AND DISCUSSION

The first three principal components (PCs) had eigenvalues greater than 1.0 and collectively accounted for 84.57% of the total variance, indicating a high level of data reduction while retaining essential variability. Specifically, PC1 exhibited the highest eigenvalue (5.46), contributing 49.64% of the total variability. PC2 accounted for 18.50% of the variance with an eigenvalue of 2.03, whereas PC3 contributed 16.42% with an eigenvalue of 1.81, together representing a robust cumulative variance suitable for multivariate trait interpretation (Table 1, 2 and Fig. 1). The coefficients of the first two principal components (PC1 and PC2), which together explained 68.14% of total variability (Table 3 , Fig. 2). PC1 emerged as the most influential component, with high positive loadings observed for leaf-related traits such as leaf length (LL = 0.41), leaf perimeter (LP = 0.41), leaf blade ratio (LBR = 0.40) and leaf roundness (LR = 0.40). Other notable contributors included leaf petiole length (LPL = 0.32) and tree volume (Vol = 0.25). The high positive loadings of these traits indicate that PC1 primarily captures variation related to leaf elongation and overall tree biomass production. Accessions with higher PC1 scores are likely to exhibit longer, more elongated leaves and greater volume accumulation - features that assist in genotypic differentiation and DUS characterization. PC2 showed

strong positive loadings for clear bole height (CBH = 0.57), leaf area (LA = 0.51) and leaf breadth (LB = 0.40). The high loading of CBH suggests that this component reflects variation in tree architecture, particularly stem form and canopy lift, while the leaf traits point to differences in leaf size rather than shape. Leaf breadth (LB) displayed a negative loading on PC1 (-0.27) but a positive loading on PC2 (0.40), indicating its inverse relationship with leaf elongation traits yet positive association with general leaf size. Similarly, diameter at breast height (DBH) and volume contributed moderately to PC1 but less to PC2, suggesting that these growth traits are more closely aligned with leaf elongation and biomass rather than tree architecture. Overall, PC1 was primarily influenced by leaf elongation and tree volume traits, whereas PC2 represented variation in stem height and broader leaf characteristics. This differentiation implies that both morphological and growth parameters contribute significantly to the observed diversity among the studied accessions and can be effectively utilized in selection and breeding programs.

The PCA results demonstrate substantial morphological diversity among the 21 accessions of *Eucalyptus camaldulensis*, particularly in leaf morphology and architectural traits. The high cumulative variance (84.57%) aligns closely with findings from previous studies on *Eucalyptus* and other forest tree species. Lakshmi et al. (2020), working on *Eucalyptus* clones, identified three principal components (eigenvalues >1.0) that together explained 85.62% of total variation, with leaf length, blade ratio, petiole length and leaf area being the most discriminating traits. Vishnu et al. (2022) also observed that leaf morphometric descriptors significantly contributed to accession differentiation in teak, reinforcing the effectiveness of morphological traits in DUS characterization and multivariate diversity analysis. Their study confirmed that mature leaf descriptors strongly contribute to genotypic distinctness and serve as reliable parameters for DUS-based varietal characterization.

In a comparable study, Vinothkumar et al. (2021) on *Tectona grandis* reported three PCs with eigenvalues above 1.0, accounting for 92.8% of total variation among 122 clones, where quantitative traits such as leaf area, perimeter and stem form were dominant contributors. Sahoo and

Table 1. Summary of variation in growth and leaf morphological traits among 21 *Eucalyptus camaldulensis* accessions

Trait	Mean ± SD (m)
Tree height	15.80 ± 1.35
Clear bole height	8.24 ± 1.92
Diameter at breast height (DBH)	11.49 ± 2.02
Tree volume	0.11 ± 0.05
Leaf blade area	41.46 ± 8.80
Leaf perimeter	42.64 ± 9.76
Leaf length	18.55 ± 4.49
Leaf breadth	3.55 ± 0.80
Leaf blade ratio*	5.68 ± 2.13
Leaf roundness**	3.46 ± 1.22
Leaf petiole length	2.01 ± 0.55

* Leaf blade ratio = Leaf length / Leaf breadth, ** Leaf roundness = Leaf perimeter^2 / (4π × Leaf area)

Table 2. Principal component analysis-Eigen value and percentage of variance studied on quantitative traits of 21 accessions of *Eucalyptus camaldulensis*

PC No.	Eigen value	Percentage of variance	Cumulative percentage
PC 1	5.46	49.64	49.64
PC 2	2.03	18.50	68.14
PC 3	1.81	16.42	84.57
PC 4	0.82	7.47	92.04
PC 5	0.42	3.78	95.82
PC 6	0.35	3.21	99.03
PC 7	0.06	0.57	99.60
PC 8	0.03	0.27	99.87
PC 9	0.01	0.10	99.97
PC 10	0.0029	0.03	100.00
PC 11	0.0001	0.00	100.00

Table 3. Principal component analysis- Coefficients of PC1 and PC2

Variable	Coefficients of PC1	Coefficients of PC2
Height	0.18	0.11
CBH	0.08	0.57
DBH	0.18	-0.33
Vol	0.25	-0.22
LL	0.41	0.10
LA	0.17	0.51
LB	-0.27	0.40
LPL	0.32	0.18
LBR	0.40	-0.11
LP	0.41	0.13
LR	0.40	-0.09

Height: Tree height (m); CBH: Clear bole height (m); DBH: Diameter at breast height (cm at 1.37 m); Vol: Volume (m^3); LL: Leaf length (cm) LA: Leaf area (m^2); LB: Leaf breadth (cm); LPL: Leaf petiole length (cm); LBR: Leaf blade ratio; LP: Leaf perimeter (cm); LR: leaf roundness

Kumar (2022) and Sahoo et al. (2023) in *Eucalyptus tereticornis* demonstrated that three major components (eigenvalues >1.0) captured 86.2% and 89.5% of total variance respectively, with tree height, biomass, leaf area and leaf length-to-width ratio being the most influential traits. The close agreement between these studies and the present findings highlights the robustness of PCA as a multivariate tool in capturing complex morphological variation and

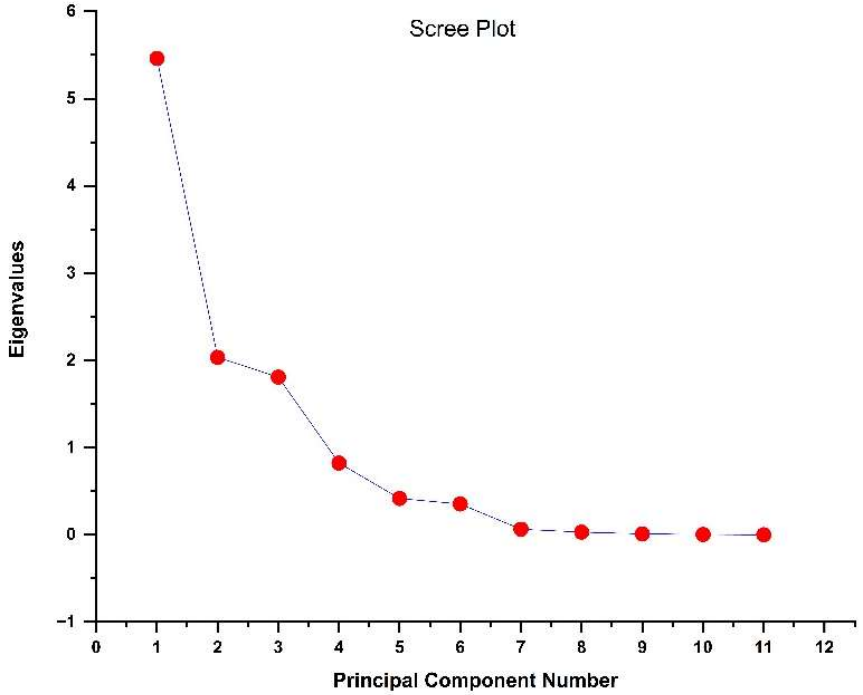

Fig. 1. Principal component analysis-scree plot showing Eigen values

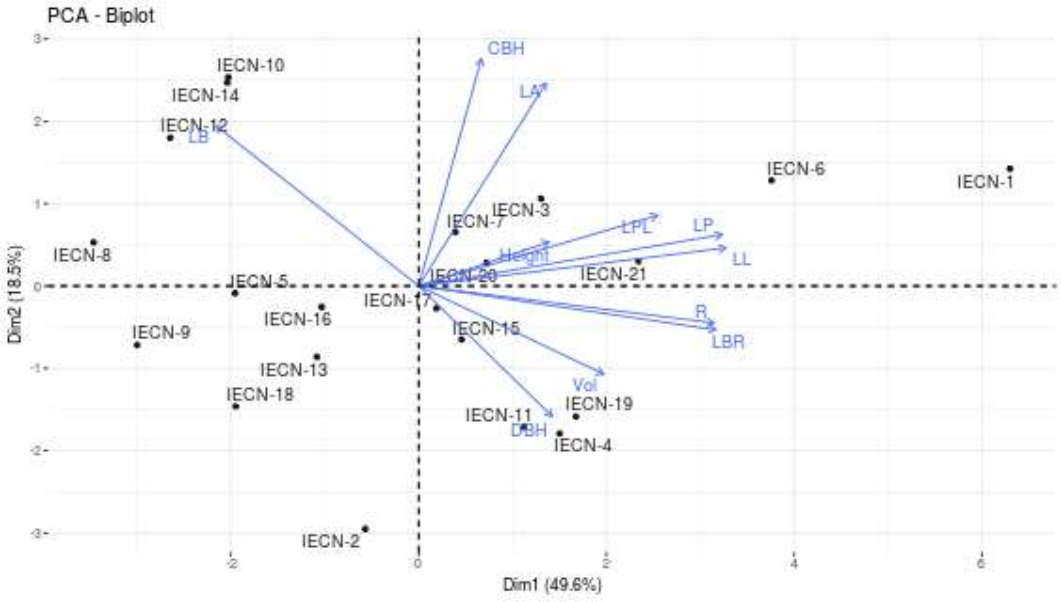

Fig. 2. Principal component analysis- Coefficients of PC1 and PC2

identifying the most informative traits for varietal differentiation and improvement.

The prominence of leaf morphological traits particularly leaf length, perimeter, blade ratio and roundness in PC1 of the present study further validates the role of foliar descriptors in expressing genetic and phenotypic divergence. Lakshmi et al. (2020) and Sahoo et al. (2023), also emphasized that mature leaf traits are heritable, easily observable and stable across developmental stages, making them suitable for varietal registration and breeding programs. The integration of leaf morphology with growth parameters such as tree height and volume enhances discriminative efficiency under multivariate frameworks, as mirrored in the present findings, where both sets of traits exhibited strong joint loadings under PC1-suggesting their combined utility in DUS testing and tree improvement strategies. The strong loadings of clear bole height and leaf breadth in PC2 indicate their effectiveness in distinguishing accessions based on tree form and canopy structure-traits that are directly associated with timber quality and stand management in plantation forestry. The moderate loadings of volume and DBH within PC1 further suggest that accessions with higher PC1 scores are likely to exhibit superior biomass accumulation and faster early growth. These findings validate the usefulness of PCA not only for quantifying phenotypic diversity but also as an indirect selection tool for breeding and clonal improvement programs. Similar interpretations was reported in *Tectona grandis* (Prasetyawati and A'ida 2019) and *Eucalyptus* (Couto et al., 2013), where multivariate analysis effectively distinguished genotypes based on foliar and architectural traits.

The observed variation among the 21 superior *Eucalyptus camaldulensis* accessions reveals a broad spectrum of growth and leaf morphological traits even among phenotypically selected individuals. Traits such as tree height, diameter, leaf area and blade ratio exhibited considerable variability, providing valuable insights for identifying elite genotypes suitable for further breeding. This diversity underscores the potential within selected material and the importance of robust characterization in advancing genetic improvement programs. The approach adopted in this study - combining field-based phenotypic selection of superior accessions with multivariate statistical analysis through PCA- provided a two-tiered strategy for refining genotype selection. Initial family level screening identified superior individuals under uniform field conditions, while PCA enabled the evaluation of trait combinations contributing most significantly to observed variation. This dual approach validated phenotypic observations and objectively identified the most influential traits contributing to accession differentiation, thus enhancing selection precision. Such integration of classical and modern methodologies improves the efficiency of genotype identification for both tree improvement and varietal registration. Similar strategies have been successfully implemented in *Populus* (Monclus et al., 2005), *Acacia nilotica* (Ndoye-Ndir et al., 2008), *Dalbergia sissoo* (Kumar et al., 2012) and *Eucalyptus tereticornis* (Couto et al., 2013; Sahoo and Kumar 2022). Collectively, these studies affirm that PCA-based morphometric evaluation is a powerful tool for identifying distinct and superior genotypes.

CONCLUSION

The present investigation revealed substantial morphological diversity among the phenotypically superior *Eucalyptus camaldulensis* accessions, with significant variation observed in both growth and leaf morphometric traits. The combined use of phenotypic selection and principal component analysis proved effective in identifying key traits particularly leaf elongation parameters and tree volume that contributed most to the observed variability. This dual approach not only enhanced the precision of genotype differentiation but also provided a robust basis for characterizing accessions under the DUS testing framework. Integrating field-based assessment with multivariate analysis, the study offers a practical model for refining genotype selection in tree improvement programs. This approach supports targeted germplasm evaluation and selection, which can further facilitate varietal registration under DUS guidelines and ultimately guide clonal deployment of superior *E. camaldulensis* material with enhanced productivity and adaptability for commercial forestry and agroforestry systems.

AUTHOR'S CONTRIBUTIONS

Conceptualization: SAH, Investigation: NM, SAH. Data collection: NM, Data analysis: SAH, NV, AYG. Writing: SAH, NM, RPG. Review and editing: SAH, RPG.

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Trait Diversity and Essential Oil Yield in Cinnamon: A Half-sib Genetic Study from Central Western Ghats, India

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***Abstract*:** *Cinnamomum zeylanicum*, known as 'true cinnamon,' is an economically significant species valued for its spice and essential oil, particularly its high eugenol content. This study assessed the growth traits, leaf oil yield, eugenol content and reproductive parameters among 15 half-sib families of *C. zeylanicum* from the Central Western Ghats, India, with the objective to identify superior genotypes for genetic improvement. The progeny trial conducted at Bakkal Botanical Garden near Sirsi, Uttara Kannada district of Karnataka. Plant height, girth, branching, leaf count, inflorescence and immature fruit production of two-year-old progenies were recorded. Significant variability was observed in growth traits. Family G11 exhibited superior vegetative growth with maximum plant height (213.33 cm) and leaf production (677.66 leaves/plant), while K16 showed the maximum basal girth (51.46 mm). Leaf oil content ranged between 1.30 and 2.20 per cent (dry weight basis), where J6 achieved the highest oil yield. Eugenol content varied from 55.78 to 89.43 per cent among half-sib families where family S5 recorded the highest concentration. The negative correlation was recorded between total oil yield and eugenol concentration, indicating the importance of strategic balancing in selection breeding. Moreover, reproductive traits also showed variation and family J2 produced the highest number of inflorescence and immature fruits per plant. Study concludes that families such as G11, J6, K16, S5 and J2 can be considered as elite germplasm for future breeding and improvement programs. These findings provide an essential insight for enhancing both yield and quality of cinnamon, contributing to sustainable industry development.

***Keywords**:* Essential oil yield, Eugenol content, Genetic diversity, Progeny evaluation, Western Ghats

Cinnamon (*Cinnamomum verum* Presl., syn. *C. zeylanicum* Blume; Family: Lauraceae) is one of the earliest known and most important tree spices of India. It is both cultivated and wild-harvested for its aromatic bark, leaves and immature fruits, which are widely used as a spice and in traditional medicine (Hanumantha and Vasudeva 2025a, 2025b). The Western Ghats and neighbouring regions of Southern India are believed to be the centre of diversity for the *Cinnamomum* genus (Sasikumar et al., 1999). The Western Ghats and some parts of North Eastern states of India exhibit wide variability in plant species (Joy et al., 1998). Cinnamon leaves find extensive use in spice production, food preparation and essential oil extraction. The leaf oil is particularly rich in eugenol, along with other constituents such as cinnamic aldehyde, benzaldehyde, pinene, phellandrene, methyl eugenol, geraniol and caryophyllene (Joy et al., 1996). Presently, India's total cinnamon cultivation area is approximately 2,800 hectares, India's total cinnamon production is around approximately 5,050 tonnes in that Karnataka's contribution is around approximately 0.2 percent of the national production (Spices Board of India 2022).

Key producers are Indonesia, China, Vietnam and Sri Lanka. Key importers are Mexico, USA, India and Bangladesh. India is a net-importer of cinnamon from countries such as Indonesia, Vietnam, and Sri Lanka as domestic supplies are too small to meet the growing demands of domestic consumption and export demand of value added spices, wherein cinnamon is mixed with other spices (Singh and Singh 2008).

India is a net-importer of cinnamon from countries such for quality and final yield. To further enhance the quality of Ceylon cinnamon, Department of Export Agriculture (DEA) in Sri Lanka introduced two varieties, namely Sri gamunu (SG) and Sri Wijaya (SW), through long-term selection (Wijesinghe and Pathirana 2000). However, farmers do not benefit from these advancements as cinnamon is primarily propagated through seeds. Additional efforts are necessary to select superior genotypes and maintain genetic uniformity. The current methods of vegetative propagation are not efficient enough to meet the demand for planting material. Moreover, farmers are hesitant to adopt vegetatively propagated materials due to unresolved crop management and maintenance issues. In order to address these challenges, a progeny trial was conducted to identify superior genotypes based on their performance.

MATERIAL AND METHODS

The present study was undertaken during 2021-22 at the Bakkal Botanical Garden, near Sirsi, Uttara Kannada district, which is located in the Central Western Ghats between 13° 55' to 15° 32' N latitude and 74° 05' to 75° 05' E longitude with a geographic area of 10,291 km^2. The study area consists of

germplasm conservation site in Bakkal Botanical Garden near Hulekal, Sirsi and it consists of 15 half sib progenies of different families with three replications in each family. The experiment was in RCBD with three replications. Sources of half sib progenies of *Cinnamomum zyalanicum* were Jaddigadde of Sirsi forest range (J2 and J6), Gejjehalli of Hangal forest range, G4, G11, G16 and G24), Kankodlu of Yellapura forest range (K5, K10, K13, K16 and K18) and local of Siddapura forest range (S1, S4, S5 and S9).

Plant height was measured by, from ground level up to the top of the plant. Girth at collar region of the plant was measured at the collar region with a digital caliper, whereas in the case of two stems, the observation was taken from both stems and the average value was calculated. Number of branches and of number of leaves per plant were manually counted and recorded. The inflorescence and immature fruits per plant were also manually counted. Similarly, total fresh weight of leaves per plant was estimated by calculating the mean fresh weight of ten sampled leaves by multiplying it with total number of leaves. The fresh weight of leaves of fruits per plant was estimated by calculating mean fruit fresh weight of ten samples by multiplying it with total number of fruits per plant. The data were subjected to a one-way analysis of variance (ANOVA) using the online statistical software OPSTAT Sheoran et al. (1998).

The leaf essential oil was extracted at the 28 months after transplanting (May, 2022). About 100-150 g of fresh leaves were collected from selected progenies and stored in the room temaparature (Shade dried) and oil extraction was done by water distillation as quoted by Hanumantha (2020).

$$\text{Essential oil (\%)} = \frac{\text{Volume of oil}}{\text{Weight of sample}} \times 100$$

The collected leaf samples were subjected to RP-HPCL at K2VR Analytical Research Pvt. Ltd., Bangaluru, Karnataka for eugenol content assessment.

RESULTS AND DISCUSSION

Variation in growth attributes: There was significant variation among the fifteen half-sib progenies of *Cinnamomum zyalanicum* for growth parameters namely girth, number of leaves and number of branches per plant at 28 months after planting (MAP), however, height was non-significant (Table 1). The highest girth of 51.46 mm was in K16 family and was lowest in the K18 (20.69 mm). The greater number of leaves (677.66 per plant) were observed in G11 and lesser number of leaves in K18 (175.33). The greater mean number of branches per plant (50.33) were also in G11 and was lowest in K5 family (14.00 per plant). These variations may be due to the genetic variations and environmental factors. The coefficient of variation) was ranged from 21.22 % (girth) to 34.17 % (number of leaves). Wang et al. (2017) also reported variation in seven months old seedling growth of *Cinnamomum camphor* and the range of variation for basal diameter was 0.1 to 2.35 cm whereas height varied from 23 to 130 cm. Hanumantha (2020)

Table 1. Variation in growth parameters (among the selected progenies of *C. zeylanicum* at 28 months after planting (Mean ± SE)

Family code	Plant height (cm)	Girth at collar region (mm)	No. of branches/plant	No. of leaves/plant
J2	168.33±23.33	40.46±4.03	33.33±5.69	380.66±34.35
J6	165.00±18.02	31.64±3.71	31.00±4.16	423.66±77.02
G4	213.00±9.074	39.04±3.52	36.66±6.38	375.66±88.00
G11	213.33±21.66	42.03±3.67	50.33±1.20	677.66±86.19
G16	147.33±28.26	22.20±1.47	24.00±3.21	240.33±67.99
G24	137.00±38.55	25.99±1.67	34.33±7.12	191.66±70.96
K5	147.33±31.97	35.03±1.57	14.00±1.15	430.33±25.49
K10	187.33±6.48	31.89±4.25	28.66±6.43	368.33±52.27
K13	210.33±30.38	36.97±7.48	29.66±6.36	318.33±44.19
K16	184.00±10.69	51.46±6.39	38.00±6.08	444.00±42.00
K18	112.33±4.48	20.69±3.26	31.33±8.64	175.33±14.83
S1	171.33±6.83	38.85±5.43	44.33±8.66	665.33±194.65
S4	164.00±11.01	37.44±3.16	51.00±7.50	533.00±76.51
S5	162.33±21.69	31.37±4.45	47.66±5.04	334.66±38.40
S9	185.33±5.23	29.97±2.21	33.66±4.63	320.00±5.77
CD (p=0.05)	NS	12.25	17.84	225.19
CV (%)	21.36	21.22	30.14	34.17

assessed the 90 *C. zeylanicum* progenies and reported significant variation in plant height at 24 MAT and attained mean height of 73.12 cm. Such observation was also reported by Swarnapali and Subasinghe (2004)

Variation in leaf oil and eugenol content: Wide variation was recorded in leaf oil among the selected 15 progenies from different half-sib families of *Cinnamomum zyalanicum*. Oil content (v/w dry weight basis) ranged from 1.30 to 2.20 per cent with 9.7 per cent CV (Fig. 1). The maximum leaf oil content (2.20%) was recorded in family J6, followed by S4 (2.10%) and it was least (1.30%) in G24 family (Table 2). The variation in leaf oil content is attributed due to genetic factors. Apart from genotypic variation, plant protection and climatic factors also contribute to variations in leaf oil content (Kaul et al., 1996, Bakkali et al., 2008). Hanumantha (2020) reported leaf oil content of 1.28 to 1.60 per cent variation in *C. zeylanicum*. Ariyarathne et al. (2018) also assessed variability in amount of leaf oil using different *Cinnamomum* species. Further, as per Joy et al. (1998) and Krishnamoorthy et al. (1992), the leaf oil variation was reported to be 0.39 to 3.16 per cent. Considering cinnamon leaf eugenol, it is widely used in perfumery industries which possess antimicrobial and antifungal properties. In this study, a notable variation in eugenol content was recorded among the selected 15 progenies and it varied from 55.78 to 89.43 per cent (Table 2). The highest eugenol content was recorded in S5 (89.43%), K16 (88.57%) and G24 (87.43%) families and it was lowest in J6 (59.29%). Variation in eugenol content in leaf oil sample may be attributed by genetic effect, since these genotypes are grown in uniform environmental condition. Such variation for eugenol content was also reported by Hanumantha (2020) in *Cinnamomum zeylanicum* leaf oil (73.60 to 95.80 %) at Western Ghats of Karnataka, Chalchat and Valade (2000) reported 80.53 to 93.67 per cent variation in Odakkalli accessions of Kerala, Schmidt et al. (2006) recorded 74.90 to 76.74 per cent variation from Sri Lanka population, and Paranagama et al. (2001) reported 73.27 per cent eugenol content in cinnamon leaf from the Brazil.

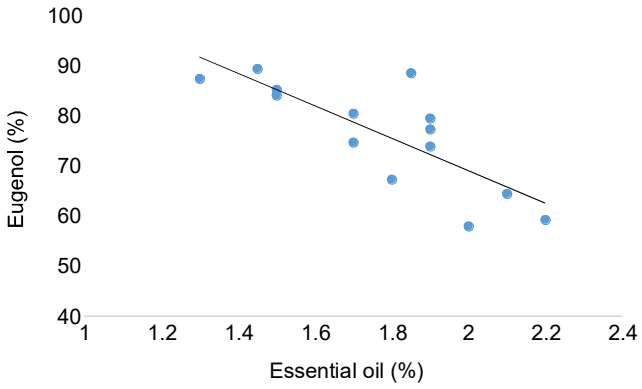

Fig. 1. Correlation between leaf oil (%) and eugenol content (%) in *C. zyalanicum*

There was strong negative association was observed between total leaf oil and eugenol content (R^2 = 0.630). This inverse relationship could be attributed to the compositional complexity of cinnamon leaf oil, which, apart from eugenol, also contains other constituents such as cinnamaldehyde, linalool and camphene. As the overall oil yield increases, the relative proportion of eugenol may decline due to the increased presence of these other compounds. Eugenol is one of the commercially valuable constituents of cinnamon oil, such a negative association should be carefully considered in selection and breeding program. These findings highlight the need for a balanced approach when selecting genotypes for higher oil yield to ensure that the concentration of key compounds like eugenol is not compromised.

Variation in reproductive attributes: The immature fruits of *C. zeylanicum* are a valuable commercial product with high market demand and price. Surprisingly, this characteristic has not been considered for selection in any previous studies. The large coefficient of variation was observed in total inflorescence per plant (125.42), followed by fruit weight per plant (113.94) and lowest was in immature fruit per plant (115.77). The maximum inflorescence (16.66 no./plant) and immature fruit (6.00 per plant) was in J2 family (Table 3). Hanumantha (2020) observe , four parameters *i.e.* fruit

Table 2. Variation in leaf oil and eugenol content among the selected progenies of *C. zeylanicum* at 28 months after planting

Family I.D.	Leaf oil content (%)	Eugenol (%)
J2	1.70	80.49
J6	2.20	59.29
G4	1.70	74.73
G11	2.00	58.00
G16	1.50	84.12
G24	1.30	87.43
K5	1.50	85.27
K10	1.90	73.93
K13	1.90	79.53
K16	1.85	88.57
K18	1.80	67.33
S1	1.90	77.35
S4	2.10	64.48
S5	1.45	89.43
S9	No data	No data
CV (%)	9.78	19.44

Table 3. Variation in reproductive parameters among the selected progenies of *C. zeylanicum* at 28 months after planting (Mean ± SE)

Family code	Inflorescence/plant (numbers)	Immature fruits/ plant (numbers)	Fruit weight/ plant (g)
J2	16.66±5.45	6.00±2.08	0.23±0.08
J6	3.33±2.02	2.00±1.00	0.21±0.11
H29	5.33±2.90	5.33±2.90	0.157±0.10
H36	15.66±9.90	4.00±2.08	0.27±0.14
H41	0.33±0.33	4.66±4.66	0.00±0.00
H49	5.66±5.66	1.66±1.66	0.03±0.03
K5	3.33±3.33	0.66±0.66	--
K10	8.00±6.02	4.33±2.40	--
K13	1.33±1.33	1.66±1.66	--
K16	11.33±6.96	2.33±1.20	0.11±0.07
K18	4.00±2.08	3.00±1.73	0.09±0.09
S1	13.33±6.88	3.66±2.02	0.16±0.09
S4	10.00±7.02	3.66±0.33	0.23±0.01
S5	4.33±2.33	2.33±1.20	0.15±0.07
S9	3.33±1.76	2.33±1.45	0.14±0.09

bearing density of individual trees, the number of immature fruits per foot of inflorescence and the fresh/dry weight of immature fruits per tree were examined to identify the best individuals. Among the trees assessed, Siddapura exhibited the highest mean fruit bearing density (2.80). The tree from Jaddigadde displayed the highest coefficient of variation for fruit bearing density (42.89%). The number of immature fruits per foot of inflorescence also varied among the selected mother trees which ranged from 10 to 135 fruits. The tree identified as G6 produced the maximum number of immature fruits (135). Additionally, Gejjehalli had the highest mean number of fruits per foot of inflorescence (88.32), indicating that it is a suitable source for selecting trees with high production of immature fruits. Krishnamoorthy et al. (2001) evaluated yield and quality parameters of ten *Cinnamomum cassia* accessions and reported significantly higher coefficient of variation for fruit yield per tree (107.11 per cent).

CONCLUSION

Variation in growth traits, leaf oil and eugenol content, and reproductive attributes among half-sib progenies of *C. zeylanicum*. Half-sib families like G11, J6, K16, S5 and J2 demonstrated superior performance in various economic traits, indicating these are ideal candidates for future breeding and improvement programs. The negative correlation between oil yield and eugenol content highlights the need for a balanced selection approach to optimize both quantity and quality. Furthermore, the study identified potential in immature fruit production, an often-overlooked trait with commercial relevance. These findings provide a valuable foundation for selecting elite genotypes aimed at enhancing cinnamon's economic value, ensuring sustainable production and supporting both spice and essential oil industries in India.

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Soil Nutrient Dynamics under Horse Gram Intercropping in *Melia dubia*–Based Agroforestry in the Central Dry Zone of Karnataka

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***Abstract*:** Agroforestry is a sustainable land-use system that integrates trees and crops, enhancing soil fertility and productivity, particularly in semi-arid regions. This study evaluated the impact of intercropping *Macrotyloma uniflorum* (horse gram) in *Melia dubia* (Malabar neem)-based agroforestry on soil nutrient status in the central dry zone of Karnataka. Soil samples were collected from five depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm) before and after harvesting, and analyzed for key soil parameters using a response index approach. The intercropping significantly reduce soil pH (from 7.2 to 6.8), with a response index of -4.8%, due to organic acid release from decomposed litter. Electrical conductivity (EC) decreased from 0.42 dS m^{-1} to 0.35 dS m^{-1}, with a response index of -16.6%, indicating improved soil structure. Soil organic carbon (SOC) increased from 0.48% to 0.62%, with a response index of +29.2%, attributed to organic matter accumulation. Available nitrogen (N) improved from 215 kg ha^{-1} to 265 kg ha^{-1}, showing a response index of +23.2%. Similarly, available phosphorus (P_2O_5) and potassium (K_2O) increased from 16.8 to 22.5 kg ha^{-1} and 240 to 280 kg ha^{-1}, with response indices of +33.9% and +16.7%, respectively, largely due to nutrient cycling and organic matter decomposition. Statistical analysis indicated improvements in soil fertility under intercropped conditions compared to sole cropping. These findings highlight that *M. dubia*-based agroforestry with horse gram enhances soil nutrient retention and fertility, offering a viable strategy for sustainable agriculture in resource-limited dryland agriculture

***Keywords*:** Agroforestry, Soil fertility, Intercropping, Nutrient cycling, Sustainable agriculture

In present time agriculture across the globe in general and India in particular is going through severe crisis of land, water, food under the pressure of climate change (Pathak et al., 2014). It was observed that the yield component is being affected severely by practicing monoculture cropping in various regions (Larsen et al., 2025). Monoculture practices also lead to loss of gene pool, decrease in yield, productivity and quality along with land degradation through loss of soil fertility and health (Meena et al., 2025). In this connection, intercropping is a suitable measure which may be used to improve the quality and health of the soil through agroforestry practices that would also help in improving soil fertility (Kumari et al., 2025, Jinger et al., 2023). It would also provide a guideline for selecting suitable climate-resilient cropping system depending upon the existing climatic conditions (Kumar et al., 2024).

The growing demand for food, fodder, fuel, and timber, coupled with diminishing land resources, necessitates the adoption of sustainable land-use practices to enhance productivity per unit area (Shuite et al., 2025). This challenge is particularly significant in semi-arid regions like the central dry zone of Karnataka, where limited water availability and poor soil fertility constrain agricultural output. Traditional farming systems, reliant on rainfed conditions, often result in low yields and economic vulnerability. To address these challenges, agroforestry-an integrated land-use system combining trees with crops offers a promising solution by enhancing soil fertility, optimizing resource use, and improving farm resilience (Jinger et al., 2022, Prajapati et al., 2022).

Melia dubia (Malabar neem), a fast-growing, multipurpose tree species, has gained prominence in agroforestry due to its economic value and adaptability to diverse climatic conditions (Thakur et al., 2018, Jinger et al., 2024, Malek et al., 2024). It is widely cultivated for timber, plywood, and industrial applications, making it a viable option for integrating into farming systems (Ashok et al., 2017, Thakur et al., 2020, 2023, Jinger et al., 2025) with no allopathic effect on understorey crops (Kumar et al., 2017, Parmar et al., 2019). On the other hand, horse gram (*Macrotyloma uniflorum*), a hardy, drought-tolerant pulse crop, serves as an excellent intercrop in agroforestry systems (AFs) due to its ability to fix nitrogen (N), improve soil organic matter (SOM), and provide nutritional and economic benefits to farmers (Prasad and Singh 2015).

Intercropping horse gram with *M. dubia* has the potential to enhance soil nutrient status by increasing organic carbon (OC) content, N availability, and overall soil fertility through litter decomposition and nutrient cycling. Additionally, AFs mitigate soil degradation, reduce erosion, and enhance water retention, making them well-suited for semi-arid regions (Subba and Dhara, 2017, Dobhal et al., 2024). Despite the recognized benefits, limited research exists on the impact of intercropping horse gram in *M. dubia*-based AFs, particularly on soil nutrient dynamics.

It was hypothesized that the integration of horse gram in *M. dubia*–based AFs significantly enhances soil physico-chemical properties and overall fertility compared to monocropping systems. The objective of this study was carried out to evaluate the influence of horse gram cultivation within *M. dubia*–based agroforestry on key soil parameters, thereby generating evidence to support sustainable agriculture and agroforestry practices in dryland regions.

MATERIAL AND METHODS

Study sites: The experimental field was conducted at the Zonal Agricultural and Horticultural Research Station of Hiriyur, Chitradurga district of Karnataka lying between in 13°56'57" N and 76°37'13" E with an elevation of 600 above MSL. The climate of the area reflects a dry zone having an average annual rainfall of about 660 mm. The average temperature ranged between 17.7-31.5 °C with an average relative humidity of 72%.

Experimental details: Experiment was set up in the year 2018-19. At the time of cultivation the age of *M. dubia* was three years old which was intercropped with horse gram in randomized complete block design with five replications which includes the treatment combination as- T1 – 4 m × 1 m spacing with horse gram T2 – 4 m × 2 m spacing with horse gram T3 – 4 m × 3 m spacing with horse gram T4 - Sole horse gram crop

Soil sample collection and preparation: Soil samples were drawn from five depths: d1 (0-20 cm), d2 (20-40 cm), d3 (40-60 cm), d4 (60-80 cm), and d5 (80-100 cm) before and after harvesting from all the treatments. Collected soil samples were brought to the laboratory in polythene bags for further processing. The soil samples were dried under shade, ground with a pestle and mortar, and sieved through 2 mm sieve. The processed soil samples were analyzed for pH, EC, available N, phosphorus (P_2O_5), and potassium (K_2O). For OC analysis, the powdered soil samples were further ground in an agate mortar and passed through a 0.5 mm sieve. The treatments considered were different spacing between *M. dubia* trees: T1 (4 m × 1 m), T2 (4 m × 2 m), T3 (4 m × 3 m), and T4 (sole HG). The procedure for the analysis of various characteristics in initial and post-harvest soil samples was followed as per standard laboratory protocols.

Soil chemical analysis: The collected soil samples were analyzed for key chemical properties using standard laboratory procedures. Soil pH was measured using a digital pH meter in a 1:2.5 soil-water suspension (Jackson, 1973). Electrical conductivity (EC) (dSm^{-1}) was determined using a conductivity meter in a 1:2.5 soil-water suspension (Richards, 1954). % organic carbon (SOC) was estimated using the Walkley and Black (1934) wet oxidation method. Available N (kg ha^{-1}) was determined using the alkaline permanganate method (Subbiah and Asija 1956). Available phosphorus (kg ha^{-1}) was measured using the Olsen's method (Olsen et al., 1954). Available potassium (kg ha^{-1}) was estimated using neutral normal ammonium acetate extraction followed by flame photometry (Jackson 1973).

Statistical analysis: The data was analyzed with SPSS package. Correlation study between the soil attributes before and after harvesting of horse gram intercropping system was done in order to established the influence of soil attributes among themselves. The treatment means of the soil parameters of various treatments were done through Duncan's Multiple Range Test (DMRT) to evaluate the variation within the treatment means.

RESULTS AND DISCUSSION

The initial soil chemical analysis before intercropping horse gram revealed variations in pH, EC, SOC, and nutrient availability across different treatments and soil depths. Soil pH ranged from 8.22-8.81 (Table 1), with the highest measured in sole horse gram plots (8.81 at 60-100 cm depth) and the lowest in T1 (4m × 1m) (8.22-8.32). Electrical conductivity (EC) varied from 0.24 to 0.39 dS m^{-1} with the highest in sole crop (0.39 dS m^{-1} at 0-20 cm) and the lowest in T1 (0.28-0.25 dS m^{-1}). Nutrient analysis indicated that available N ranged from 98.00 to 186.20 kg ha^{-1} (Table 1), phosphorus from 8.30 to 28.40 kg ha^{-1} and potassium from 186.60 to 304.80 kg ha^{-1}, with the highest values observed in T3 (4m × 3m) at 0-20 cm. Similarly, SOC ranged from 0.19-0.46% (Table 2), with the highest value in T3 (0.46% at 0-20 cm) and the lowest in sole horse gram (0.19-0.23%). These findings suggest that wider tree spacing (T3) enhanced nutrient retention and OC accumulation, whereas sole cropping had higher pH and EC but lower SOC and nutrient availability. Post-harvest, significant variations in soil properties were observed across different treatments and soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm). The highest pH (8.11-8.82) was in sole horse gram plots (Table 3), while among *M. dubia* treatments, T3 consistently had the highest pH, followed by T2 (4m × 2m)

and T1 (4m × 1m). EC followed a similar trend, with sole crop horse gram exhibiting the highest EC (0.33-0.38 dS m^{-1}), while T3 recorded the highest EC among *M. dubia* treatments across all depths (Table 4). The availability of N (161.80-197.40 kg ha^{-1}), phosphorus (14.20-33.60 kg ha^{-1}) (Table 5), potassium (284.60-310.70 kg ha^{-1}), and SOC (0.21-0.48%) was highest in T3. In contrast, sole crop horse gram had the lowest values for these nutrients. These results indicate that *M. dubia* spacing influenced soil properties, with wider spacing improving nutrient availability and OC accumulation more effectively than closer spacing (T1) or sole cropping.

The impact of *M. dubia* intercropping on soil chemical properties was further reflected in the response index, where soil pH and EC showed negative values across all treatments. Conversely, available N, phosphorus, potassium, and SOC exhibited positive response indices when horse gram was intercropped but negative under sole cropping. The response index ranged from -0.018 to -0.001

Table 1. Soil pH, EC and available nitrogen recorded before horse gram intercropping as influenced by different treatments

Treatment	pH					EC (dS m^{-1})					Available nitrogen (kg ha^{-1})				
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm
T_1 (4 m × 1 m)	8.22	8.25	8.28	8.30	8.32	0.28	0.27	0.26	0.26	0.25	137.00	131.60	126.20	120.40	115.40
T_2 (4 m × 2 m)	8.28	8.30	8.31	8.33	8.34	0.29	0.28	0.27	0.25	0.24	162.40	156.00	149.60	143.80	138.20
T_3 (4 m × 3 m)	8.32	8.34	8.36	8.37	8.37	0.34	0.33	0.32	0.30	0.28	186.20	179.00	172.40	166.00	160.20
T_4 (Sole HG)	8.76	8.78	8.80	8.81	8.81	0.39	0.37	0.36	0.35	0.34	108.40	104.60	101.60	99.80	98.00
CD (p=0.05)	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	6.58	5.89	5.62	5.33	6.03

Table 2. Soil available phosphorous (P_2O_5), potassium (K_2O) and organic carbon recorded before horse gram intercropping as influenced by different treatments

Treatment	Available P_2O_5 (kg ha^{-1})			Soil available K_2O (kg ha^{-1})			Soil organic carbon (%)		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1(4 m × 1 m)	23.58	15.00	10.80	261.40	250.20	238.60	0.39	0.31	0.24
T_2(4 m × 2 m)	25.80	19.70	13.60	278.80	265.40	253.00	0.44	0.36	0.28
T_3(4 m × 3 m)	28.40	22.20	13.80	304.80	292.60	283.60	0.52	0.44	0.36
T_4(Sole HG)	18.40	11.60	8.30	202.60	191.20	182.20	0.29	0.23	0.20
CD (p=0.05)	1.26	0.84	0.85	5.20	5.68	5.01	0.01	0.02	0.02

Table 3. Soil pH, EC and available nitrogen recorded after harvest of horse gram as influenced by different treatments

Treatment	pH			Electric Conductivity (dS m^{-1})			Available nitrogen (kg ha^{-1})		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1 (4 m × 1 m)	8.11	8.28	8.32	0.24	0.23	0.22	141.60	130.80	117.40
T_2 (4 m × 2 m)	8.13	8.31	8.33	0.25	0.23	0.22	169.60	156.40	140.20
T_3 (4 m × 3 m)	8.17	8.35	8.37	0.27	0.24	0.23	197.40	179.80	161.80
T_4 (Sole HG)	8.76	8.80	8.82	0.38	0.35	0.33	106.40	100.20	96.40
CD (p=0.05)	0.03	0.02	0.02	0.02	0.01	0.01	6.74	5.88	5.80

Table 4. Soil available phosphorous (P_2O_5), potassium (K_2O) and organic carbon recorded after harvest of horse gram as influenced by different

Treatment	Available P_2O_5 (kg ha^{-1})			Available K_2O (kg ha^{-1})			Soil organic carbon (%)		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
T_1 (4 m × 1 m)	25.40	16.20	11.20	263.70	251.42	239.10	0.41	0.32	0.25
T_2 (4 m × 2 m)	29.50	22.30	14.20	283.00	267.00	253.80	0.47	0.38	0.29
T_3 (4 m × 3 m)	33.60	25.70	12.50	310.70	295.30	284.60	0.56	0.46	0.37
T_4 (Sole HG)	17.00	10.74	7.90	201.20	189.60	181.40	0.28	0.22	0.19
CD (p=0.05)	1.18	0.73	4.50	4.64	5.64	5.23	0.01	0.02	0.02

for pH (Fig. 1), -0.006 to -0.233 for EC (Fig. 2), -0.012 to 0.060 for N (Fig. 3), -0.132 to 0.183 for phosphorus (Fig. 4), -0.008 to 0.019 for potassium (Fig. 5), and -0.061 to 0.096 for SOC (Fig. 6).

Higher level of variation was recorded between the treatment means of available N and potassium (Table 5). Lesser variation of the treatment means was observed for rest of the parameters. This therefore indicates that the soil attributes reflected significant variation in the available N and potassium level before horse gram intercropping. Further, the correlation matrix of the soil attributes before horse gram intercropping reflected positive correlation between pH and EC. Further, N, phosphorous, potassium and OC was positively and significantly correlated with each other (Fig. 7).

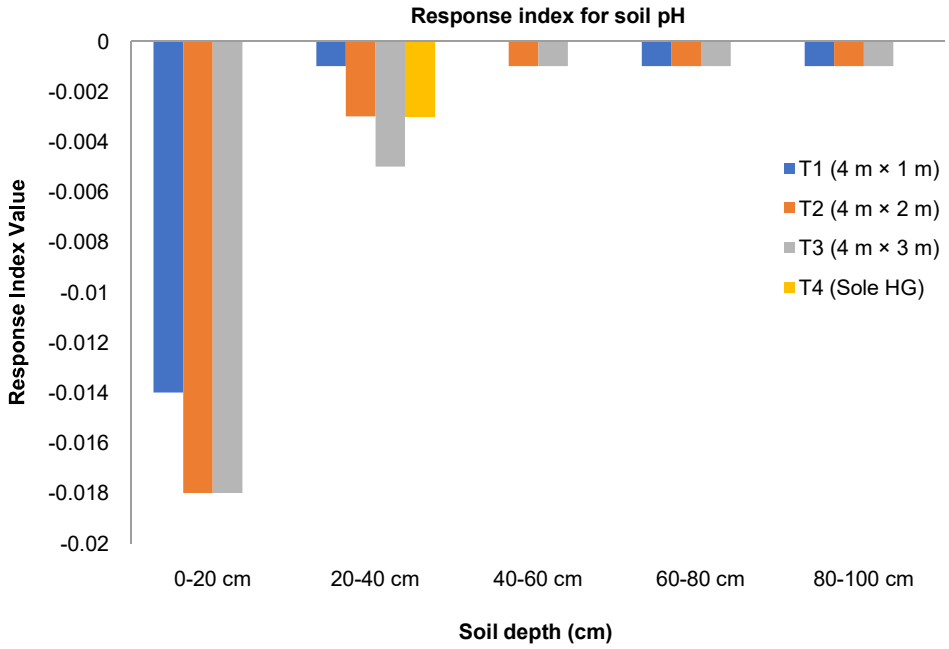

Fig. 1. Response index for pH as influenced by different treatments

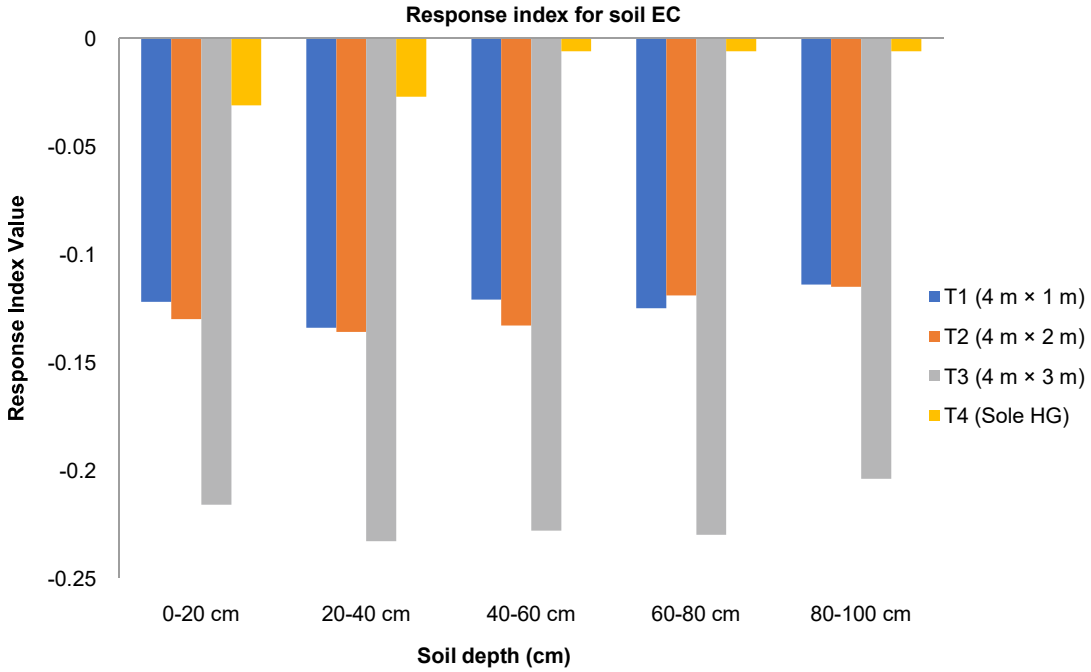

Fig. 2. Response index for EC as influenced by different treatments

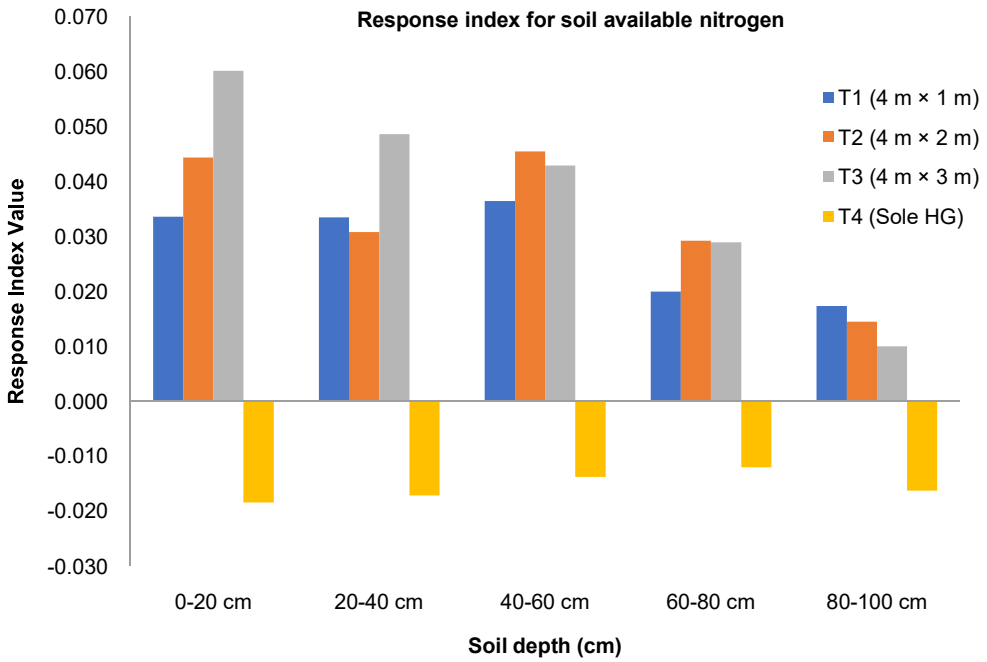

Fig. 3. Response index for available nitrogen as influenced by different treatments

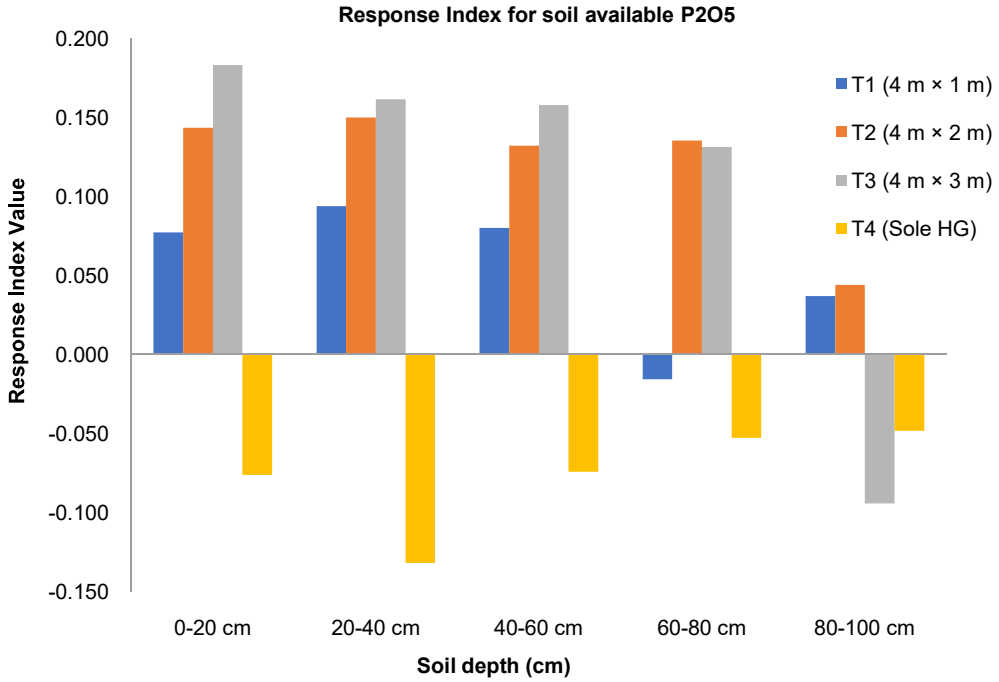

Fig. 4. Response index for available phosphorus as influenced by different treatments

Table 5. Variation of treatment means of soil attributes before horse gram intercropping

Treatment	pH	EC	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Soil available K_2O (kg ha^{-1})	Soil organic carbon (%)
T_1 (4 m × 1 m)	8.274^{b}	0.264^{b}	126.12^{bc}	16.276^{a}	249.88^{b}	0.314^{ab}
T_2 (4 m × 2 m)	8.312^{b}	0.266^{b}	150.08^{ab}	19.76^{a}	265.72^{ab}	0.358^{ab}
T_3 (4 m × 3 m)	8.352^{b}	0.314^{ab}	172.76^{a}	21.62^{a}	293.44^{a}	0.44^{a}
T_4 (Sole HG)	8.792^{a}	0.362^{a}	102.48^{c}	12.52^{a}	191.84^{c}	0.238^{b}

Similar trend of higher level of variation was recorded between the treatment means of available N and potassium (Table 6). Lesser variation of the treatment means was observed for rest of the parameters. This indicates that the soil attributes reflected significant variation in the available N and potassium level after horse gram intercropping represents similar trend of correlation matrix as was observed before horse gram intercropping. pH was positively and significantly correlated with EC (Fig. 8). Available N, phosphorous, potassium and OC was be significantly and positively correlated among themselves.

The present study demonstrated that *M. dubia*-based AFs, particularly the tree-legume intercropping treatment (T3), significantly enhanced soil fertility indicators such as soil organic carbon (SOC), available nitrogen (N), phosphorus (P), and potassium (K), while reducing soil pH

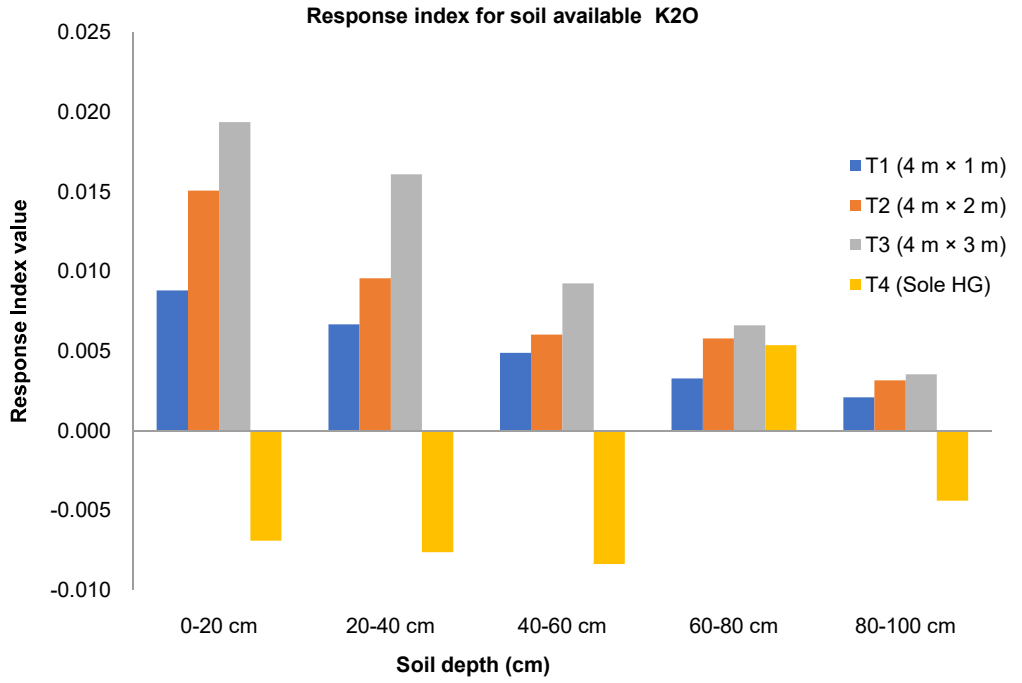

Fig. 5. Response index for available potassium as influenced by different treatments

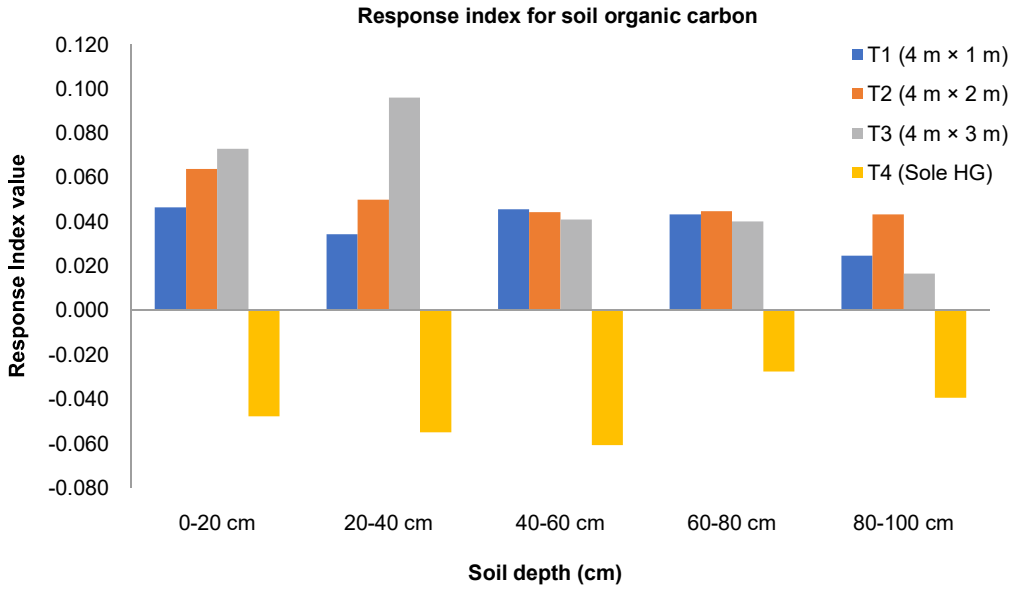

Fig. 6. Response index for soil organic carbon as influenced by different treatments

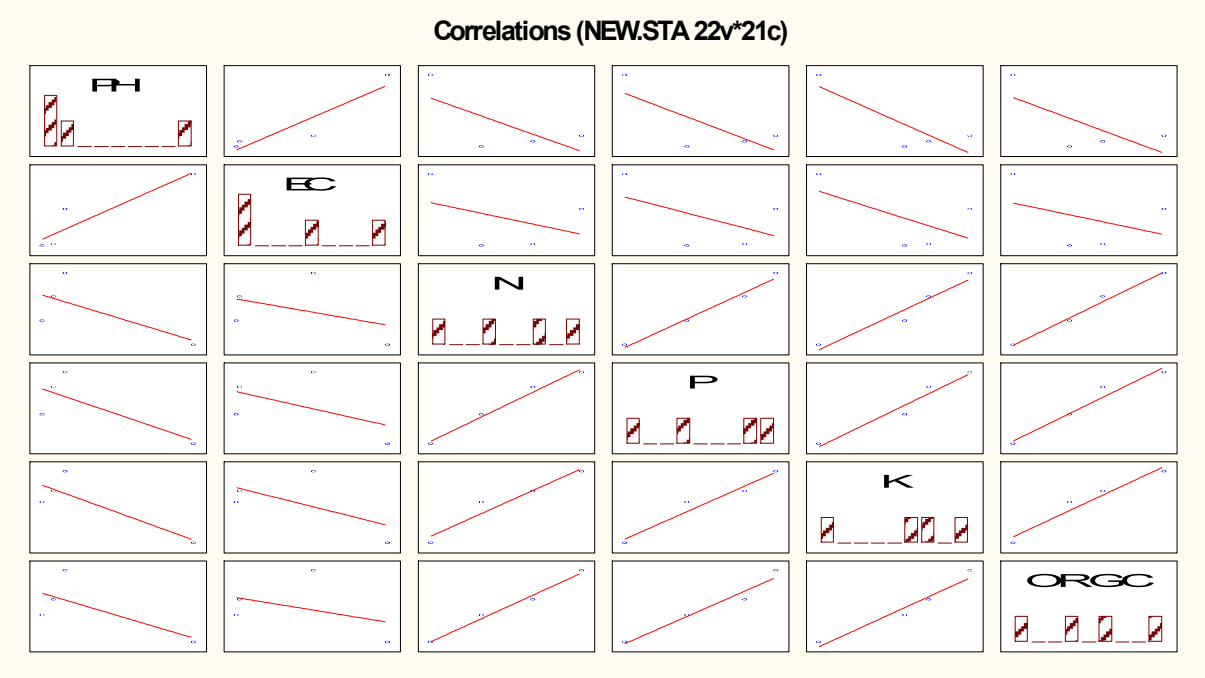

Fig. 7. Correlation matrix of soil attributes before horse gram intercropping

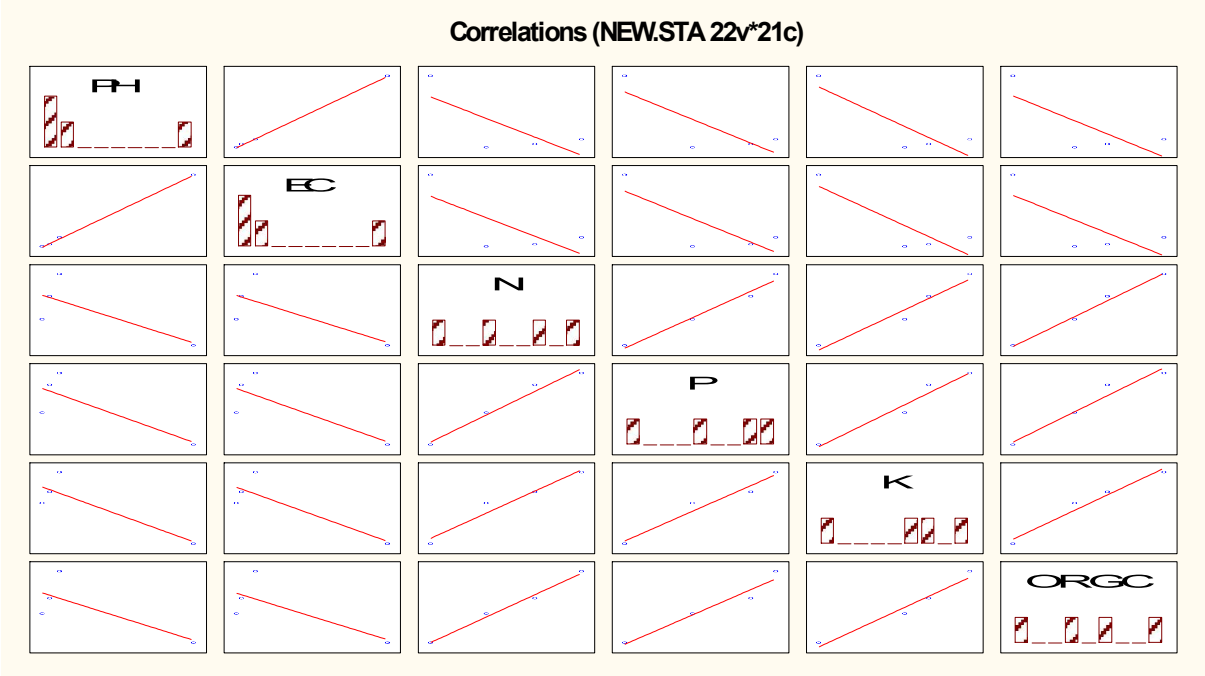

Fig. 8. Correlation matrix of soil attributes after horse gram intercropping

Table 6. Variation of treatment means of soil attributes after horse gram intercropping

Treatment	pH	EC	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Soil available K_2O (kg ha^{-1})	Soil organic carbon (%)
T_1 (4 m × 1 m)	8.248^{b}	0.228^{b}	129.72^{bc}	17.28^{a}	251.224^{b}	0.326^{ab}
T_2 (4 m × 2 m)	8.274^{b}	0.232^{b}	155^{ab}	22.28^{a}	267.86^{b}	0.378^{ab}
T_3 (4 m × 3 m)	8.31^{b}	0.244^{b}	179.36^{a}	24.4^{a}	296.7^{a}	0.468^{a}
T_4 (Sole HG)	8.79^{a}	0.354^{a}	100.88^{c}	11.498^{a}	190.98^{c}	0.228^{b}

and electrical conductivity (EC).The reduction in soil pH under *M. dubia* aligns with Kumar et al., (2008), where similar acidification in tree-based systems due to organic acid release from litter decomposition in dry semi-arid conditions of central India. Nanda et al. (2021) observed similar trends in drylands of Rajasthan. Singh et al. (2018), also observed that legumes to raise soil pH through biological Nitrogen fixation and less acidic root exudates in arid regions. The decrease in EC, particularly in T3, can be attributed to better nutrient uptake and improved SOM mineralization, similar to observations by Ravi (2005) in southern India and Patel et al. (2018) in semi-arid Gujarat. SOC accumulation was highest in surface soils under *M. dubia*, supported by findings of Kar et al. (2019) where increased SOC in AFs in Odisha due to higher litter input and reduced oxidation from canopy cover. The decline in SOC with depth is also in line with Salve et al. (2018), due to reduced microbial activity and organic input in subsoil layers under agroforestry in Maharashtra. Enhanced N, P, and K availability in intercropped plots was driven by improved litter quality and microbial activity, which agrees with Bharadwaj et al. (2017) and Kaur et al., (2022), where higher phosphorus availability is linked with increased phosphatase activity in Haryana and Punjab respectively,. Uthappa et al. (2015) also reported enhanced nutrient cycling in semi-arid Karnataka. The superior performance of T3 further supports the compatibility of *M. dubia* with legumes, as observed by Thakur et al. (2019) in *M. dubia* + *Cymbopogon* systems in Chhattisgarh. Overallur findings confirm the sustainability potential of *M. dubia*-based AFs under dryland conditions, aligning with broader national and global evidence (Dhyani 2014, Jinger et al., 2022, 2023, 2024, Dobhal et al., 2024), which highlights agroforestry as a nature-based solution for improving soil health, enhancing nutrient cycling, and restoring productivity in degraded or low-input ecosystems.

CONCLUSION

The intercropping horse gram with *M. dubia* in dry zone significantly improved soil fertility by enhancing SOC, available N, P, and K through litter decomposition and nutrient cycling. The decline in soil pH under tree-based systems indicated improved microbial activity and SOM breakdown. Compared to sole cropping, wider tree spacing reflected higher nutrient retention and OC accumulation than sole cropping and hence can be recommended to be applied under field condition for improvement of soil fertility. Therefore, intercropping demonstrated better nutrient availability, highlighting AFs as a sustainable land-use strategy for semi-arid regions. This approach not only enhances soil health but also provides economic and ecological benefits, promoting resilience to climate variability and improving farm incomes.

AUTHOR'S CONTRIBUTIONS

Syed Ali, Salma Kabeer and Manoj Kumar Jhariya wrote the main manuscript. Syed Ali, Manoj Kumar Jhariya and, Arnab Banerjee prepared the figures, Vasudev L, Manoj Kumar Jhariya, Lalji Singh, Sangram B Chavan and J.S. Singh reviewed the manuscript.

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Agrobiodiversity under Agroforestry Systems in Garhwal Himalayan Region: A Case Study

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***Abstract*:** Agrobiodiversity refers to the variety and variability of all living organisms that form part of agricultural ecosystems. It encompasses crops, livestock breeds, soil organisms, pollinators, and wild relatives. The present investigation was conducted to assess agrobiodiversity in two agroforestry systems (Apple and Oak) across three districts (Tehri, Uttarakashi and Rudraprayag) of Uttarakhand, within two elevation ranges: 1500-2000 m and 2000–2500 m amsl. Data were collected through questionnaire surveys, field observations, and quadrat sampling. The results revealed that agrisilviculture, agrihorticulture, and silvipasture systems were present in all three districts at both elevations, except in the higher elevation zone of Uttarkashi district. Interestingly, a unique agroforestry system, aquaculture, was recorded only in Rudraprayag district at the upper elevation. In total, five crop categories were documented under apple- and oak-based agroforestry systems within the two elevation ranges. These included cereals and pulses (7 species), millets (2 species), oilseeds (3 species), and vegetables (28 species), with vegetables representing the highest diversity. Additionally, a total of 106 wild plant species were recorded across the study sites, comprising 49 herbs, 19 shrubs, 13 grasses, 4 vines, and 21 tree species across both agroforestry systems and elevation ranges in all three districts. Pollinator diversity was represented by five insect orders. The highest number of pollinators (11 species) belonged to Hymenoptera, followed by Diptera (6 species) and Lepidoptera (6 species), while the lowest diversity was observed in Hemiptera. Order-wise analysis indicated that Hymenoptera contributed the highest proportion of pollinators, whereas Hemiptera accounted for the least across all districts. Overall, the study highlights the rich agrobiodiversity within the agroforestry systems of Uttarakhand, with notable variations in crop composition, wild vegetation, and pollinator diversity across districts and elevation ranges.

***Keywords*:** Agrobiodiversity, Pollinator, Vegetation, Species, Himalayan, Crop category

Agrobiodiversity refers to the variety of species and genetic resources present in agroecosystem. All biotic factors related to agriculture, such as, plants, animals, fish, reptiles, insects, birds and microbes are components of agrobiodiversity (Mohapatra 2016). It plays a crucial role in ensuring global food security, enhancing the resilience of ecosystems, and encouraging sustainable agricultural practices. This diversity comprises a wide range of crops, livestock, and microorganisms that provide different food options, aid in nutritional well-being, and contribute to the preservation of cultural heritage. Agricultural biodiversity or agrobiodiversity is a subset of biodiversity including all crops and livestock and all interacting species of pollinators, symbionts, pests, parasites, predators, and competitors (Nair et al., 2022). Agricultural landscapes with substantial agroforestry activities are effective for the conservation of biodiversity in managed ecosystems and play a significant role in conserving and even enhancing biodiversity from farms to the landscape level (Abebe et al., 2013).

India is recognized as the center of origin for several important crops, including rice, brinjal, citrus, banana, and cucumber. It is also exceptionally rich in food crops, oilseeds, horticultural crops, spices, lichens, algae, fungi, insects, and medicinal plants. The country possesses nearly 15,658 rice landraces and is the world's largest exporter of Basmati rice. In addition, India produces numerous indigenous and local varieties of wheat, pulses, and millets, many of which are valued for their high nutritional content (Jacob et al., 2020). As one of the 12 mega-diverse regions of the world, India harbors approximately 127,000 species of animals, plants, and microbes. It contributes about 6% of global insect diversity, with nearly 51,000 identified insect species. The country is also the center of domestication for around 25 crop species and supports over 18,000 species of higher plants, including 160 major and minor crops and 325 of their wild relatives. Furthermore, indigenous communities make extensive use of biodiversity, with about 1,500 wild edible plant species utilized comprising 145 roots and tubers, 521 leafy vegetables, 647 fruits, and 118 species of seeds and nuts (Anderson 2008).

The mountain region exhibits diverse agro-climatic conditions, ranging from the flat foothill areas known as the *tarai* to mid-mountain zones and high-altitude lands approaching the snow line. Although the mountainous areas of the state are food deficient, they maintain a rich repository of diversified agricultural traditions and products (Rais and Farooquee 2013). Agroforestry systems (AFS), which generally sustain much higher species diversity than conventional agriculture or plantation forestry (Toky et al.

1989), are increasingly facing biodiversity losses due to system simplification. For instance, traditional shaded coffee and cacao production systems are being transformed into un shaded monocultures under intensive management, a process often referred to as agro-deforestation. Despite such challenges, tropical AFS particularly multi-strata systems remain highly significant for biodiversity conservation and possess an inherent capacity to promote both aboveground and belowground diversity (Nair et al., 2022).

This invaluable gift of nature is increasingly under threat and being indiscriminately degraded by human activities, particularly tropical deforestation, developmental projects, road widening etc., which has led to severe ecological consequences (Bhagwat et al., 2008). According to the Convention on Biological Diversity (CBD), to which India is a signatory, the major threats to biodiversity include habitat fragmentation, degradation and loss, overexploitation of natural resources, erosion of genetic diversity, invasive exotics species, declining forest resources, climate change and desertification, the impacts of development projects, and various forms of pollution. Given the diverse socio-cultural context and the often competing demands of different stakeholders, there is an urgent need to intensify and expand efforts aimed at biodiversity conservation and sustainable utilization through nature based solution. Equally important is ensuring the fair and equitable sharing of benefits derived from the use of genetic resources (Dobson 2005).

MATERIAL AND METHODS

Sampling area: The study was carried out in three hilly districts of Uttarakhand, namely Tehri Garhwal, Rudraprayag and Uttarkashi. For assessing the plant (trees, shrubs and herbs) diversity in the agroforestry systems (Oak and Apple based agroforestry system) four villages from each district were chosen for assessment of agrobiodiversity in agroforestry systems (Table 1). These districts lie in the middle and upper Himalayan ranges, with elevation ranging from approximately 900 to over 6,000 meters, encompassing steep mountain slopes, river valleys, and alpine meadows. Major rivers such as the Bhagirathi, Alaknanda, and Mandakini traverse these districts, playing a crucial role in shaping the landscape and supporting livelihoods. The region is predominantly agrarian, where traditional farming of crops like paddy, wheat, millets, barley, pulses, and vegetables is practiced along with animal husbandry and horticulture. Assessment of various agricultural crops, type of trees species, herbs, shrubs, wild plants and pollinators was carried out in all three selected district.

Assessment of agro-biodiversity: The study was carried out in the oak and apple based agroforestry system in all three districts with both elevation ranges, and field survey was conducted in each selected village for data collection. Thirty households were selected from each village engaged in agroforestry practices. Household surveys, questionnaires, and direct field observations was done to collect agrobiodiversity information from study sites. Information was collected like cultivated agriculture crops, horticulture crops and agroforestry tree species under selected agroforestry systems, and pollinator diversity at the household/village level, diversity of useful wild plants at each selected sites. Also, interviews were conducted with the local farmers that has specialized knowledge about agrobiodiversity. The major objective of the study is to explore the agro-biodiversity of selected areas. So there is a prerequisite that the respondent should be closely related to agriculture, either directly or indirectly. The random sampling was applied for the selection of household as well as the study of vegetation.

Table 1. Details of study sites

District	Name of village	Latitude (N)	Longitude(E)	Elevation range
Tehri Garhwal	Jhakogi	30.44432	78.30450	1500-2000 m amsl
	Chopdiyal gaun	30.38621	78.36339	
	Thangdhar	30.41903	78.33199	2000-2500 m amsl
	Digothi (Rueskhet)	30.28921	78.41716	
Rudraprayag	Chaunra (Satoli)	30.41038	78.89346	1500-2000 m amsl
	Chirbatiya (Budna)	30.38909	78.83717	
	Hilanai (Bajeera)	30.43133	78.86068	2000-2500 m amsl
	Taleda (Palakurali)	30.41478	78.83502	
Uttarkashi	Kimmi	30.77189	78.12351	1500-2000 m amsl
	Naini	30.77993	78.14284	
	Bingsi (Syunri)	30.76540	78.15591	2000-2500 m amsl
	Kandau	30.76235	78.13100	

RESULTS AND DISCUSSION

In Garhwal Himalayan region the major traditional agroforestry systems are agrisilviculture (AS), agrihortisilviculture (AHS) agrihorticulture (AH) and homegarden with main trees *Grewia optiva*, *Celtis australis*, *Melia azedarach*, *Ficus* and citrus fruit along with agricultural crops (Dadhwal et al., 1989).

The maximum (6) number of agroforestry system was in Uttarkashi district at lower elevation followed by Tehri Garhwal (5) at lower elevation and Rudraprayag (5) at upper elevation while, minimum (3) number of agroforestry system was also in Uttarkashi district at upper elevation. Among the Agroforestry system agrisilviculture, agrihorticulture and silvipasture system were found in all three district at both elevation except upper elevation of Uttarkashi district. A unique agroforestry system aqua culture was found only in Rudraprayag district at upper elevation. Similar agroforestry system was also observed in earlier studies (Bijalwan et al., 2011, Vikrant et al., 2016, Kumar et al., 2025). The main traditional agroforestry systems in the Narendranagar and Thauldhar block were agrisilviculture, agrihortisilviculture and agrihorticulture.

The 5 crop category were found in all 3 selected district under apple and oak based agroforestry system within two elevation ranges (1500-2000 m amsl) and (2000-2500 m amsl) (Table 3). The maximum (28) crops were recorded under vegetable category. In cereal category *Triticum aestivum* and *Hordeum vulgare* was cultivated by all 3 selected districts under both agroforestry systems in lower and upper elevation. However, *Chenopodium quinoa* was only in Tehri district under Oak based Agroforestry system at lower elevation. In pulses category *Phaseolus vulgaris* and *Lens culinaris* were in all 3 districts under both agroforestry system and elevation ranges. *Vigna sinensis* was found only in Rudraprayag district under oak based agroforestry system at lower elevation. Two millets crops namely *Eleusine coracana* and *Echinochloa frumentacea* was the common millet crop in both elevation and all selected site under oak and apple based agroforestry system. *Brassica campestris* was in all three study districts under both agroforestry systems at lower and upper elevation under oil seed crop category. However, *Sesamum indicum* was found only at lower elevation under Oak based Agroforestry system at selected districts. In vegetable crop category *Pisum sativum, Solanum tuberosum* and *Phaseolus vulgaris* are found majorly in all three districts covering both Agroforestry system and elevation. *Abelmoschus esculentus, Allium cepa, Brassica oleracea var-botrytis* and *Zingiber officinale* only found under Oak based Agroforestry system at lower elevation in all 3 selected districts. *Trichosanthus dioica, Lagenaria siceraria* found only at lower elevation under oak based agroforestry system., *Amaranthus viridis* was reported only under oak based agroforestry system at upper elevation. Crop diversity within agroforestry, regarded as a cornerstone of food security, is essential for sustaining agricultural systems (Sati 2012). The diverse cropping contributes significantly to maintaining the stability and resilience of agro ecosystems through multiple mechanisms. Number of crops and variety in particular sites is mainly depend on various factor like preference of growers, land holding, availability of irrigation, transportation, migration, wildlife interaction and market accessibility. Similar crop diversity was also reported in Garhwal Himalaya by Mahato et al. (2016). Kala et al. (2010) in an agroforestry of the middle Himalaya region in Tehri Garhwal observed 26 herbaceous food crop species out of them 12 crop were species, 5 cereals and 6 pulses. Crops diversity under cash crops was higher than the cereals. Maximum number of vegetable crop was found under agroforestry system in all district might be due to favorable condition for vegetable cultivation and nature of cash crop (Singh et al., 2023).

Wild vegetation makes more diversity in any agro ecosystem and helps to enhance agrobiodiversity of that region. Total 106 wild vegetations was recorded from studied sites in which 49 herbs, 19 shrubs, 13 grasses, 04 vines and 21 tree species was recorded under both agroforestry system and elevation in all 3 selected districts (Table 4). *Rubus niveus* was found in all selected district under both agroforestry systems and *Oxalis corniculata* was in all

Table 2. Existing agroforestry system in studied districts

District	Elevation	Agroforestry system	Number of Agroforestry system
Tehri Garhwal	Lower elevation (1500-2000 m)	(AS), (AH), (SP), (ASH), (HG)	05
	Upper elevation (2000-2500 m)	(AS), (AH), (SP), (ASP)	04
Rudraprayag	Lower elevation (1500-2000 m)	(AS), (AH), (SP), (HG),	04
	Upper elevation (2000-2500 m)	(AS), (AH), (SHP), (SP), Aqua culture	05
Uttarkashi	Lower elevation (1500-2000 m)	(AS), (AH), (HA), (SP),(HG), (ASP)	06
	Upper elevation (2000-2500 m)	(AS), (HA), Horti-pastoral	03

Agrisilviculture (AS), Agrihortisilviculture (AHS), Agrihorticulture (AH), HG= homegarden, SP= Silvopastoral, ASP= Agrisilvopastoral, HA= Hortiagri

Table 3. Agrobiodiversity under agroforestry system at Tehri, Rudraprayag and Uttarkashi district

Scientific name	Family	Tehri District (Agroforestry system)				Uttarkashi (Agroforestry system)				Rudraprayag (Agroforestry system)			
Crop name		Oak based		Apple based		Oak based		Apple based		Oak based		Apple based	
	Elevation	L	U	L	U	L	U	L	U	L	U	L	U
Triticum aestivum	Poaceae		√	√	√	√	√	√	√	√	√	√	√
Perilla frutescens	Lamiaceae	√	-	-	-	√	√	√	√	√	√	√	√
Zea mays	Poaceae	√	-	-	-	-	√	-	√	√	√	√	-
Fagopyrum esculentum	Polygonaceae	√	-	-	-	-	√	-	-	-	-	-	-
Hordeum vulgare	Poaceae	√	√	√	√	√	√	√	√	√	√	√	√
Amaranthus caudatus	Amaranthaceae	√	√	-	-	√	√	-	-	√	√	-	√
Chenopodium quinoa	Chenopodiaceae	√	-	-	-	-	-	-	-	-	-	-	-
Vigna sinensis	Fabaceae	-	-	-	-	-	-	-	-	√	-	-	-
Vigna umbellata	Fabaceae	√	√	-	-	√	√	√	-	√	√	-	-
Vigna mungo	Fabaceae	√	-	-	-	√	-	√	-	√	-	-	-
Phaseolus vulgaris	Fabaceae	√	√	√	√	√	√	√	√	√	√	√	√
Lens culinaris	Fabaceae	√	√	√	√	√	√	-	√	√	√	-	√
Dolichos uniflorus	Fabaceae	√	-	-	-	√	-	√	-	√	-	-	-
Cajanus cajan	Fabaceae	√	-	-	-	√	-	-	-	√	-	-	-
Eleusine coracana	Poaceae	√	√	√	-	√	√	√	√	√	√	√	√
Echinochloa frumentacea	Poaceae	√	√	-	√	√	√	-	-	√	√	-	√
Sesamum indicum	Pedaliaceae	√	-	-	-	√	-	-	-	√	-	-	-
Glycine max	Fabaceae	√	√	-	-	√	√	√	-	√	√	√	-
Brassica campestris	Brassicaceae	√	√	√	√	√	√	√	√	√	√	√	√
Abelmoschus esculentus	Malvaceae	√	-	-	-	√	-	-	-	√	-	-	-
Allium cepa	Liliaceae	√	-	-	-	√	-	-	-	√	-	-	-
Allium sativum	Liliaceae	√	√	√	√	-	√	-	√		√	√	√
Amaranthus viridis	Amaranthaceae	-	-	-	-	-	-	-	-		√	-	-
Brassica juncea	Brassicaceae	√	√	√	-	-	√	-	√	√	√	√	√
Brassica oleracea var-botrytis	Brassicaceae	√	-	-	-	√	-	-	-	√	-	-	-
Brassica oleracea var-capitata	Brassicaceae	√	√	√	-	√	√	√	-	√	-	√	√
Capsicum annum	Solanaceae	-	-	-	-	-	-	√	-	√	-	√	-
Capsicum frutescens	Solanaceae	-	-	-	-	√	√	-	-	√	-	-	-
Colocasia antiquorum	Areceae	√	-	-	-	√	-	-	-	-	√	-	-
Colocasia esculenta	*Araceae*	-	-	-	√	-	-	-	-	-	√	-	-
Coriandrum sativum	Apiaceae	√	√	-	-	-	√	√	√	-	√	√	-
Cucumis sativus	Cucurbitaceae	√	-	√	-	√	√	-	-	√	√	-	-
Cucurbita maxima	Cucurbitaceae	√	√	√	-	√	√	-	-	√	√	-	-
Curcuma longa	Zingiberaceae	√	√	-	-	-	√	-	-	√	√	-	-
Daucus carota	Apiaceae	-	-	-	-	-	-	-	-	-	√	-	-
Lagenaria siceraria	Cucurbitaceae	-	-	-	-	-	-	-	-	√	-	-	-
Luffa acutangula	Cucurbitaceae	-	-	-	-	-	-	-	-	√	-	-	-
Lycopersicon esculentum	Solanaceae	-	-	√	-	-	-	√	-	√	-	√	-
Momordica charantia	Cucurbitaceae	-	-	-	-	√	-	-	-	√	-	-	-
Pastinaca sativa	Brassicaceae	√	√	-	-	-	√	√	√	√	√	-	-
Phaseolus vulgaris	Fabaceae	√	√	√	√	-	√	√	√	√	√	√	√
Pisum sativum	Fabaceae	√	√	√	√	√	√	√	√	√	√	√	√
Solanum melongena	Solanaceae	-	-	-	-	√	√	-	-	-	-	√	-
Solanum tuberosum	Solanaceae	√	√	√	√	√	√	-	√	√	√	√	√
Spinacea oleracea	Brassicaceae	√	√	√	-	√	√	-	√	√	√	√	-
Trichosanthus dioica	Cucurbitaceae	-	-	-	-	√	-	-	-	-	-	-	-
Zingiber officinale	*Zingiberaceae*	√	-	-	-	√	-	-	-	√	-	-	-

L= Lower elevation, U= Uppper elevation, √ = presence of species, - = absence of species

Table 4. Wild vegetation in three selected districts

Scientific name	Family	Life form	Tehri District (Agroforestry system)				Uttarkashi (Agroforestry system)				Rudraprayag (Agroforestry system)			
			Oak		Apple		Oak		Apple		Oak		Apple	
			L	U	L	U	L	U	L	U	L	U	L	U
Achyranthes aspera L.	Amaranthaceae	Herb	-	√	-	-	-	√	-	-	√	√	-	-
Achyranthes bidentata Blume	Amaranthaceae	Herb	√	-	-	-	-	-	-	-	√	√	-	-
Aechmanthera gossypina	Acanthaceae	Shrub	-	-	√	√	√	-	√	-	-	-	-	-
Ageratum conyzoides	Asteraceae	Herb	√	√	-	√	-	√	√	-	√	-	-	-
Agrimonia pilosa	Agavaceae	Herb					-	√	-	√	-	-	-	-
Amaranthus viridis	Amranthaceae	Herb	√	√	-	-	-	√	-	√	√	√	√	√
Anaphalis contorta (D.Don) Hook f.	Asteraceae	Herb	-	-	-	-	-	-	-	-	-	√	-	-
Anisomeles indica (L.) Kuntze	Lamiaceae	Herb	-	-	-	-	-	-	-	-	-	√	-	-
Apluda mutica L	Poaceae	Grass	-	-	-	-	-	-	-	-	√	√	-	-
Artemisia capillaris Thunb.	Asteraceae	Herb	-	-	-	-	-	-	-	-	-	-	-	-
Artemisia nilagirica (Clarke) Pamp.	Asteraceae	Herb	-	-	-	-	-	-	-	-	-	√	-	-
Avena fatua L.	Poaceae	Grass	√	-	-	-	-	-	-	-	√	√	√	√
Avena sativa L.	Poaceae	Herb	-	-	-	-	-	-	-	-	-	-	-	-
Berberis aristata	Berberidaceae	Shrub	-	-	-	-	-	-	-	-		√		√
Bidens pilosa L.	Asteraceae	Herb	√		√	√	-	-	-	-	√	√	√	√
Campylotropis eriocarpa	Fabaceae	Shrub	-	-	-	-	-	√	-	-	-	-	-	-
Cannabis sativa	Cannabaceae	Shrub	-	-	-	-	√	-	√	-	-	√	-	√
Carissa opaca	Apocyanaceae	Shrub	-	-	-	-	√	-	-	-	-	-	-	-
Carpinus viminea			-	-	-	-	-	-	-	-	-	-	-	-
Cassia occidentalis L.	Caesalpiniaceae	Herb	-	-	-	-	-	-	-	-	-	√	√	√
Cedrus deodara	Pinaceae	Tree	-	-	-	-	-	√	-	-	-	-	-	-
Celtis australis	Ulmaceae	Tree	-	-	-	-	√	-	-	-	√	-	-	-
Centella asiatica	Apiaceae	Herb	-	√	-	-	-	√	-	√	-	√		√
Chenopodium album L.	Chenopodiaceae	Herb	√	√	√	-	-	-	-	-	√	√	√	√
Chenopodium ambrosioides	Chenopodiaceae	Herb	√	√	-	-	-	-	-	-	-	-	-	-
Cirsium wallichii DC.	Asteraceae	Herb	-	-	-	-	-	-	-	-	-	√	-	√
Citrus aurantifolia	Rutaceae	Tree	√	-	-	-	-	-	-	-	-	-	-	-
Citrus sinensis	Rutaceae	Tree	√	-	-	-	-	-	-	-	-	-	-	-
Cleome viscosa L.	Cleomaceae	Herb	√	-	-	-	-	-	-	-	√	-	√	-
Commelina benghalensis L.	Commelinaceae	Herb	√	√	-	-	-	-	-	-	-	-	-	-
Convolvulus arvensis L.	Convolvulaceae	Vine	-	√	√	√	-	-	-	-	√	√	√	-
Conyza bonariensis	Asteraceae	Herb	√	-	-	-	-	-	-	-	-	-	-	-
Cornus capitata	Cornaceae	Tree	-	√	-	-	-	-	-	-	-	-	-	-
Cuscuta reflxa	Cuscutaceae	Vine	-	-	-	-	-	-	-	-	-	√	-	-
Cynodon dactylon (L.) Pers.	Poaceae	Grass	-	√	√	√	-	-	-	-	√	√	√	√
Cyperus compressus	Cyperaceae	Grass	√	√	-	√	-	-	-	-	-	-	-	-
Cyperus rotundus	Cyperaceae	Grass	√	√	√	√	-	-	-	-	√		√	
Dactyloctenium aegypticum (L.) P. Beauv.	Poaceae	Grass	-	-	-	-	-	-	-	-	√	√	-	√

Cont...

Table 4. Wild vegetation in three selected districts

Scientific name	Family	Life form	Tehri District (Agroforestry system)				Uttarkashi (Agroforestry system)				Rudraprayag (Agroforestry system)			
			Oak		Apple		Oak		Apple		Oak		Apple	
			L	U	L	U	L	U	L	U	L	U	L	U
Datura stramonium	Solanaceae	Herb	-	-	-	-	√	-	-	-	√	-	-	√
Desmodium elegans	Fabaceae	Shrub	-	-	-	√	√	√	-	-	-	-	-	-
Dichanthium annulatum (Forsk.) Stapf	Poaceae	Grass	-	-	-	-	-	-	-	-	-	√	-	√
Digitaria sanguinalis (L.)	Poaceae	Grass	√	√	-	-	-	-	-	-	-	-	-	-
Duchesnea indica	Rosaceae	Herb	-	√	-	-	-	-	-	-	-	-	-	-
Echinochloa colona (L.) Link	Poaceae	Grass	-	-	-	-	-	-	-	-	√	√	-	-
Eleusine indica (L.) Gaertn	Poaceae	Grass	√	√	-	-	-	-	-	-	√	√	-	√
Emilia sonchifolia	Asteraceae	Herb	-	-	-	-	√	√	-	-	-	-	-	-
Eupatorium adenophorum	Asteraceae	Shrub	√	√	-	-	-	-	-	-	√	√	√	√
Euphorbia hirta	Euphorbiaceae	Herb	√	√	-	√	-	√	-	-	√	√	√	
Euphorbia prostrata Aiton	Euphorbiaceae	Herb	-	-	-	-	-	-	-	-	√	-	-	-
Ficus roxburghii	Moraceae	Tree	-	-	-	-	√	-	-	-	√	-	-	-
Fumaria indica	Fumariaceae	Herb	√	√	-	-	-	-	-	-	-	-	-	-
Galinsoga ciliate	Asteraceae	Herb	√	√	√	√	-	-	-	-	-	-	-	-
Galinsoga parviflora Cav.	Asteraceae	Herb	√	√	√	√	-	-	-	-	√	√	√	√
Galium acutum	Rubiaceae	Herb	-	-	-	-	-	-	-	-	-	-	-	-
Geranium nepalense Sweet	Geraniaceae	Herb	-	-	-	-	-	-	-	-	-	√	-	√
Grewia optiva	Tiliaceae	Tree	√	-	-	-	√	-	-	-	√	-	-	-
Himalrandia tetrasperma	Rubiaceae	Shrub	-	-	-	-	-	√	-	-	-	-	-	-
Imperata cylindrica (L.) P. Beauv.	Poaceae	Grass	-	-	-	-	-	-	-	-	-	√	-	√
Indigofera heterantha	Fabaceae	Shrub	√	-	-	-	-	-	-	-	-	-	-	-

L= Lower elevation, U= Uppper elevation, √ = presence of species, - = absence of species

selected districts except oak based agroforestry system in Tehri Garhwal. *Prunus cerasoides* was only in Oak based agroforestry system in both elevations at all 3 selected districts. *Anaphalis contorta, Anisomeles indica, Artemisia nilagirica* and *Pyracantha coccinea* was only in upper elevation under oak based agroforestry system in Rudraprayag district. However, *Zanthoxylum armatum* was recorded only at Tehri District under oak based agroforestry system in upper elevation. *Cyperus rotundus, Galinsoga ciliate, Galinsoga parviflora* and *Trifolium repens* was recorded in both elevation and Agroforestry system in Tehri Garhwal district. *Oxalis corniculata, Rubus niveus* and *Urtica dioica* was in Uttarkashi district under both agroforestry system and elevation. However, *Amaranthus viridis, Bidens pilosa, Chenopodium album, Eupatorium adenophorum* and *Oxalis corniculata* was at both elevation under apple and oak based agroforestry system in Rudraprayag district. Kala (2010) recorded that the total of 26 herbaceous foods crop species and 21 woody species that were raised by farmers in the selected villages of Uttarakhand. Thirty seven plant species available in the agro-forestry system and used for curing various ailments by traditional healers were also documented during the survey which is lower than in present study. Gopal et al. (2017) observed 53 species in agrisilviculture system at mid altitude in Garhwal Himalaya while under silvipasture system there were about 27 species of tree, shrub and grass species. Bijalwan et al. (2016), Atul and Khosla (1990) in the AH system greater number of trees were observed at mid-elevations.

The insect pollinator diversity in selected district under agroforestry system indicated 5 order of insect was reported, maximum (11) number of pollinator was from Hymenoptera order followed by Diptera and Lepidoptera and lowest pollinator in Hemiptera (Table 5). Out of total pollinator in parenthesis only 25 pollinator species was reported in Tehri District, 23 insect pollinator species in Rudraprayag district however in Uttarkashi district 17 insect pollinator species was

recorded. Among the insect pollinator Carpenter bees was found only in Uttarkashi district. Eleven insect pollinators were common among the all three district, while Coleoptera order pollinator was in all districts except *Montipora spp.in* Uttarkashi district. Keasar (2010) and Kumar et al. (2024) observed five major insect orders were with Hymenoptera contributing the highest number of pollinator species. The lower diversity in Uttarkashi may be attributed to management practices, variations in altitude, microclimatic conditions, and floral resources, which influence pollinator abundance and distribution. Common insect pollinator indicating a core group of pollinators that are well adapted to the agroforestry landscapes of the Garhwal Himalaya. Such patterns of presence and absence are likely shaped by local management practices, vegetation types, resource availability, and climatic gradients. Kumar et al. (2024) reported a similar pattern of insect pollinator diversity at their study sites, with most species belonging to the orders Coleoptera, Diptera, Lepidoptera, and Hymenoptera. However, the introduction of hybrid crop varieties has

Table 5. Pollinator's diversity in study sites under apple based agroforestry system.

Common name	Species	District		
		Tehri	Rudraprayag	Uttarkashi
Order- Hymenoptera				
Asian honey bee	*Apis cerana indica*	✓	✓	✓
Dwarf bee	*Apis florea*	✓	✓	×
European bee	*Apis mellifera*	✓	✓	✓
Solitary bee	*Andrena coitana*	✓	×	✓
The red paper wasp	*Polistes canadensis*	✓	✓	✓
Yellow jacket wasp	*Polistes sp.*	✓	✓	×
Carpenter ant	*Camponotus sp.*	✓	✓	✓
Bumble bee	*Bombus sp.*	✓	✓	✓
Asian hornet	*Vespa velutina*	✓	✓	×
Matianense sweat bee	*Lasioglossum (Evylaeus) matianense*	√	×	✓
Carpenter bees	*Xylocopa sp.*	×	×	✓
Diptera				
Green bottle fly	*Lucilia sericata*	✓	✓	×
Housefly	*Musca domestica*	✓	✓	✓
Drone fly	*Eristalis tenax*	✓	×	✓
Syrphid flies		✓	✓	✓
The marmalade hoverfly	*Episyrphus balteatus*	×	✓	✓
Blue bottle fly	*Calliphora sp.*	✓	✓	×
Coleoptera				
Asian lady beetle	*Harmonia axyridis*	✓	✓	✓
Altica (blue beetle)	*Montipora spp.*	✓	✓	×
Common Red Soldier Beetle	*Rhagonycha fulva*	✓	✓	✓
Hemiptera				
Red cotton bug	*Dysdercus koenigii*	✓	✓	×
Lepidoptera				
Cabbage white	*Pieris brassicae*	✓		×
Grass yellow	*Eurema daira*	✓	✓	✓
Common spotted flat	*Celaenorrhinus leucocera*	✓	✓	×
Tricolored pied flat	*Coladenia indrani*	✓	✓	×
Lemon enigrant	*Catopsilia pomona*	✓	✓	✓
Great black vein	*Aporia agathon*	✓	✓	✓

Note- ✓ = presence of species, x = absence of species

Table 6. Percentage of pollinators in each Order under Apple base Agroforestry system

Order	Tehri Garhwal			Rudraprayag			Uttarkashi		
	Number of pollinators order	Number of pollinator species	% of pollinator species per order	Number of pollinators order	Number of pollinator species	% of pollinator species per order	Number of pollinators order	Number of pollinator species	% of pollinator species per order
Coleoptera	3	25	12.00	3	23	13.04	2	17	11.76
Diptera	5	25	20.00	5	23	21.73	4	17	23.52
Hemiptera	1	25	4.00	1	23	4.34	0	17	0.00
Hymenoptera	10	25	40.00	8	23	34.78	8	17	47.05
Lepidoptera	6	25	24.00	6	23	26.08	3	17	17.64

disrupted the natural interactions between crops and their pollinators. In addition, the extensive use of synthetic pesticides has caused significant mortality among pollinator species, pushing some of them towards the brink of extinction.

The highest number of pollinator was from Hymenoptera and lowest from Hemiptera order for all 3 selected district (Table 6.) In District Tehri Garhwal highest percentage of pollinator species was recorded from Hymenoptera order (40%) followed by Lepidoptera (24%) order. Minimum (4%) pollinator was from Hemiptera order. Similar trend was observed in Rudraprayag district Uttarkashi district recorded maximum (47.05%) pollinator from Hymenoptera order followed by Diptera (23.52 %) order while, no pollinator was recorded from Hemiptera order. The variations suggest that while Hymenoptera consistently dominate pollination across districts, the relative contribution of other orders is influenced by local ecological and environmental conditions (Dhawan 2013, Verma et al., 2021).

CONCLUSION

The study highlights that the highest number of agroforestry systems was recorded in Uttarkashi district at lower elevations, while a unique aquaculture-based agroforestry system was identified in Rudraprayag district at higher elevations. Agrobiodiversity was richer in oak-based agroforestry systems compared to apple-based systems across all selected districts and both elevation ranges. Vegetable species diversity was highest at all study sites, indicating the favorable climate and microclimatic conditions provided by agroforestry for off-season vegetable cultivation. Among cultivated crops, the highest diversity was observed in the Fabaceae family, followed by the Cucurbitaceae. Within wild vegetation, herbs represented the dominant life form. In terms of pollinator diversity, significant pollinators in apple-based agroforestry systems belonged to the Hymenoptera order, with the highest abundance in Tehri district. Conversely, pollinators from the Hemiptera order were in very low numbers across all districts.

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Yield, Economic Returns and Biomass Carbon of Neem-Legume Agroforestry in Semi-arid Tropics of Bundelkhand

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Abstract: Agroforestry has emerged as a sustainable strategy to address the climate variability challenges in semi-arid regions. This study assessed the performance of legume crops—lentil, chickpea, broad bean, and grass pea under neem (*Azadirachta indica)* based agroforestry systems in Bundelkhand, Central India. Field experiments over two cropping seasons evaluated crop yield, biomass production, harvest index, lentil equivalent yield, economic returns, and tree growth dynamics. Results indicated that neem association did not significantly reduce crop yields, with lentil and chickpea performing best. Neem + chickpea recorded the highest biological yield (5,029 kg/ha), while neem + lentil produced the maximum lentil equivalent yield (1,447 kg/ha). Broad bean consistently showed the lowest yield potential, underlining its unsuitability in semi-arid conditions. Economic analysis revealed that neem + lentil and neem + chickpea offered maximum monetary returns, comparable with sole cropping, thereby ensuring income security. Neem growth was positively influenced by legume intercropping, with neem + chickpea recording the highest biomass increment (12.48 Mg/ha) and carbon gain (6.24 Mg C/ha). These findings suggest that neem-based agroforestry with suitable legumes enhances crop productivity, improves farm profitability, and strengthens carbon sequestration, making it a viable option for climate-resilient agriculture in Bundelkhand and similar dryland regions.

Keywords: Bundelkhand, Crop productivity, Climate resilience, Carbon sequestration, Economic returns, Legumes, Neem agroforestry

Agricultural systems worldwide are under severe threat from climate change. Rising temperatures and shifting precipitation patterns are already depressing crop yields in many regions. Studies show that global staple crop production will decline by about 4.4% for every 1°C rise in global mean temperature (Hultgren et al., 2025). The Intergovernmental Panel on Climate Change (IPCC) advocated the reduced yields of maize, wheat, and other staples in many tropical and subtropical regions, with food security particularly at risk due to rising unstable climatic conditions (IPCC 2019, IPCC 2021). Bundelkhand, a semi-arid plateau in central India receives an average annual rainfall of about 800–900 mm, with irregular patterns that leave farmers ill-prepared for sowing and often trigger drought even in “good” years. In short, climate change is amplifying existing vulnerabilities in rainfed farming systems like Bundelkhand, threatening livelihoods and food security (IPCC 2019, Hultgren et al., 2025, Singh et al., 2024). In this context, sustainable adaptation strategies are urgently needed. Agroforestry is widely recognized as a promising nature-based solution that can simultaneously mitigate and adapt to climate change (Yadav et al., 2025, Kumar et al., 2025). Meta-analyses show that a well-designed agroforestry system can raise crop yields by about 5–15%. Globally, agroforestry possesses the potential to remove 10^{15} to 10^{16} kg of CO_2 from the atmosphere over decades (Nair et al., 2011, Singh et al., 2024, Yadav et al., 2025a). Thus, agroforestry can improve farm-level climate resilience and contribute to the goals of climate change mitigation and biodiversity conservation (Nair et al., 2011, Singh et al., 2024, Yadav et al., 2024a). The region of Bundelkhand has one natural advantage that it is India's “pulse bowl”. Pulses occupy over 30% of the cropped area contributing roughly one third of agricultural output in this region. As a result, enhancing pulse yields and system stability has emerged as a local priority (Singh et al., 2024)

Neem, native semi-arid tree species, offers complementary advantages to these legumes. It is renowned for its extreme hardiness as it can tolerate very high temperatures (normal range ~10–37 °C) and can endure 7 to 8 months of dry dormancy once established. These traits make Neem an ideal candidate for Bundelkhand's environment. To add on, neem's carbon sequestration is non-trivial as recent field studies report that well grown Neem trees harbor a moderate aboveground carbon pool (25–50 Mg CO_2 eq per tree over decades) and thus act as significant carbon sinks (Harsolia et al., 2023). Neem -legume systems can be designed with flexibility either by planting Neem in wide spacing with inter-row pulses or by integrating them as boundary plantations. This layout accommodates neem light demanding nature at maturity and optimizes the use of space and sunlight (Chaudhary and Ghaley 2025). Experimental trials suggest that understory legumes perform best when introduced a few years after neem establishment, allowing

the trees to stabilize and support beneficial microhabitats (Kaur et al., 2018) and legume crops such as chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), grass pea (*Lathyrus sativus*), and broad bean (*Vicia faba*) also contribute significantly to soil fertility by fixing atmospheric nitrogen ranging from 100 to 125 kg N/ha per season through symbiotic associations with *Rhizobium* (Kumar and Sharma 2019).

Furthermore, the compatibility of neem and legumes with Bundelkhand's climatic conditions underscores the system's ecological sustainability. Neem, being drought-hardy and native to the dry tropics, and legumes, which already form a staple in local crop rotations, make this combination both viable and adaptive (Kumar et al., 2014). Evidence indicates that a Neem–legume agroforestry system could substantially improve climate resilience in Bundelkhand. This would improve soil health, tree litter and legume residues add organic matter, increase microbial activity, and recycle nutrients (N, P, K) in place (Nair et al., 2011, Kumar et al., 2025) and boosts biodiversity and ecosystem services, multi-tier vegetation supports a richer biological community and provides services such as natural pest control, pollination, and forage (Kumar et al., 2025, Yadav et al., 2024b). Additionally increases drought tolerance by moderating the field microclimate, preserving subsoil moisture, and providing alternative fodder/food sources (tree pods, leaves) during crop failures (Kumar et al., 2025). Farmers practicing agroforestry often report less variability in yields and income across drought years which is precisely the stability needed in Bundelkhand (Singh et al., 2024), This research was planned to evaluate the feasibility of the neem-legume based agroforestry system mainly in the region of Bundelkhand with objective find out the economic feasibility, carbon sequestration potential and the interaction of the components in respect to crop yield and yield contributing parameters.

MATERIAL AND METHODS

Study area: The field experiment was conducted in the semi-arid Bundelkhand region during 2021-22 and 2022-23 cropping seasons to evaluate the performance of neem-legume agroforestry systems under climate-resilient conditions. The experimental site is characterized by typical semi-arid tropical climate with erratic rainfall patterns and high temperature variations, making it suitable for evaluating drought-tolerant agroforestry interventions.

Management practices and experimental design: The experiment was laid out in a randomized block design with three replications following standard experimental protocols. Eight treatment combinations were evaluated, comprising four neem-based agroforestry systems (Neem + Lentil, Neem + Chickpea, Neem + Broad bean, Neem + Grass pea) and four sole legume cropping systems as controls (Lentil, Chickpea, Broad bean, Grass pea) to assess the comparative performance under different cropping scenarios. Neem (*Azadirachta indica*) saplings were planted at 5 m x 6 m spacing in August 2019 to ensure adequate light penetration for understory legume crops while maximizing tree growth potential. Tree establishment was done prior to the commencement of crop seasons to allow proper root development and minimize initial competition effects. Legume species [Lentil (*Lens culinaris*), Chickpea (*Cicer arietinum*), Broad bean (*Vicia faba*), and Grass pea (*Lathyrus sativus*)] were selected based on their adaptability to semi-arid conditions and nutritional significance. Crops has been sown by following the agronomic practices as prescribed by Wery et al. (1988) for (*Lens culinaris*), Dhull (2022) for (*Vicia faba*), Singh & Diwakar (1995) for (*Cicer arietinum*) and Campbell (1997) for *Lathyrus sativus.* The experiment has been established in the randomized complete block design (RCBD) with eight treatments and four replications.

Legume yield estimation: The physiological maturity legume grain yield (kg/ha) was measured as fresh weight of grains after proper cleaning and moisture adjustment to 14% moisture content, stover yield (kg/ha) recorded as dry weight of above-ground vegetative parts excluding grains, biological yield (kg/ha) calculated as sum of grain yield and stover yield, and harvest index was determined as ratio of grain yield to biological yield. Tree measurements were recorded in 2021 and 2023 to assess growth increment, including height measured using measuring pole, diameter at breast height (DBH) recorded at 1.37 m height using the tree caliper. Above-ground biomass calculated using following equation equations

$$AGB = 0.65 \times (DBH^2) H$$

Below-ground biomass estimated as 25% of above-ground biomass following standard conversion factors (Mokany et al., 2006). Total biomass computed as sum of above-ground and below-ground biomass, and biomass carbon calculated assuming 50% carbon content in dry biomass.

Economic analysis: Economic analysis was performed using prevailing market prices and minimum support price of rabi 2021-22 and rabi 2022-23 with grain returns calculated as grain yield multiplied by minimum support price per kg, stover returns determined as stover yield multiplied by fodder price per kg, and total returns computed as sum of grain, stover returns and returns from neem wood considering the biomass as fuel wood. To compare different legume crops on a common basis, Lentil Equivalent Yield (LEY) was

calculated as LEY = (Yield of test crop × Price of test crop) / Price of lentil, which was applied for Lentil Equivalent Grain Yield (LEGY), Lentil Equivalent Stover Yield (LESY), and Lentil Equivalent Biological Yield (LEBY) following standard economic evaluation procedures.

Statistical analysis: Data collected from both the years were subjected to Analysis of Variance (ANOVA) using OPSTAT Software (Sheoran et al., 1998) to test treatment effects, with Critical Difference (C.D.) calculated at 5% level of significance for comparison of treatment means and Standard Error of Mean (SE(m)) computed for all parameters (Moore et al., 2023). Combined analysis across both years was performed to derive mean values and assess treatment consistency, with all data presented as mean ± standard error and statistical significance determined at $P < 0.05$ level (Moore et al., 2023). Quality control measures included maintenance of uniform plot sizes across all treatments, border rows to minimize edge effects, proper randomization in each replication, standardized measurement protocols, and regular monitoring throughout the experimental period.

RESULTS AND DISCUSSION

Yield analysis: The two-year study revealed significant variations in grain yield among different neem (Age 3 years) legume agroforestry combinations compared to sole cropping systems (Table 1). Among the agroforestry treatments, neem + lentil recorded the highest mean grain yield (1,447 kg/ha), which was statistically comparable to sole lentil cultivation (1,456 kg/ha), indicating minimal yield penalty under agroforestry. Kumar et al. (2018) also reported that well-managed agroforestry systems can maintain crop yields within 90-95% of sole cropping systems through optimized tree-crop spacing and management practices. Similarly, neem + chickpea combination yielded 1,369 kg/ha compared to 1,381 kg/ha in sole chickpea, representing only a 0.9% reduction, which corroborates the findings of Sharma and Singh (2020) where legume crops show better adaptation to partial shade conditions in agroforestry systems due to their nitrogen-fixing capability. Broad bean showed the lowest grain yields in both agroforestry (720 kg/ha) and sole cropping (728 kg/ha) systems, which is consistent with the inherent lower yield potential of these crops in semi-arid conditions as reported by Patel et al. (2019). Grass pea demonstrated intermediate performance with 1,288 kg/ha under neem association versus 1,300 kg/ha in sole cropping, indicating good compatibility with tree-based systems.

The biological yield patterns followed similar trends, with neem + chickpea recording the highest biological yield (5,029 kg/ha) followed by neem + lentil (4,895 kg/ha). Dhyani et al. (2021) also observed that leguminous crops under neem-based agroforestry maintain higher biomass production due to improved soil fertility through nitrogen fixation and reduced water stress.

Harvest Index: The harvest index values ranged from 0.27 to 0.31 across treatments, with grass pea showing the highest harvest index (0.31) under agroforestry, suggesting efficient partitioning of photosynthates to economic yield despite light competition. Rao and Nair (2017) in their studies on legume performance under tree canopies observed similar trend (Table 2).

Lentil equivalent yield (LEGY): The lentil equivalent yield analysis provided a comprehensive comparison of different legume crops on a common economic basis (Table 3). Neem + lentil naturally showed the highest lentil equivalent grain yield (1,447 kg/ha), followed by neem + chickpea (1,217

Table 1. Grain yield (kg/ha), stover yield (kg/ha) and biological yield (kg/ha) under neem-legume based agroforestry

Treatments	Grain yield (kg/ha)			Stover yield (kg/ha)			Biological yield (kg/ha)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
Neem + Lentil	1567	1327	1448	3733	3163	3448	5301	4491	4896
Neem + Chick pea	1477	1261	1369	3950	3370	3660	5427	4631	5029
Neem + Broad bean	779	660	720	2097	1783	1940	2876	2443	2660
Neem + Grass pea	1443	1133	1288	3603	2833	3218	5047	3967	4507
Lentil	1568	1344	1456	3405	2922	3164	4973	4267	4620
Chick pea	1478	1283	1381	3867	3361	3614	5345	4644	4995
Broad bean	786	670	729	2170	1848	2009	2957	2519	2738
Grass pea	1455	1144	1299	3597	2828	3212	5052	3972	4512
CD (p=0.05)	28.3	52.4	30.4	50.4	160.4	97.2	40.1	205.5	111.4
CD (Y x T) (p=0.05)	-	-	42.96	-	-	118.76	-	-	150.1
CV %	1.82	4.03	2.13	1.30	4.93	2.72	0.74	4.52	2.23

kg/ha), which is in accordance with the market price differential between these crops.

Economic returns: The economic returns analysis revealed that neem + lentil generated the highest total returns (₹1,54,703/ha), closely followed by Neem + Chick pea (₹1,42,466/ha) compared other treatments indicating that agroforestry can be more profitable while providing additional ecological benefits (Table 4). Similar results were also recorded for net returns and. neem + lentil generated the highest net returns (₹92,228/ha), closely followed by Neem + Chick pea (₹85,991/ha).

This finding resonates with the economic evaluation conducted by Singh et al. (2019), who reported that properly designed agroforestry systems can achieve 85-95% of sole crop profitability while providing long-term tree-based income and environmental services. Deshmukh et al. (2025) also reported higher return in lentil-Melia dubia based agroforestry system then sole crop of lentil.

Neem + chickpea recorded total returns of ₹76,705/ha compared to ₹77,281/ha in sole chickpea, representing a marginal difference that can be compensated by the additional benefits from neem trees including timber, non-timber forest products, and ecosystem services. These results are consistent with the comprehensive economic analysis by Kumar and Yadav (2021), who demonstrated that short-term apparent losses in agroforestry systems are often offset by diversified income streams and risk reduction. The

Table 2. Harvest Index under neem-legume based agroforestry

Treatments	Harvest Index		
	2021-22	2022-23	Pooled
Neem + Lentil	0.30	0.29	0.29
Neem + Chick pea	0.27	0.27	0.27
Neem + Broad bean	0.27	0.27	0.27
Neem + Grass pea	0.29	0.28	0.28
Lentil	0.31	0.31	0.31
Chick pea	0.28	0.27	0.27
Broad bean	0.27	0.26	0.27
Grass pea	0.29	0.28	0.29
CD (p=0.05)	0.01	0.01	0.01
CD (Y x T) (p=0.05)	-	-	NS
CV %	2.51	2.56	2.15

Table 3. Lentil equivalent grain yield (LEGY), lentil equivalent stover yield (LESY) and Lentil equivalent biological yield (LEBY) (kg/ha) under neem-legume based agroforestry

Treatment	LEGY (kg/ha)	LESY (kg/ha)	LEBY (kg/ha)
Neem + Lentil	1,447±6.5	4,895±22.2	3,447±16.0
Neem + Chick pea	1,217±6.1	4,877±28.4	3,660±22.7
Neem + Broad bean	492±2.4	2,431±19.8	1,939±20.9
Neem + Grass pea	472±3.5	3,690±43.4	3,218±42.8
Lentil	1,456±14.4	4,620±52.9	3,163±50.5
Chick pea	1,227±14.1	4,841±63.8	3,613±53.3
Broad bean	498±9.0	2,506±24.9	2,009±19.6
Grass pea	476±3.6	3,688±33.3	3,212±31.0
CD (p=0.05)	24.3	107.6	97.1
CV %	2.27	2.72	2.32

Table 4. Economic analysis of neem-legume based agroforestry

Treatment	Cost of cultivation (₹/ha)	Gross returns (Crop+tree) (₹/ha)	Net returns (₹/ha)	Benefit: cost ratio
Neem + Lentil	62476	154703	92228	2.5
Neem + Chick pea	56375	142466	85991	2.5
Neem + Broad bean	35465	82771	47296	2.3
Neem + Grass pea	32615	74683	42208	2.3
Lentil	57280	90546	33366	1.6
Chick pea	51160	77281	26101	1.5
Broad bean	30370	31878	1698	1.1
Grass pea	27140	31806	4626	1.2

Benefit: cost ratio was higher (>2.0) in agroforestry systems compared to sole cropping of the legume crops.

relatively lower returns from broad bean and grass pea systems (₹31,458/ha and ₹31,561/ha respectively under agroforestry) highlight the importance of species selection and market orientation in agroforestry planning, as emphasized by Pandey et al. (2020) in their multi-location studies across semi-arid regions of India.

Tree growth and biomass accumulation: The neem trees (during 2nd to 4th year age) showed remarkable growth performance over the two-year study period, with significant differences among treatments in terms of biomass accumulation and carbon sequestration potential (Table 5). Trees associated with chickpea recorded the highest mean height (5.43 m) and DBH (13.51 cm) by 2023, followed by those grown with broad bean (5.67 m height, 12.94 cm DBH), indicating positive tree-crop interactions with certain leguminous species. This differential growth pattern aligns with the research findings of Verma et al. (2018), where legume crops enhance tree growth through improved soil nitrogen status and favorable rhizospheric conditions. The total biomass accumulation varied from 11.30 Mg/ha (neem + grass pea) to 15.79 Mg/ha (neem + chickpea), with corresponding carbon storage ranging from 5.65 Mg C/ha to 7.89 Mg C/ha, respectively. These carbon sequestration rates are comparable to those reported by Chaturvedi et al. (2020) for young neem plantations in semi-arid regions. The increment data showed that neem trees associated with chickpea showed the highest biomass increment (12.48 Mg/ha) over the two-year period, followed by broad bean (11.82 Mg/ha) and lentil (9.15 Mg/ha), suggesting that these legume crops provide more favorable growing conditions for neem trees. This finding corroborates the observations of Ahlawat *et al.* (2019) concluded that nitrogen-fixing crops enhance tree growth in agroforestry systems through improved soil fertility and organic matter addition. The corresponding carbon

Table 5. Height (m), diameter at breast height (cm), biomass (Mg/ha) and biomass carbon (Mg/ha) in neem trees in agroforestry system

Treatment	Height (m)			DBH (cm)		
	2021	2023	Increment	2021	2023	Increment
Neem + Lentil	3.74	5.13	1.39	5.31	11.84	6.53
Neem + Chick pea	4.17	5.43	1.26	6.64	13.51	6.87
Neem + Broad bean	4.09	5.67	1.57	6.30	12.94	6.64
Neem + Grass pea	3.95	4.91	0.95	5.69	11.93	6.24
CD (p=0.05)	NS	NS	NS	NS	NS	NS
SE(m)	0.11	0.21	0.21	0.36	0.58	0.42

Biomass (Mg/ha)

	Aboveground Biomass (Mg/ha)			Belowground Biomass (Mg/ha)			Total Biomass (Mg/ha)		
	Year 2021	Year 2023	Increment	Year 2021	Year 2023	Increment	Year 2021	Year 2023	Increment
Neem + Lentil	1.83	9.16	7.32	0.46	2.29	1.82	2.29	11.45	9.15
Neem + Chick pea	2.64	12.63	9.98	0.66	3.16	2.49	3.30	15.79	12.48
Neem + Broad bean	2.48	11.94	9.45	0.62	2.98	2.36	3.10	14.93	11.82
Neem + Grass pea	2.14	9.04	6.90	0.53	2.26	1.72	2.68	11.30	8.62
CD (p=0.05)	0.58	NS	NS	0.14	NS	NS	0.73	NS	NS
SE (m)	0.19	1.17	1.09	0.05	0.29	0.27	0.24	1.47	1.36

Biomass Carbon (Mg/ha)

	Aboveground Biomass C (Mg/ha)			Belowground Biomass C (Mg/ha)			Total Biomass C (Mg/ha)		
	2021	2023	Increment	2021	2023	Increment	2021	2023	Increment
Neem + Lentil	0.92	4.58	3.66	0.22	1.14	0.91	1.15	5.73	4.58
Neem + Chick pea	1.32	6.32	4.99	0.33	1.58	1.24	1.65	7.89	6.24
Neem + Broad bean	1.24	5.97	4.73	0.31	1.49	1.18	1.55	7.46	5.91
Neem + Grass pea	1.07	4.52	3.44	0.27	1.13	0.86	1.33	5.65	4.31
CD (p=0.05)	0.29	NS	NS	0.07	NS	NS	0.36	NS	NS
SE (m)	0.09	0.59	0.54	0.02	0.15	0.14	0.12	0.73	0.68

increment ranged from 4.31 Mg C/ha (neem + grass pea) to 6.24 Mg C/ha (neem + chickpea), indicating substantial carbon sequestration potential of these systems. These carbon accumulation rates are consistent with the global estimates provided by Nair et al. (2021) for tropical agroforestry systems, which range from 3-10 Mg C/ha/year depending on species composition and management practices.

Comparative analysis and system performance: The overall system performance evaluation indicates that neem-legume agroforestry can serve as a viable alternative to sole cropping in semi-arid regions, providing multiple benefits including sustained crop yields, additional tree products, enhanced carbon sequestration, and improved system resilience. The minimal yield penalties observed in this study (0.6% for lentil, 0.9% for chickpea, 1.1% for broad bean, and 0.9% for grass pea) are well within the acceptable limits for agroforestry adoption, as suggested by the comprehensive review of Garrity (2018) on global agroforestry performance. The combination of neem + lentil emerged as the most promising system, offering optimal balance between crop productivity, tree growth, and economic returns, which supports the recommendations of Dhyani and Brandis (2019) for promoting legume-based agroforestry in dryland agriculture. The differential performance of various legume species under neem association can be attributed to their varying shade tolerance, nitrogen fixation capacity, and complementary resource use patterns. Chickpea and lentil showed better adaptation to partial shade conditions, which is consistent with the physiological studies conducted by Malhotra et al. (2020) on legume crops under reduced light conditions. The superior tree growth observed with chickpea and broad bean associations suggests positive feedback mechanisms through enhanced nutrient cycling and soil improvement, as documented by Singh and Kumar (2021) in their long-term agroforestry studies. These findings collectively demonstrate that neem-legume agroforestry systems can contribute significantly to climate change mitigation through carbon sequestration while maintaining agricultural productivity and farmer livelihoods in semi-arid regions.

CONCLUSION

The present investigation on neem-legume agroforestry systems in the semi-arid Bundelkhand region demonstrates the potential of integrating tree and legume crops for sustainable agricultural production under challenging climatic conditions. The study conclusively establishes that neem-based agroforestry systems can maintain crop productivity levels comparable to sole cropping while providing additional ecological and economic benefits. Among the tested combinations, neem + lentil emerged as the most promising system, achieving grain yields of 1,447 kg/ha with minimal reduction (0.6%) compared to sole lentil cultivation, while generating equivalent economic net returns of ₹92,228/ha. Similarly, the neem + chickpea system demonstrated remarkable performance with only 0.9% yield reduction and substantial tree biomass accumulation of 15.79 Mg/ha.

The carbon sequestration potential of these systems ranges from 5.65 to 7.89 Mg C/ha within just two years, highlighting their significant contribution to climate change mitigation strategies. The superior tree growth observed with leguminous crops, particularly chickpea and broad bean, indicates beneficial tree-crop interactions through enhanced soil fertility and nitrogen availability. The harvest index values (0.27-0.31) across treatments suggest efficient resource utilization and adaptation of legume crops to partial shade conditions under tree canopies. The lentil equivalent yield analysis further confirms the economic viability of these systems, with neem + lentil and neem + chickpea showing superior performance in terms of monetary returns per unit area.

Based on the comprehensive evaluation of yield performance, economic returns, and environmental benefits, neem-legume agroforestry systems represent a viable climate-resilient agricultural strategy for semi-arid regions. The study recommends the adoption of neem + lentil and neem + chickpea combinations for farmers seeking to diversify their income sources while contributing to carbon sequestration and ecosystem services. These findings provide scientific evidence for policy makers and extension agencies to promote agroforestry as an effective adaptation strategy in dryland agriculture. Future research should focus on long-term studies to evaluate the sustainability of these systems and their impact on soil health, water conservation, and overall farm productivity over extended periods. The successful implementation of such systems could significantly enhance the resilience of agricultural communities in semi-arid tropics while addressing global climate change challenges through sustainable land use practices.

AUTHOR'S CONTRIBUTIONS

Conceptualization of the research (RP Yadav, MJ Dobriyal, A Kale); design of the experiment (P Tiwari, A Kale); contribution of the experimental material (RP Yadav, AK Pandey); execution of the field experiment and data collection (G Gupta, R Choudhary, SK Gautam); analysis of the data and interpretation (RP Yadav, T Tamrakar, R Choudhary); preparation of the manuscript (T Tamrakar, V Shekhawat, Y Mallesh, G Gupta).

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Tree Growth and Soil Nutrient Dynamics under Mahogany (*Swietenia macrophylla* G. King) and Wheat (*Triticum aestivum* L.) based Agri-silvicultural System

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***Abstract*:** The present study investigated the tree growth and soil nutrient dynamics under mahogany-based agri-silvicultural system in West Bengal. The objective was to access its role in promoting ecological functions and sustainable land use. The mahogany trees exhibited a robust and steady growth, with mean tree height increment of 8.6 m to 10.5 m, and DBH from 11.4 cm to 12.9 cm and a sustainable increase in volume (54.05%), highlighting the species' suitability to intercropping. Compared to open-field cultivation, the agroforestry system significantly improved soil health. While the open system showed a decline in key soil physico-chemical properties at both depths, the agroforestry system demonstrated a marked improvement in these parameters with organic carbon increasing from 0.76 to 0.80%, nitrogen from 176.61 to 179.76 kg ha^{-1}, phosphorous from 11.12 to 11.34 kg ha^{-1} and potassium from 163.80 to 166.88 kg ha^{-1}. A trend of soil acidification was observed in both systems, being more prominent in the agroforestry plots where pH reduced from 5.31 to 4.90. The findings indicate that a mahogany-based agri-silvicultural system provides a more sustainable soil management approach by enhancing organic matter and nutrient retention than conventional open-field cultivation.

Keywords: Agroforestry, Agri-silviculture, Growth, Soil status, Tree growth, Intercropping

Agroforestry is an integrated land-use system that is distinct from the separate practices of agriculture and forestry (Mohsin and Mohsin 2021). It is an age-old practice developed to preserve soil fertility with the primary goal being maximization of the beneficial interactions to create a more varied and sustainable productive systems (Thakur et al., 2018). Based on at least 40 years of data collected worldwide, agroforestry has demonstrated a strong impact in enhancing soil quality as a sustainable land management technique (Dollinger and Jose 2018, Prajapati et al., 2020). It is, however, challenging to generalize impact of agroforestry system on soil fertility, as it depends on the species and management strategy used (Misra 2011, Prajapati et al., 2022b). In many agroforestry systems, the nutrient demand is distributed between perennial trees and seasonal crops. Since trees contribute to nutrient inputs without harvesting root biomass, the overall nutrient export is often lower, which can lead to net nutrient gain over time. Trees contribute organic matter to the soil system in a variety of ways, including through their roots, litterfall, or root exudates in the rhizosphere, offering a variety of ecosystem services, along with other environmental benefits in both rural and urban settings (Bertin et al., 2003). The selection of fast-growing multipurpose trees that have proven to show minimal impact on agricultural yield for an agroforestry system can contribute to sustainability and aid in its diversification to get greater advantages per unit area without degrading the agro-ecosystem (Thakur et al., 2011). Tree species contribute a significant amount of litter fall, which, as it decomposes, impacts the soil physical, chemical, and biological properties, thereby enhancing the growth and yield of wheat crops (Singh and Sharma 2007, Sharma and Sah 2020, Prajapati et al., 2022a).

Mahogany (*Swietenia macrophylla* G. King) is a semi-evergreen, light hardwood tree belonging to the family Meliaceae. It was initially brought to India from the West Indies in 1795 and planted in the Royal Botanical Garden in Calcutta (Troup 1921), while *S. macrophylla* and *S. mahagony* were planted in South Malabar in 1872 (Kumar et al., 2016). The tree has been heavily exploited since the end of the seventeenth century throughout much of its native range and is classified as vulnerable species by the IUCN Red List of Threatened Species (IUCN 2017). Despite being protected, mahogany wood's commercial importance and ecological sensitivity raise serious questions about how to ensure its protection and sustainable use (Grogan et al., 2002). Mahogany is often used to restore damaged agricultural lands because of its high commercial value, and it is currently one of the most popular forestry species for reforestation and commercial plantings (Rodriguez-Morelos et al., 2014). The rapid growth of mahogany makes it one of the most demanded and prized timbers in the humid regions of southern India (Kumar et al., 2015). Because of its strong and deep roots, it minimizes soil erosion, making it an

excellent choice for degraded regions and field boundary plantations (Craig and Elevitch 2000). In regions with inadequate space for the extensive cultivation of mahogany trees, integrating shade-loving crops with these trees can have both fiscal and ecological benefits (Nasielski et al., 2015).

In the northern Indian states of Uttarakhand, Punjab, Haryana, Uttar Pradesh, and Bihar, as well as some of the central and eastern states like Madhya Pradesh, Chhattisgarh, and West Bengal, wheat is frequently intercropped with Poplar, *Eucalyptus*, and other fast-growing tree species during the rabi season *i.e.*, November-April (Bisht 2018). Although there have been several studies on agroforestry in the northern and central states, studies in West Bengal and some North-eastern states are limited with less knowledge about the suitability of intercropping species. Keeping in view the significance of Mahogany species as an emerging agroforestry and land restoration tree, the experiment aims to investigate the effect of mahogany and wheat based Agri-silvicultural system on the tree growth parameters and soil nutrient status.

MATERIAL AND METHODS

Location and site conditions: The study was conducted at Uttar Banga Krishi Vishwavidyalaya, Pundibari, Cooch Behar, West Bengal. The site is located in the plains of the Terai zone at an elevation of 43 m above the mean sea level with coordinates of 26˚45'.8"N latitude and 89˚ 23'16.7"E longitude. The region has a subtropical, humid climate. The minimum and maximum temperatures range from 8.3 ℃ in January to 36 ℃ in August. The average annual rainfall is high, up to 3200 mm, primarily occurring between June and September, during the pre-monsoon and monsoon seasons. The relative humidity ranges from 45.00% (February) to 94.00% (August), making the area warm and humid except for a brief winter period from December to February.

Experimental design: The experiment was laid out in a randomized block design with two primary systems: an open system and a mahogany-based agri-silvicultural system. Two wheat cultivars (*Triticum aestivum* L.), cvs. BHU-35 and Var. DBW-187 were grown as the agricultural component during the rabi season and a thirteen-year-old mahogany tree plantation was used as a silvicultural component.

Tree growth parameters: Various growth attributes were recorded from four rows of mahogany trees, each consisting of 15 trees within the agri-silvicultural system and was considered as a treatment to evaluate intra-system variation. The trees were maintained at a spacing of 5 m x 2.5 m during the experimental period from 2022 to 2024. Data for height, diameter at breast height (DBH), crown length and crown width were recorded before sowing and after the harvest of wheat cultivars. Crown length was measured from the tree's tip to the lowest live branch using a graduated bamboo pole. Crown was measured in two directions (North-South and East-West) and calculated by following Assman (1970) and Chaturvedi and Khanna (1982). Diameter at Breast Height (DBH) was recorded at a standard height of 1.37 m from the ground level. Tree volume was estimated using the cylindrical volume formula: $V= \pi r^2 h$, where 'r' is the average radius (derived from DBH) and 'h' is the average bole height.

Soil attributes: Under open and agri-silvicultural systems soil organic carbon, pH, available nitrogen, phosphorus, potassium and bulk density was estimated. Soil samples were collected from two depths: 0-15 cm and 15-30 cm, both before sowing and after harvesting the wheat crop.

Statistical analysis: For tree growth assessment, observations were recorded and the mean values were subjected to statistical analysis. For soil physico-chemical analysis, the data were analyzed following a factorial randomized block design considering three factors: system, soil depth, and time.

RESULTS AND DISCUSSION

Mahogany tree growth: The growth performance of mahogany trees over a span of three consecutive years under an agri-silvicultural system, including height, diameter at breast height (DBH), and volume was observed (Table 1).

The mean tree height increased significantly from 8.6 m in Year 1 to 10.5 m in year 3, with an average increment of 1.8 m. The consistent growth indicates good site adaptability and vigor of mahogany under prevailing environmental conditions. The DBH also showed a steady rise from 11.4 cm in year 1 to 12.9 cm in year 3, with a mean increment of 1.4 cm, which was statistically significant. Volume increment ranged from 0.0362 to 0.0634 m^3, with a mean increment of 0.0482 m^3, corresponding to a significant average percentage increase of 54.05%. Notably, even with modest increase in height and DBH, mahogany showed substantial volume increase, highlighting its high timber yield potential. Comparable growth attributes were reported by Murmu (2022) where gamhar and mango trees intercropped with seasonal crops such as groundnut and mustard exhibited superior tree growth compared to sole plantations. Similar trends were observed by Kumar (2019) in poplar varieties intercropped with wheat. Kumar et al. (2025) found that different fertilizer levels enhanced both mahogany growth and intercropped rhizome yield in Kerala, suggesting efficient nutrient sharing and the benefits of optimized fertilization in mahogany-based agroforestry systems.

The mean crown length showed a significant increase

over the study period, rising from 3.5 m in Year 1 to 3.9 m in year 2 and 5.0 m in year 3 (Table 2). This reflects an average increment of 1.5 m. The differences in crown length between the years were statistically significant between year 1 and 2 and between year 2 and 3. These findings reflect a steady yearly rise in crown expansion, suggesting healthy canopy growth. Individually, Row 3 had the longest crown length (5.4 m in Year 3), while Row 1 had the shortest (3.2 m in Year 1).

The mean crown width also showed a steady increase, rising from 2.9 m in Year 1 to 3.5 m in year 2 and 4.9 m in year 3, with an average increment of 2.0 m. In contrast to crown length, the variations between years were not significant at the 5% (NS), which implies that even though crown width increased, the variability within the data was high. Individually, Row 1 had the largest crown width (5.3 m in Year 3), while row 3 had the smallest (2.6 m in Year 1). Both crown length and width showed an increasing trend with tree age. Based on these results, crown length appears to be a more accurate measure of early canopy development than crown width under these conditions. Similar results of positive implications *i.e.* better tree growth and productivity as a result of intercropping fodder grasses (Prajapati et al., 2020, 2023) and medicinal plants (Thakur et al., 2018) with *Melia dubia* by earlier workers further confirm the present study inferences.

Soil nutrient status: The physico-chemical properties of the soil at two depths (0-15 cm and 15-30 cm) under open system and agroforestry system (AFS) indicate that at 0-15 cm depth the organic carbon (%) in agroforestry system showed an increasing trend from 0.76% before sowing to 0.80% after harvest (Table 3). Similarly, at 15-30 cm depth, OC was higher in AFS (0.62-0.65%) compared to the open system (0.50-0.48%). The OC content at 0-15 cm depth was 0.62% in the open system and slightly lowered (0.59%) after harvest. The differences between systems were statistically significant indicating that agroforestry practices improved soil organic carbon through increased litterfall, root turnover, and organic matter assimilation. In both soil depths, AFS had a consistently higher nitrogen content. The available N rose from 176.61 to 179.76 kg ha^{-1} at 0-15 cm in AFS as compared to 170.10-167.37 kg ha^{-1} in open system. AFS soils maintained greater values (148.68-151.20 kg ha^{-1}) at a depth of 15-30 cm compared to open soils (144.90-140.28 kg ha^{-1}). Agroforestry improved nitrogen retention, as evidenced by the statistically significant differences which may be due to better organic matter cycling.

Available phosphorous was greater in AFS soils across both depths. At 0-15 cm available phosphorus levels increased from 11.12 and 11.34 kg ha^{-1} in AFS whereas in the open system it decreased from 10.02 and 9.43 kg ha^{-1}. Additionally, AFS had a higher phosphorus increment (8.29-8.65 kg ha^{-1}) at a depth of 15-30 cm compared to open plots (8.12-7.28 kg ha^{-1}). The improvement under AFS was substantial, despite the smaller range of change, indicating that the incorporation of trees may have increased phosphorus availability. Potassium

Table 1. Growth parameters of mahogany tree during the experimental period 2022-2024

	Height (m)				DBH (cm)				Volume (m^3)	
	Year 1	Year 2	Year 3	Increment	Year 1	Year 2	Year 3	Increment	Volume Increment	Volume Increment (%)
Row 1	9.0	9.3	10.9	1.9	13.1	13.8	14.6	1.6	0.0634	52.88
Row 2	8.5	9.1	10.3	1.8	12.4	13.1	13.7	1.3	0.0494	48.53
Row 3	8.6	9.2	10.5	1.9	10.3	11.2	11.8	1.5	0.0439	61.86
Row 4	8.6	9.3	10.2	1.7	10.1	10.6	11.4	1.3	0.0362	52.94
Mean	8.6	9.2	10.5	1.8	11.4	12.2	12.9	1.4	0.0482	54.05
CD (p=0.05)	0.27	0.38	0.20	0.17	1.15	1.46	0.88	1.07	0.15	1.32

Table 2. Increment in crown dimensions of mahogany tree during the experimental period 2022-2024

	Crown length (m)				Crown width (m)			
	Year 1	Year 2	Year 3	Increment	Year 1	Year 2	Year 3	Increment
Row1	3.2	3.4	4.7	1.5	3.3	3.7	5.3	1.7
Row2	3.5	3.9	4.9	1.4	2.8	3.5	4.9	2.1
Row3	3.9	4.5	5.4	1.5	2.6	3.3	5.2	2.3
Row4	3.4	3.8	4.9	1.6	3.0	3.5	4.7	1.7
Mean	3.5	3.9	5.0	1.5	2.9	3.5	4.9	2.0
CD (p=0.05)	0.09	0.54	0.50	NS	0.28	NS	NS	NS

Table 3. Soil physico-chemical properties before sowing and after harvest of wheat under open system and mahogany based agroforestry system

System	OC (%)		N (Kg/ha)		P (Kg/ha)		K (Kg/ha)		pH		BD (g cm^{-3})	
	BS	AH	BS	AH	BS	AH	BS	AH	BS	AH	BS	AH
Open (0-15 cm)	0.62	0.59	170.10	167.37	10.02	9.43	144.48	141.4	6.55	6.26	1.26	1.24
AFS (0-15 cm)	0.76	0.80	176.61	179.76	11.12	11.34	163.80	166.88	5.31	4.90	1.30	1.28
CD (p=0.05)	0.09	0.09	19.81	12.64	0.67	0.45	12.60	11.54	1.24	0.62	0.30	0.22
CV	5.60	2.14	3.25	2.07	1.82	1.23	3.59	3.36	5.96	3.18	6.17	5.12
Open (15-30 cm)	0.50	0.48	144.90	140.28	8.12	7.28	110.04	106.68	6.83	6.37	1.45	1.38
AFS (15-30 cm)	0.62	0.65	148.68	151.2	8.29	8.65	132.24	135.99	5.64	5.23	1.47	1.41
CD (p=0.05)	0.03	0.08	2.71	2.39	1.48	1.11	5.26	3.89	0.66	0.41	0.05	0.11
CV	6.02	6.63	0.52	0.47	5.15	3.97	1.90	1.44	3.02	2.03	1.11	2.33

BS-Before sowing; AH-After harvest; AFS-Agroforestry system

displayed greater values under agroforestry system compared to open system. The available potassium increased from 163.80-166.88 kg ha^{-1} under AFS, and lowered from 144.48 and 141.40 kg ha^{-1} under open system at 0 to 15 cm. The statistical significance of the differences confirmed that AFS practices increase K availability

The pH of the soil decreased noticeably at both depths under AFS as compared to the open system. The pH reduced from 6.55-6.26 in the open system to 5.31-4.90 under AFS at 0-15 cm and from 6.83-6.37 to 5.64-5.23 at 15-30 cm, suggesting a tendency toward acidity in agroforestry systems, which could be explained by the breakdown of organic matter. The nutrient availability was better under AFS despite reduced pH, demonstrating the beneficial contribution of trees towards soil fertility. The bulk density was marginally greater (1.30-1.28 g cm^{-3} at 0-15 cm and 1.47-1.41 g cm^{-3} at 15-30 cm) than under the open system (1.26-1.24 g cm^{-3} and 1.45-1.38 g cm^{-3}, respectively). The tendency indicates that tree-based systems may enhance compaction because of larger root biomass and organic inputs, even if the differences were not statistically significant. Similar to the present study, Kanwal (2022) reported enhanced organic carbon levels and greater water-holding capacity in the top soil (0-15 cm) under agroforestry practice. Sarkar et al. (2022) also observed that *Simarouba glauca* and *Anthocephalus cadamba* based agroforestry improved soil micronutrients through litter fall and deep root cycling indicating greater sustainability than conventional farming.

CONCLUSION

This study demonstrates that the mahogany-based agri-silvicultural system is a viable and beneficial land use strategy. The mahogany trees exhibited robust growth across all measured parameters, with a particularly substantial increase in volume, highlighting their significant potential for timber production. The study revealed significant differences in soil nutrient dynamics between the open and agroforestry systems. Compared to the open system, the mahogany-based agri-silvicultural system significantly enhanced the soil fertility by increasing key parameters including organic carbon, nitrogen, phosphorous, and potassium at both soil depths. Although a slight decrease in soil pH and a marginal increase in bulk density was observed, these were outweighed by the substantial improvements in overall soil nutrient status. The research highlights how tree-based systems can improve soil health by contributing organic matter, enhancing nutrient cycling and boosting biological activity. These findings underscore the dual benefits of mahogany-based agroforestry system: providing an economically viable timber crop while sustainably improving soil quality for agricultural production.

AUTHOR'S CONTRIBUTIONS

Gurung T conceptualized the study, conducted fieldwork and prepared the manuscript. Ghosh A assisted in statistical analysis and data interpretation Dey A N, Chakravarty S, Mitra B and Das S reviewed the manuscript.

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Effect of Spacing and Banana Pseudo stem-Based Nutrients on Cowpea Yield under Agroforestry

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Abstract: The present investigation was carried out to check the effect of various spacings and foliar sprays of Novel (banana pseudo stem based organic liquid nutrients) on growth and yield of cowpea (*Vigna ungiculata* L.) under mango-based agroforestry system during 2021 and 2022 at Navsari Agricultural University, Navsari, India. The trial was framed with eight treatment combinations of two factors *viz*., two levels of spacing and four levels of foliar spray of banana pseudo stem based organic liquid nutrients under mango orchard and open condition. The closer spacing (S_1: 30 cm x 30 cm) recorded significantly maximum plant height of cowpea at harvest. However, the highest f collar diameter, number of branches per plant, number of clusters per plant, yield per plant, plot and hectare were observed with spacing 45 cm x 45 cm as compared to 30 cm x 30 cm under mango-based agroforestry system as well as in open condition. Among various foliar application of novel fertilizers, Novel plus containing banana pseudo stem based organic liquid nutrients + botanical pesticides @ 1 % recorded significantly maximum cowpea growth parameters (plant height, collar diameter and number of branches per plant) as well as yield parameters (number of clusters per plant, and yield per hectare).

Keywords: Spacing, Foliar Spray, Novel, Cowpea, Agroforestry

In developing country like India, demand for food and nutrition is continuously increasing with raising population which creates pressure and challenges for agriculture. It is difficult to meet food and nutritional goals as the already limited agricultural is rapidly being diverted to other developmental activities. Therefore, diversification of land use systems with agroforestry is a necessary strategy to meet these challenges by compatible intercrops with perennial fruit crops for higher yield returns. Fruit-based agroforestry systems have been emerging in almost all the region of India on the basis of either planting of trees, pastures, arable crops *etc*. in existing fruit orchards or *vice versa* (Bhusara et al., 2016, Kumar and Chaturvedi 2017, Thakur et al., 2017). Integration of annual crops with fruit trees yields multiple outputs that ensure production and income generation in a sustainable manner (Verma and Thakur 2010, 2011, Awasthi 2018,). Among the fruit trees in the tropics *Mangifera indica* L., enjoys a dominant position both in terms of diversity and extent and farmers take intercrops in the early stage of mango orchards. Vegetables are one of the essential nutrient suppliers and can be easily integrated with fruit trees or forestry plantation or any other agroforestry systems in early stages. The cowpea is an annual herbaceous legume and can be grown under partially shade.

Due to increased inclination towards organic or natural farming is being advocated to produce chemical free vegetable, pulses grains fruits *etc*. Further health-related issues and promotion of organic and natural farming in India, use of organic fertilizers in vegetable production is increasing by researchers and farmers for quality production. Organic fertilizers are naturally available mineral sources that contain moderate amount of essential plant nutrients (Shaji et al., 2021). Novel, Novel Prime and Novel Plus [a product developed under National Agricultural Innovation Project (NAIP), Navsari Agricultural University, Navsari, are an enriched sap of banana pseudo stem contains essential plant nutrients and naturally occurring plant growth enhancers like cytokinin, NAA, GA_3, macro and micro elements with botanical fungicide and pesticide property. The study was conducted with a view to generate the information regarding tree-crop interaction with use of organic fertilizers on cowpea under commercial fruit tree canopies.

MATERIAL AND METHODS

Experimental site: This study was conducted in February-June during 2021 and 2022 at Navsari Agricultural University, Navsari, geographically situated at latitude of 20° 57' N and longitude of 72° 54' E and at an altitude of about 9 m above the mean sea level. Climate of the area is sub-humid with average annual rainfall of 1500-1700 mm. The soil of experimental site was moderately drained clayey soils classified as “Deep Black Soil” predominated with montmorillonite clay mineral by its origin and medium in fertility (Kumar et al., 2020).

Experimental design and treatments: The experiment was laid out in randomized block design with factorial concept with three replications and eight treatment combinations of two different factors. i) spacing with two levels *viz*., 30 cm x 30 cm and 45 cm x 45 cm and ii) foliar spray of novel organic liquid fertilizers with four levels *viz*., F_1: control (No spray), F_2: Novel @ 1 % (banana pseudo stem based organic liquid nutrients), F_3: Novel prime @ 1 % (banana pseudo stem based organic liquid nutrients + botanical fungicide) and F_4: Novel plus @ 1 % (banana pseudo stem based organic liquid nutrients + botanical pesticides). The experiment was carried out under 10 years old mango orchard in which mango trees were planted at 9 m x 9 m spacing in open field condition. AVCP-1 (Anand Vegetable Cowpea) variety of Cowpea (*V. ungiculata* L.) was selected for present study. The crop was raised as per the recommended package of practices.

Novel, novel plus and novel prime organic liquid fertilizers were procured in 100 per cent concentration. The required concentrations of solutions were prepared in water at the time of application. First foliar spray of novel fertilizers was carried out after the initiation of flowering and second foliar spray was applied after 15 days of first spray according to treatments in each plot under mango and in open condition. The green pods for vegetable purpose were harvested manually by plucking when they were tender and at marketable size and continued over a considerably long period of cowpea. The data pertaining to various growth parameters of cowpea were recorded at the end of experiment. The yield parameters of cowpea were recorded at each picking and then total of all picking was averaged out.

RESULTS AND DISCUSSION

Cowpea growth: The data on growth parameters (plant height, collar diameter and number of branches per plant) of cowpea variety AVCP – 1 as influenced by spacing and foliar spray of novel organic liquid fertilizers under mango-based agroforestry system and open condition was recorded (Table 1). Effect of spacing on plant height, collar diameter and number of branches per plant at harvest of cowpea was significant under mango based agroforestry system and in open condition. The maximum plant height (47.40 cm,), minimum collar diameter (11.94 mm) and number of branches per plant (7.48) were registered in closer spacing (S_1: 30 cm x 30 cm) under mango-based agroforestry system. The minimum plant height (41.04 cm), maximum collar diameter (14.05 mm) and number of branches per plant (8.13) were registered in wider spacing (S_2: 45 cm x 45 cm). Moreover, in open condition, maximum plant height (51.40 cm), minimum collar diameter (14.42 mm) and numberof branches per plant (9.09) were noted in closer spacing (S_1: 30 cm x 30 cm) whereas minimum plant height (45.29 cm), maximum collar diameter (16.51 mm) and number of branches per plant (9.94) were observed in S_2: 45 cm x 45 cm (Table 1).

Significantly higher plant height was recorded in closer spacing as compared wider spacing. This might be due to more competition for available resources especially for sunlight (Singh et al., 2013). Furthermore, stems are shaded from light resulting in accumulation of auxin (a growth hormone) that stimulates cell division and elongation of internodes, thereby increasing the height. In widely spaced

Table 1. Growth parameters of cowpea as influenced by spacing and foliar spray of novel organic liquid fertilizers under mango-based agroforestry system and open condition

Treatments	Plant height (cm)		Collar diameter (mm)		No. of branches per plant	
	AF	Open	AF	Open	AF	Open
S: Spacing (S1: 30 cm x 30 cm; S2: 45 cm x 45 cm)						
S_1	47.40	51.40	11.94	14.42	7.48	9.09
S_2	41.04	45.29	14.05	16.51	8.13	9.94
CD (p=0.05)	1.66	1.78	0.62	0.59	0.39	0.40
F: Foliar spray of Novel organic liquid fertilizers (F1: Control; F2: Novel (1 %); F3: Novel prime (1%); F4: Novel plus (1%)						
F_1	41.20	45.14	11.72	14.14	6.78	8.77
F_2	44.17	48.28	12.96	15.22	7.90	9.42
F_3	45.45	49.57	13.53	15.70	8.13	9.70
F_4	46.06	50.41	13.77	16.81	8.43	10.16
CD (p=0.05)	2.34	2.52	0.88	0.84	0.55	0.56
CD (p=0.05) S×F	NS	NS	NS	NS	NS	NS
C.V. %	6.33	6.23	8.12	6.50	8.45	7.04

AF= Agroforestry system (mango-cowpea); NS=Non-significant

plants, auxin destruction by light occurs resulting in plants being shorter in height (Alemayehu et al., 2015). The results are in line with findings of Malami and Sama'ila (2012), Rima Taipodia and Nabam (2013) and Adigun et al. (2014) in cowpea; Alemayehu et al. (2015) in haricot bean (*P. vulgaris*), Katara et al. (2022) in kabuli chickpea (*Cicer arietinum*) and Chaudhari et al. (2023) in green gram (*V. radiata*).

However, collar diameter and number of branches per plant were maximum in wider spacing. This might be because of less light competition encourage lateral growth and suppress apical growth resulting in excessive branching. The results are analogues with earlier findings of Ndor et al., (2012) in cowpea; Mureithi et al., (2012) in french bean (*P. vulgaris*), Murade et al. (2014) in urd bean (*V. mungo*), Alemayehu et al. (2015) in haricot bean (*P. vulgaris*), Kalsariya et al. (2017) and Chaudhari et al., (2023) in green gram (*V. radiata*). The plant height, collar diameter and numberof branches per plant at harvest of cowpea was significantly influenced by foliar application various novel organic liquid fertilizers. Maximum plant height (46.06 cm), collar diameter (13.77 mm) and number of branches per plant (8.43) were in F_4: Novel plus (1 %) under mango-based agroforestry system. However, in case of open condition, maximum plant height (50.41 cm), collar diameter (16.81 mm) and no. of branches per plant (10.16) were obtained with F_4: Novel plus (1 %).

Significantly higher plant height, collar diameter and number of branches were recorded in plants receiving foliar spray of various novel organic liquid nutrients. The increment in plant height and higher number of branches might be due to the fostered meristematic activities which was catalyzed by growth regulator contains in novel organic liquid nutrients *viz*., gibberellic acid, naphthalene acetic acid and cytokinin which leads to enhance cell division and cell elongation (Desai et al., 2016). This might also be due ample amount of nitrogen content in liquid nutrient which enhances cell division, cell elongation as well as formation of more tissues resulting in luxuriant vegetative growth which leads to increase in plant height (Krishna Chotaliya et al., 2018). Moreover, nitrogen also increases the cation exchange capacity of plant roots which makes them efficient in absorbing other nutrients ions like phosphorus, potassium *etc*. which helps to terminate vegetative growth (Champaneri et al., 2021). Similar results are also reported by Kavitha et al. (2019), Savaliya (2020) and Rabade et al. (2022) in cowpea; Mandre et al. (2020) in black gram (*V. mungo*), Champaneri et al. (2021) in Indian bean (*Lablab purpureus*), Selvarani et al. (2021) and Akshika Bhawariya et al. (2022) in cluster bean (*C. tetragonoloba*).

The plant height and other growth parameter were higher in open condition as compared to under mango-based agroforestry system it might be due to sufficient amount of light available to cowpea plants in open condition while, under mango less availability of light suppressed the growth of plants. The interaction effect of different spacing (S) and foliar spray of Novel organic liquid fertilizers (F); S x F was not significant for all growth parameters of cowpea at harvest under mango-based agroforestry system and in open condition.

Cowpea yield: Yield parameters *viz*., number of clusters per plant, yield per plant (g) and yield (t ha^{-1}) of cowpea variety AVCP – 1 as affected by spacing and foliar spray of Novel organic liquid fertilizers under mango-based agroforestry system and open condition was recorded during the (Table 2). Effect of spacing on number of clusters per plant, yield per plant and yield per hectare was found significant under mango-based agroforestry system and in open condition. The maximum number of clusters per plant (23.88), yield per plant (147.77 g), and yield per hectare (3.65 t) was in spacing S_2: 45 cm x 45 cm under mango-based agroforestry system.

In open condition, number of clusters per plant (27.22), yield per plant (182.44 g), and total yield (9.01 t ha^{-1}) were observed in spacing S_2: 45 cm x 45 cm as compared to S_1: 30 x 30 cm (Table 2). Significantly the number of clusters per plant, and total yield of cowpea were observed in wider spacing in comparison to closer spacing. This might be due to less competition for light, moisture and nutrients associated with wider spacing and thereby having an edge in producing more reproductive parts when compared to higher plant population density (Karukonda et al., 2020). Higher number of clusters per plant observed might be due to higher number of branches per plant at wider plant spacing as higher number of branches benefits to more sites for flower development, which attributed to a prolific pod production (Alemayehu et al., 2015). These results are in conformity with the earlier findings of Malami and Sama'ila (2012), Prabhamani et al. (2019) and Karukonda et al. (2020) in cowpea; Singh et al. (2013) in faba bean (*V. faba*), Alemayehu et al. (2015) in haricot bean (*P. vulgaris*) and Katara et al. (2022) in kabuli chickpea (*C. arietinum*). The foliar spray of Novel organic liquid fertilizers significantly affects the yield parameters of cowpea under mango-based agroforestry system and in open condition.

Under mango-based agroforestry system, number of clusters per plant (21.15), yield per plant (117.11g), and total yield (3.90 t ha^{-1}) was recorded with F_4: Novel plus (1 %) (Table 2). In open condition, number of clusters per plant (25.22) and total yield (9.82 t ha^{-1}) was in F_4: Novel plus (1 %). The significantly the higher number of clusters per plant, yield per plant and total yield of cowpea were in plants receiving foliar spray of various novel organic liquid

Table 2. Yield parameters of cowpea as influenced by spacing and foliar spray of novel organic liquid fertilizers under mango-based agroforestry system and open condition

Treatments	No. of clusters per plant		Yield per plant (g)		Yield (t ha^{-1})	
	AF	Open	AF	Open	AF	Open
S: Spacing (S1: 30 cm x 30 cm; S2: 45 cm x 45 cm)						
S_1	14.21	17.26	55.69	75.98	3.09	8.44
S_2	23.88	27.22	147.77	182.44	3.65	9.01
CD (p=0.05)	1.82	2.26	6.61	5.20	0.19	0.37
F: Foliar spray of Novel organic liquid fertilizers (F1: Control; F2: Novel (1 %); F3: Novel prime (1 %); F4: Novel plus (1 %)						
F_1	15.43	18.41	84.71	112.71	2.86	7.56
F_2	19.44	21.70	96.75	123.09	3.18	8.30
F_3	20.17	23.64	108.33	136.51	3.54	9.22
F_4	21.15	25.22	117.11	144.52	3.90	9.82
CD (p=0.05)	3.13	3.20	9.34	7.35	0.28	0.53
CD (p=0.05) S×F	NS	NS	13.21	10.40	NS	NS
C.V. %	13.61	17.21	10.98	6.81	9.76	7.24

AF= Agroforestry system (mango-cowpea); NS=Non-significant

fertilizers. The increase in numbers of pods and yield might be due to a reason of supply of more nutrients at critical stage (*i.e*., flowering and fruit setting) as various novel organic liquid fertilizers contain macro and micro nutrients. It also improves photosynthetic activity which ultimately enhanced utilization of photosynthates and increased allocation of photosynthates towards the economic part.

Moreover, higher pod yield might be due to vigorous vegetative growth with accelerated photosynthetic activities thereby increasing the supply of carbohydrates to the plants (Selvarani et al., 2021). The spraying of water-soluble nutrients increase uptake of nutrients and water along with easy availability of nutrients, resulting in more photosynthesis and enhanced food accumulation in edible parts. These findings are supported by work of Kavitha et al. (2019), Fernando and Brintha Karunarathna (2020), Savaliya (2020), Mandaliya (2021) and Sakpal et al. (2021) in cowpea; Meena et al. (2017) in urd bean (*V. mungo*), Mandre et al. (2020) in black gram (*V. mungo*), Champaneri et al. (2021) in Indian bean (*Lablab purpureus*), Selvarani et al. (2021) in cluster bean (*C. tetragonoloba*) and Hiremath et al. (2023) in chickpea (*C. arietinum*).

Further, significantly the higher yield of cowpea was produced in open condition as compared to mango-based agroforestry system. The lower yield under more shaded conditions was probably due to poor photosynthetic capacity of plants as they are not receiving proper sunlight under tree canopies. These findings are supported by work of Kaushik et al. (2014), Sharma et al. (2017), Miah et al. (2018), Rahman et al. (2018), Kona et al. (2020), Bony et al. (2021) and Islam et al. (2021).

The interaction effect of different spacing (S) and foliar spray of Novel organic liquid fertilizers (F) was remained non-significant for all yield parameters of cowpea except yield per plant in pooled analysis under mango-based agroforestry system and in open condition. Significantly maximum yield per plant (168.75 and 202.06 g $plant^{-1}$) was produced by S_2F_4 which was on same bar with S_2F_3 (160.45 and 192.68g $plant^{-1}$). However, the minimum yield per plant was in S_1F_1 (49.65 and 64.47 g $plant^{-1}$) respectively under mango-based agroforestry system and in open condition.

CONCLUSION

Slight reduction in growth and yield parameters of cowpea was observed under mango-based agroforestry system as compared to open growing condition. Growing of cowpea in open condition resulted in significant increase in various growth as well as yield parameters as compared to mango-cowpea agroforestry system. Between two spacing, wider spacing of 45 cm x 45 cm registered overall maximum values of growth and yield parameters of cowpea. Among foliar application of various novel fertilizers, overall highest values of growth and yield parameters of cowpea was registered in foliar application of Novel plus @ 1 % (banana pseudo stem based organic liquid nutrients + botanical pesticides) in both growing conditions.

AUTHOR'S CONTRIBUTION

Mehfuza Patel- Research implementation, data collection; M. B. Tandel- Planning, management, and writing of manuscript; S. M. Patel – trial management; M. K. Desai – Data analysis; M. P. Ahir – Data collection and grouping; Y. A.

Garde – Statistical analysis and interpretation.

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Agroforestry as Scientific Tool for Promoting Sustainable Livelihood in Rural Communities: A Review

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Abstract: Agroforestry, the integrated cultivation of trees and shrubs alongside crops and livestock, has emerged as a scientifically grounded and multifunctional land-use system that supports sustainable rural livelihoods. This review explores the scientific foundations and socio-economic impacts of agroforestry, highlighting its role in soil fertility enhancement, climate change mitigation, water management, and biodiversity conservation. It also emphasizes innovative approaches such as silvi-medicinal systems, geospatial monitoring tools, and participatory methods that empower rural communities. Having several benefits, agroforestry faces challenges also including limited financial support, insecure land tenure, and inadequate extension services. Addressing these issues through education, capacity building, and policy support can ensure the successful adoption of agroforestry as a climate-resilient and economically viable strategy for sustainable rural development Agroforestry contributes significantly to carbon sequestration, biodiversity conservation, and sustainable resource management. Through a synthesis of empirical evidence and case studies, the study highlights agroforestry's transformative potential when scientifically informed and locally adapted. It reinforces agroforestry as a strategic tool for advancing rural development and achieving long-term sustainability in alignment with global development goals.

Keywords: Agroforestry, Climate change mitigation, Carbon sequestration, Biodiversity conservation, Rural development, Sustainability

Traditionally, people raised trees, crops, and animals together on the same land to meet family needs through mixed farming. Agroforestry is a collective term for land use systems, practices, or technologies that combine woody perennials with agricultural crops and/or animals in the same piece of land, either in some form of spatial and temporal sequence. Agroforestry is a land-use system that offers deliberate retention and incorporation of trees or other woody perennials in crop-animal production fields to get maximum return from the resultant ecological and economic interactions. The National Agroforestry Policy (2014) describes agroforestry as a combination of land-use systems which collectively combines trees and shrubs on farmlands and rural landscapes with/without livestock to improve productivity, profitability, diversity, and ecosystem sustainability. Agroforestry is deeply intertwined with scientific principles, as it is based on understanding the interactions between trees, crops, livestock, and the environment. Various researchers, scientists explore how these components interact at various levels (biological, ecological, social, and economic) to improve sustainability, productivity, and resilience in agricultural systems (Pancholi et al., 2023). Agroforestry is a scientifically improved practice to the farmers to expand the ecological, economic, environmental as well as social status of the community as a whole (Roghan et al., 2024). In keeping the exclusivity and sustainability of agroforestry system, management practices have played an important task. Supervision of the agroforestry system is complex because of the diverse mixed species as compared to monoculture (Manna et al., 2018). Agroforestry contributes in a way to enhance carbon sequestration, soil fertility, water management, climate change mitigation, and biodiversity conservation (Thakur et al., 2011, Bhusara et al., 2016, Thakur et al., 2017a, Kumar et al., 2020, Kumar et al., 2025). Integrating traditional knowledge with innovative scientific techniques, agroforestry offers multifaceted strategy that supports food security, income diversification, and climate resilience, especially for smallholder farmers in low- and middle-income countries (Kumar et al., 2023).

The aim of this review is to synthesize empirical and scientific research on agroforestry's role in enhancing rural livelihoods. We discuss ecological and economic mechanisms, innovative scientific techniques, socio-environmental outcomes, and policy implications - particularly for smallholder farmers in low- and middle-income countries.

MATERIAL AND METHODS

The article primarily based on a comprehensive review about the agroforestry system that enhance livelihood benefits in rural area by integrating traditional practices of farming with different scientific techniques. This review collectively analyzed different information from rich source of relevant literature spanning 26 years to get a vivid depiction of agroforestry and its contribution towards rural livelihood

RESULTS AND DISCUSSION

Agroforestry as Scientific Approach for Sustainable Rural Development

Soil fertility enhancement: Trees play a crucial scientific role in promoting rural livelihoods by enhancing soil fertility through the addition of organic matter, their leaf litter, root decomposition, and biomass from pruning contribute significantly to soil organic carbon content, which improves soil structure, nutrient availability, soil health through enhanced flora and fauna and overall agricultural productivity (Aldeen et al., 2013, Rachel et al., 2012, Singh et al., 2010, Sharma et al., 2019, Prajapati et al., 2022a,b). It also minimizes soil erosion (Table 1), improve soil quality, vegetative cover, land productivity and lift the farmer's level of living through sustained farm productivity (Chakraborty et al., 2015, Dissanayaka et al., 2024).

Study in the central Punjab, India revealed that integration of poplar and wheat agroforestry system in the winter season and green gram in the summer season increases the net soil organic carbon, there was an increase of 0.36 per cent in the sole crop in agriculture soil whereas 0.66 per cent increase was in the agroforestry soil and same addition increases with tree age (Gupta et al., 2013). Yadav et al. (2019) and Solanki et al., (2015) also observed in their study that these leaf litters or organic matter have high carbon content, which further increase porosity and soil's water holding capacity that enhances overall microbial biodiversity and soil quality. Similar observations were found by Sharma et al. (2017), where organic carbon content in soil was more and decreases as the distance from trees increases. Prajapati et al. (2022a, b) also reported enhanced soil biota under agroforestry systems (*Melia dubia*+ *Sorghum bicolor* x *Sorghum bicolor* var. *Sudanese/* hybrid Napier) as compared to sole cropping (sole tree or sole grass).

Climate change mitigation: Agroforestry systems and their

Table 1. Impact of agroforestry system on degraded land

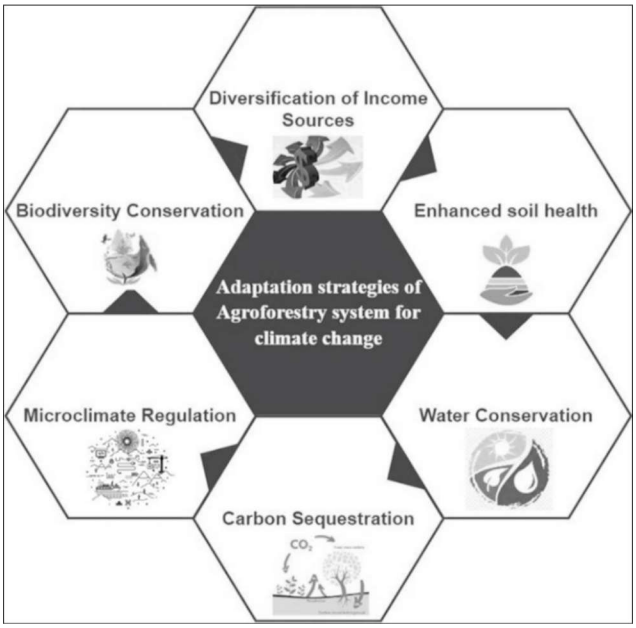
Type of degraded land	Location	Agroforestry system	Impact	Reference
Degraded sloping land	North-East India	Hedgerow cropping	Reduced soil loss and runoff by 94% and 78%, respectively	Saha et al. (2012)
	Dehradun	Silvipasture system	No soil loss with an annual return of about Rs. 4,000 ha^{-1} $year^{-1}$ from commercial grass alone besides additional returns from Eucalyptus.	Sharda and Venkateswarlu (2007)
	Shivalik hills	Horti-pasture system	*Emblica officinalis* + *Chrysopogon fulvus* Horti-pasture system saved water and soil by 4.9–30.7 cm and 862–2,818 kg ha^{-1}	Prasad et al. (2012)
	Karnataka	Ley farming (Vegetative barriers)	*Cenchrus ciliaris* and *Cymbopogon martini* reduced the runoff by 38% and soil loss by 16%	Ramajayam et al. (2007)
	Kashmir	Silvi-agriculture	Reduced scorching heat and the same time reduced soil erosion, besides increased crop production	Mughal and Makaya (2000)
Gullied and ravine lands	Gujarat	Agri-horticulture system with soil moisture conservation practices	They revealed that sapota with trenches and bench terraces reduced runoff by 16%–34% and soil loss by 15%–25%	Kumar et al. (2020)
	Gujarat	Agroforestry system of cowpea + castor + sapota	Reduced total soil loss and runoff by 37.7 and 19.1% and system productivity increased by 81.9% compared to sole tree plantation	Jinger et al. (2022)
	Uttar Pradesh	Agri-horticulture system	Recorded higher yield of Ber, pearl millet, wheat and fuel wood	Prakash et al. (2011)
	Rajasthan	Alley cropping	Higher yield, land equivalent ratio and soil organic carbon were recorded in *Leucaena*-based alley-cropping systems	Dhyani et al. (2007)
Shifting cultivation land	North-East India	Multipurpose tree plantation (fast- growing nitrogen-fixing trees) in fallows	Reduction in bulk density by 15.9% and erosion ratio by 39.5%, and increase in SOC by 96.2%, aggregate stability by 24.0%, porosity by 10.9%, and available soil moisture by 33.2%	Saha et al. (2012)
	Odisha	Alley cropping	The runoff and soil loss was reduced by 23%–32% and 49%–52%, respectively	Adhikary et al. (2017)
	East India	*Gliricidia sepium* hedgerow and grass filter strip	The runoff and soil loss was reduced by 32 and 35%, respectively	Lenka et al. (2012)

Source: Jinger et al. (2023)

services can be used as strategies for climate change mitigation as indicated in Figure 1.

Agroforestry has developed as a key approach to increasing climate resilience by integrating agriculture and forestry to create synergistic advantages (Mbow et al., 2014). Implementation of agro-forestry practices has larger potential to increase carbon sequestration of mainly agroforestry dominated lands than monocrop agriculture (Lee and Jose 2003, Nair 2003, Morgan et al., 2010, Panwar et al., 2022) (Table 2). Trees are capable of storing about 50-60% of carbon in the above-ground biomass on the other hand pasture grasses store only 10% above-ground, (Houghton and Hackler 2000, Sharrow and Ismail 2004). In agroforestry systems, trees and shrubs act as carbon sinks, absorbing carbon dioxide and storing it in their biomass and soil (Thakur et al., 2011, Bhusara et al., 2016, Handa et al., 2020).

Agroforestry is more effective than sole cropping in sequestering CO_2 and improving soil quality, tree-crop diversification boosts carbon sequestration and supports



Source: Barman et al. (2024)

Fig. 1. Agroforestry system for climate change

Table 2. Carbon sequestration through agroforestry in different regions of the country

Agro-climatic zones	Agroforestry system	Carbon sequestration potential (Mg C ha^{-1} $year^{-1}$)	References
Central Plateau & Hill Region	Agri-silviculture (*Acacia* + greengram-mustard)	3.70	Newaj et al. (2008)
West Coast Plains & Ghats Region	Agri-silvi-horticulture (*Artocarpus heterophyllus* + *Acacia auriculiformis* + black pepper)	9.90	Kunhamu et al. (2012)
		11.3	
Eastern Plateau & Hills Region	Agri-silviculture (*Albizia procera* + wheat)	5.70	Newaj et al. (2012)
Upper Gangetic Plains Region	Agri-silviculture (*Dalbergia sisso* + mustard)	2.83	Newaj et al. (2012)
Lower Gangetic Plains Region	Agri-silviculture (*Eucalyptus tereticornis* + rice-wheat)	10.7	Sirohi and Bnagrawa (2017)
Southern Plateau and Hills Region	Silvipasture system (*Leucaena leucocephala* + *Gliricidia sepium Stylosanthes hamata*)	23.2	Handa et al. (2019)
East Coast plains & Hills region	Horti-silviculture *(Acacia mangium* + pineapple)	5.51	Handa et al. (2019)
The Island Regions	Horti-pasture (*Cocos nucifera* + *Calliandra calothyrsus*)	3.50	Joy et al. (2019)
Western Plateau & Hills Region	Agri-silviculture (*Ailanthus excelsa* + cowpea-mustard)	9.64	Handa et al. (2019, 2020)
Western Himalayan Region	Agri-horticulture (*Prunus armeniaca* + *Ocimum sanctum*)	1.80	Handa et al. (2020)
	(*Prunus persica* + *Ocimum sanctum*)	2.0	
Western Dry Region	Silvipasture system (*Ailanthus* + *Cenchrus ciliaris/ Panicum antidotale*)	9.64	Handa et al. (2020)
Eastern Himalayan Region	Silvi-pasture (*Morus alba* + *Setaria anceps* grass)	1.55	Handa et al. (2020)
Middle Gangetic Plains Region	Agri-silviculture (*Tectona grandis* + sorghum/groundnut)	2.32	Handa et al. (2020)
Trans-Gangetic plains Region	Agri-silviculture (*Populus deltoides* + wheat/potato/turmeric)	9.12	Chavan et al. (2022)
Gujarat Plains & Hills Regions	Silvo-aromatic (*Melia dubia* + lemon grass)	20–25	Jinger et al. (2022)

Source: Jinger et al. (2023)

both climate change mitigation and adaptation (Aggarwal and Kumar 2020). Climate changes become more challenging day by day and the key solution is to increase the forest and tree cover by practicing agroforestry system with increasing resilience of the farming system by the sole crop adopters of the farmers (Dhyani 2014). Agroforestry systems play an important role in moderating the microclimate. Carbon sequestration stores carbon component from atmosphere and mitigates greenhouse gas emissions, which is a chief element of Climate-Smart Agriculture (Riyadh et al., 2021). Agroforestry sequesters up to 30% more carbon than monoculture farming, simultaneously mitigate climate change and enhance soil health (Fahad et al., 2022).

Water management and climate adaptation: Trees act as natural reservoirs, soaking up excess rain and releasing water stored within them during droughts, hence mitigating both flood and drought risks (Dubashi 2025). Unlike in annual systems where the land lies bare for extended periods, agroforestry systems with perennial tree components can make use of the water remaining in the soil after harvest and the rainfall received outside the crop season (Table 3). Secondly, agroforests rise the productivity of rain water by seizing a larger proportion of the annual rainfall by reducing the runoff and by using the water deposited in deep layers. Thirdly, the changes in microclimate (lower air temperature, windspeed and saturation deficit of crops) decrease the evaporative demand and make more water available for transpiration (Rao et al., 2007). The trees also tend to develop or redirect their roots to the upper soil layers, if water recharge below the root zone is infrequent as it occurs in low rainfall years and in the absence of plant existing nutrients (Rao et al., 2004). Agroforestry systems increase water holding capacity by promoting soil structure, organic matter levels, and decreasing surface runoff (Fahad et al., 2022). It was also observed that soils are not capable of holding sufficient moisture as a consequence of lower litter content in the field (Islam et al., 2016). Therefore, combination of trees with crops are preferable.

Biodiversity conservation: Agroforestry systems enhance species richness owing to its varied structure and composition, resources and services (Fig. 2) which is devoid in monoculture systems. Its integration into agricultural practices offers a sustainable pathway to maintain and enhance biodiversity (Thakur et al., 2005, Thakur et al.,

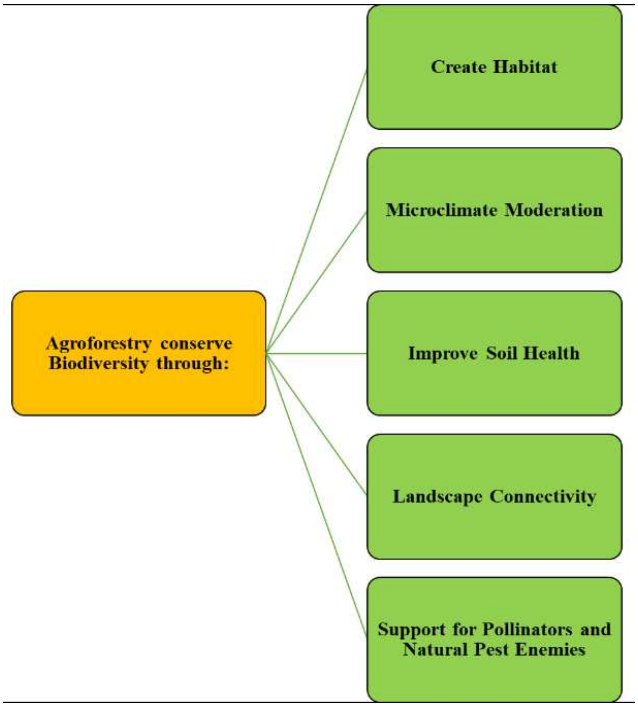


Fig. 2. Role of Agroforestry to conserve biodiversity

Table 3. Water use efficiency and transpiration loss of different tree species

Name of species	Water use	Transpiration loss	References
Acacia nilotica	1,248 mm year^{-1}	–	Khanzada et al. (1998)
Prunus armenica	–	1.5–2.37 L day^{-1}	Barradas et al. (2005)
Populus euphratica	–	2.0 mm day^{-1}	Khamzina et al. (2006)
Acacia tortilis		2.63 m mol.m^{-2} s^{-1}	Akram et al. (2008)
Punica granatum	1,255–3,671 L year^{-1}	–	Bhantana and Lazarovitch (2010)
Eucalyptus grandis	13,184–77,031 kg ha^{-1} day^{-1}	–	Kallarackal (2010)
Dalbergia sissoo		2.67–3.28 m mol. m^{-2} s^{-1}	Prasath et al. (2014)
Azadirechta indica		2.88 ± 0.2 gm leaf^{-1} h^{-1}	Pagare et al. (2014)
Eucalyptus tereticornis	–	0.28–4.0 mm day^{-1}	Venkatraman and Ashwath (2016)
Acacia mangium	–	0.45–4.0 mm day^{-1}	Venkatraman and Ashwath (2016)
Pongamia pinnata	–	0.1–2.64 mm day^{-1}	Venkatraman and Ashwath (2016)

Source: Jinger et al. (2023)

2017a, Udawatta et al., 2019). One of the purposes of agroforestry tree domestication is improvement of stability and productivity of agro-ecosystems by expanding on-farm tree species composition (presence and abundance). Diversification and strengthening of land use through domestication of agroforestry trees is one of the three pillars of the research of the World Agroforestry Centre (Kindt and Lengkeek 1999, ICRAF 2000). Agroforestry permits for co-occurrence of numerous species, minimizes pest infestation, and ensures the protection of threatened plant and animal species, eventually enhancing ecosystem resilience to environmental changes (John et al., 2024). Agroforestry is distinctively suited to deliver eco-agriculture solutions that successfully combine purposes for increased food security and biodiversity conservation (Atta-Krah et al., 2004, Garrity 2004, McNeely 2004, Simons and Leakey 2004). Agroforestry reduces the degradation of protected areas, by increasing biodiversity within working landscapes, and/or introducing different trees species in farming systems (Garrity 2004, Thakur et al., 2004).

Agroforestry for rural livelihood security: Agroforestry plays a vital role in providing abundant income streams for the farming households or farm manager (Fig. 3) and simultaneously fulfilling daily needs of people, such as fodder, fuel-wood, and dietary supplements from fruit–trees, highlights its multiple benefits to rural livelihoods (Jose et al., 2004, Thakur et al., 2015, Tiwari et al., 2017).

Forests and tree-based agricultural systems contribute providing both the facility of direct and indirect ecosystem services which is reflected by greater access to livelihood capitals (Arnold et al., 2011, Bansal et al., 2021).

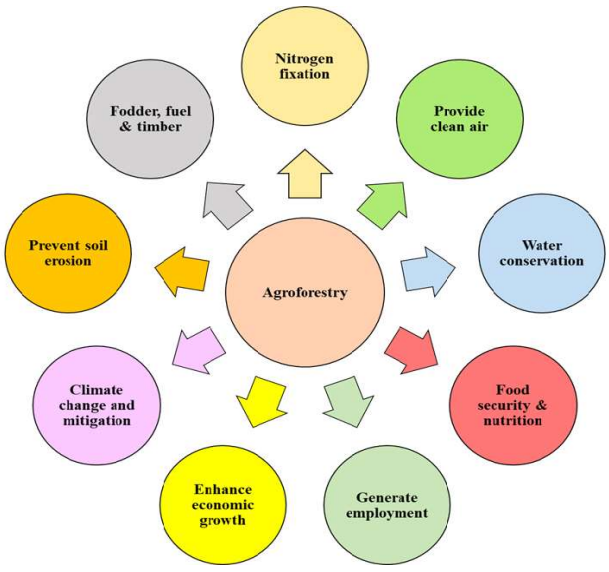


Fig. 3. Benefits of Agroforestry

Agroforestry-based businesses such as mushroom farming, beekeeping and non-timber forest products increase additional income sources that enhancing sustainable rural development (Kumar et al., 2021) and also mitigating the adverse impact of climate change (Islam and Quli 2016). Agroforestry systems generate employment in rural areas by enlarged supply of wood in the market a substantial dealing with wood and wood-based products (Dhyani and Handa 2013). Tree-crop based systems expand soil stability and prevent erosion through several processes. Increased ground cover from leaf litter and “tree mulch” intercepts rainfall, decreases the velocity of runoff water, reduces evapotranspiration, and limits soil crusting (Sepulveda and Carillo 2015). Its different components act as an alternate source of income, as loss in market value of one product can be compensated by better prices of other products, such as timber, crops, fruits, nuts, mushrooms, forages, livestock, biomass, Christmas trees, and herbal medicine (Wilson and Lovell 2016, Thakur et al., 2017b).

Gum-yielding trees like *Acacia senegal*, *Acacia nilotica*, *Butea monosperma*, and *Boswellia serrata* are valuable for agroforestry models and should be promoted widely to ensure sustained income and livelihood security for resource-poor rural communities (Chavan et al., 2016). Kanwal et al., 2022 also concluded higher overall productivity in agroforestry system as compared to sole agriculture especially in hilly states.

Study reported that in western Uttar Pradesh, fuelwood was more than 50% of the farmer's major source of income, which also reduced the dependence of the other conventional fuel followed by additional income 25% of farmers adopted the agroforestry model (Dwivedi et al., 2010). The estimated fuelwood consumption in different villages of Chamoli districts of Garhwal Himalayas estimated during summer per village is 83.41 kg/day to 535.40 kg/day and in winter 150.70 kg/day to 757.05 kg/day and the utilization of fodder tree 301.05 kg/day to 1009.15kg/day in the summer and in the winter 650.50 kg/day to 2011.50 kg/day which is supplemented by traditional agroforestry trees (Rawat et al., 2016).

Innovative technologies in agroforestry for rural sustainability: Innovative agroforestry practices blend modern science with traditional practices helping rural communities improve land management, boost productivity, and support sustainable livelihoods while protecting the environment (Table 4).

Sanwal et al., (2018) estimated seven medicinal plants and found *Anacyclus pyrethrum* (Akarkara), *Mucuna* (Kaunch), *Solanum virginianum* (Kantkari), and *Andrographis* (Kalmegh) economically suitable in mountain

regions. *Spilanthes, Mucuna*, and Solanum showed highest yields on northern slopes, with net returns up to Rs. 34,639/ha in 4-6 months. Similarly, lower Himachal Himalayas Verma et al. (2010), Verma and Thakur (2010, 2011), Thakur et al. (2012), Thakur and Verma (2012) and Thakur et al. (2017b) reported *Ocimum sanctum, Withania somnifera and Mucuna pruriens* as ecologically and economically sound agroforestry combinations. Such silvi-medicinal systems offer promising alternate livelihoods for communities ranging from mountains to plans and coastal areas (Suvera et al., 2015, Suvera and Thakur 2016, Kumar et al., 2016, 2017). The All India Coordinated Research Project (AIRCP) on Agroforestry and ICAR-Central Agroforestry Research Institute Jhansi suggested *Morus* and *Grewia-based* system for the western Himalayas, alder-based for the North Eastern Hill region, aonla, *Ailanthus, Hardwickia* and *Prosopis* based for the semi-arid and arid regions, poplar and eucalyptus-based for the Indo- Gangetic region and *Gmelina, bamboo, Acacia*-based system for Humid and Sub-humid regions and, teak-based for the tropical region (Handa et al., 2024). Innovative agroforestry interventions in the North Western Himalayas include bamboo-based agri-silvicultural systems, bamboo for construction, silvi-medicinal models using native medicinal plants, spice-based systems to counter crop loss from wildlife, sea buckthorn cultivation in high-altitude areas, and Van Silk (forest-based sericulture) to support forest-dependent communities-offering diverse livelihood and enterprise opportunities (Sanwal et al., 2019)

Scientific research methods for community empowerment: Agroforestry, combined with Remote Sensing technology using indices like NDVI, SAVI, LAI, and NDMI, enable precise monitoring of vegetation health, moisture, and productivity, supporting sustainable agroforestry, carbon finance, and ecosystem restoration-key elements in improving farmer incomes and advancing climate resilience (Ghosh and Sharma 2024). Agroforestry adoption was significantly enhanced through participatory methods that built trust, addressed local needs, and empowered communities with knowledge and skills (Suparwata et al., 2021). Agroforestry enhanced livelihood security by adopting practices like lac cultivation and sericulture. Traditional lac host trees such as *Ber (Zizyphus mauritiana)* and *Palas (Butea monosperma)* can be planted along field bunds, while fast-growing species like *Flemingia semialata* are also promising. Sericulture can be supported through agroforestry species that serve as host plants for silkworms-*Terminalia tomentosa*, *T. arjuna* and *Shorea robusta* for Tasar; *Morus* species for mulberry silkworms (Handa et al., 2016). Active participation is considered as one of the effective methods for community empowerment. This ensures that the strategies are tailored to the specific needs and preferences of the community, leading to better acceptance and more sustainable outcomes (Mayo 2004).

Table 4. Innovative agroforestry system in rural livelihood

Agroforestry system	Benefits	References
Agrisilviculture system (Woody perennials-Trees/shrubs + Agricultural crops)	Actively indulge in climate change and mitigation as agrisilvicultural systems have the potential to minimize direct N2O and CH4 emissions by up to 2.0 times.	Kwak et al. (2019)
	It positively enhances earthworm abundance, and organic matter in soil.	Cardinael et al. (2019), Marsden et al. (2020)
Agri-silvipastoral system (agricultural crops + timber/forest trees + pasture)	This complex tri component structure improves ecological sustainability and livelihood resilience, predominantly for smallholders and rural communities in diverse Agroclimatic zones.	Singh and Panday (2011)
Horti-silviculture System (fruit trees + timber/forest trees)	It increases both farm income and economic sustainability by optimal use of land.	Nair (1993)
	It also enhances microbial biodiversity- like in oleaginous tree species *Elaeis guineensis* + *Theobroma cacao*.	Ashraf et al. (2018)
Silvipastoral Systems (Trees/shrubs + pasture/grasses + livestock)	These systems are predominantly practiced in arid and semi-arid areas.	Kumar (2006)
	System fulfils the demands of fuel and fodder in rural areas and reduces the impact of climate change.	Dhyani (2013)
Home Gardens (multi-strata agroforestry system/ kitchen garden)	This system is known for its high species richness, vertical structure, and constant food and fodder production throughout the year.	Nair (1993)
	It improves and maintains the food and nutritional security in both rural and urban areas.	Nair (2008)
Alley Cropping (hedgerow intercropping of annual crops+ trees/shrubs)	This system widely practiced for soil fertility enhancement, control of soil surface runoff in marginal lands.	Young (1989)
	Many studies under agroforestry research show the importance of alley cropping in improving soil fertility and promote efficient nutrient cycling.	Adhikary et al. (2017, Jakhar et al. (2017 and Lenka et al. (2012)

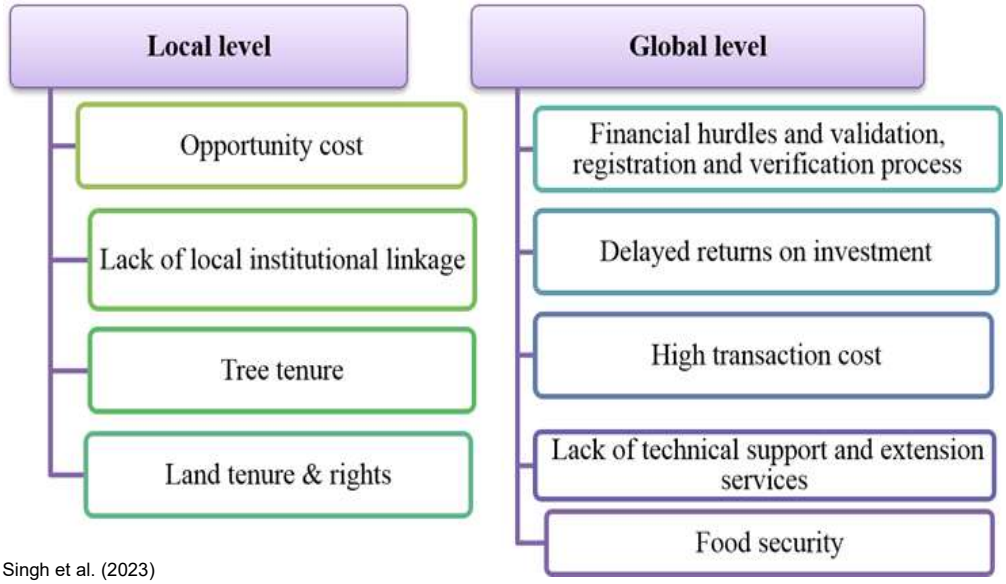


Fig. 4. Challenges in Agroforestry

Another pivotal strategy is capacity building. By equipping community members with the necessary skills, knowledge, and resources, they can effectively manage their resources, engage in profitable ventures, and mitigate potential risks (Hastings and Saunders 2001).

Challenges: Despite of several benefits agroforestry system still has challenges (Fig. 4). The inadequate availability of credit facilities and incentives is one of the key challenges affecting the use of inputs on farms and the planting of trees (Alemagi et al., 2015, Makee 2016).

Oduro et al. (2018), mentioned financial barriers to tree stock development on farms are often mentioned by farmers as being one of the major hindrances, and providing incentives to farmers such as grants and inputs is an effective way to reassure them to plant trees on their farms (Oduro et al., 2018). Plant species for intercropping, if not accurately selected may cause interspecific competition and minimize its environmental benefits (Jose et al., 2004). Adesina and Chianu 2002 stated in their study that because of limited contact with extension agents (demonstration days) proved a barrier to agroforestry systems adoption for landowners.

CONCLUSION

Agroforestry is a sustainable, science-based land-use system that enhances rural livelihoods by improving soil health, conserving biodiversity, mitigating climate change, and providing diverse income sources. With innovations like geospatial tools and participatory methods, it supports climate resilience and food security. However, challenges like limited credit, insecure land tenure, and inadequate support services must be addressed. Agroforestry represents a scientifically robust and socially inclusive approach to rural development. By organizing education programmes and sharing experiences among farmers can be useful method to achieve effective implementation of profitable agroforestry System. When effectively implemented, agroforestry offers a powerful solution for sustainable rural development and environmental conservation. Agroforestry is a system or modern scientifically enhanced technique for the cultivators to improve our safety of socioeconomic conditions and environment cleanliness by the fixed size of the land cultivated all components in the same field. It is clearly shown that traditional and present-day's scientific agroforestry practices primarily have different positive assets for the gaining profit of improved biodiversity, which helps environment reformation and economic return of output for the producers across the world.

AUTHOR'S CONTRIBUTION

Monika Sharma: writing, review, methodology, data collection, editing and conceptualization; Meenakshi Gupta: supervision and review; K.K. Sood: supervision and resources. Lalit Mohan Gupta**:** review and editing.

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Assessing Biomass Production and Carbon storage in Agroforestry Systems Located at Proximity Gradients to Gobind Sagar Reservoir

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Abstract: This study assessed biomass and carbon storage dynamics across different agroforestry systems and distance gradients from a reservoir. Biomass estimation was carried out using stratified quadrat sampling for trees and crops, with carbon stock quantified as the sum of the aboveground and belowground components. There was significant variation in the total carbon storage among agroforestry systems and across distance classes, with their interaction effect also being noteworthy ($P = 0.429$). The home garden system exhibited the highest carbon stock (54.05 t ha^{-1}), while the agri-silviculture system recorded the lowest (29.42 t ha^{-1}). Across spatial gradients, carbon stocks declined with increasing distance from the reservoir, ranging from 45.69 t ha^{-1} at D1 (0-2 km), to 29.95 t ha^{-1} at D7 (12-14 km). The combined influence of management practices, species composition, and site conditions plays a decisive role in carbon accumulation. These findings affirm that diversified and intensively managed agroforestry systems, particularly home gardens, have greater potential for enhancing carbon storage than less diversified systems.

Keywords: Agroforestry systems, Aboveground biomass & carbon, Below ground biomass and carbon, Distance gradient

Agroforestry, the deliberate integration of trees with crops and/or livestock, is widely acknowledged as a land use practice that delivers multiple ecological, economic, and social benefits. Among its various ecosystem services, the ability to generate substantial biomass and sequester atmospheric carbon dioxide makes agroforestry a crucial strategy for climate change mitigation (Jose 2009, Thakur et al., 2011, Singh et al., 2015, Chaturvedi et al., 2016, Luna et al., 2016). Trees in these systems act as long-term carbon sinks, storing carbon in their biomass (Bhusara et al., 2016, Singh et al., 2019, Rakshita et al., 2025) and soils while also contributing to soil fertility, nutrient cycling, and biodiversity enhancement (Sarvade et al., 2014a, Sarvade et al., 2016a, Sarvade et al., 2019, Thakur et al., 2024). Furthermore, agroforestry moderates microclimatic extremes, reduces soil erosion, and provides timber, fodder, fruits, and fuelwood, ensuring livelihood security for rural communities (Sarvade et al., 2014b, Thakur et al., 2015). In the context of increasing climate variability, its role in balancing productivity with environmental conservation is gaining global recognition (Sharma et al., 2022).

The spatial arrangement of agroforestry systems plays a significant role in determining the biomass production and carbon storage potential. Factors such as soil moisture availability, nutrient status, and microclimatic conditions can vary considerably depending on the proximity to water bodies (Sarvade et al., 2016a, 2016b). The Gobind Sagar Reservoir in Himachal Pradesh, formed by the construction of the Bhakra Dam on the Sutlej River, exerts a notable influence on the surrounding agroforestry landscapes (Anonymous 2005, Sarvade 2024). These systems are distributed across multiple distance classes from the reservoir, where hydrological influences, soil characteristics, and human management practices interact to shape vegetation growth and productivity (Wu et al., 2004). Understanding how these spatial gradients impact biomass and carbon dynamics can provide valuable insights for targeted land use planning and climate resilience.

The varied topography and climatic diversity of Himachal Pradesh create favorable conditions for a wide range of agroforestry models. The presence of the Gobind Sagar Reservoir adds an additional layer of hydrological moderation, potentially improving soil moisture regimes and supporting higher biomass yields near the water body (Degu et al., 2011, Sarvade et al., 2016a. Sarvade et al., 2016b). Studies from other regions have indicated that proximity to reservoirs is often correlated with increased tree growth rates and biomass accumulation due to stable water availability and moderate temperature fluctuations. However, little research has been conducted to examine how these proximity effects translate into variations in carbon sequestration potential, particularly in the Himalayan foothill

agroforestry context. This knowledge gap limits our ability to optimize agroforestry systems for both ecological and economic gains.

Evaluating biomass production and carbon sequestration across different proximity classes in the Gobind Sagar Reservoir offers dual benefits: advancing scientific understanding and guiding sustainable land management (Sarvade et al., 2016a, Sarvade et al., 2016b). Insights from such research can help policymakers and local communities design agroforestry interventions that maximize carbon capture, while enhancing productivity and income generation. Furthermore, quantifying these patterns contributes to accurate regional carbon accounting, which is a key requirement for implementing climate-smart agricultural and forestry programs. These findings also support participation in carbon credit mechanisms, providing additional financial incentives for farmers to adopt and maintain tree-based systems.

Against this backdrop, the present study aimed to investigate biomass yield and carbon storage dynamics in different agroforestry systems located at varying distances from the Gobind Sagar Reservoir. By systematically comparing agroforestry systems across defined proximity gradients, this study sought to identify patterns of spatial variation, determine the key environmental and management factors influencing biomass and carbon levels, and recommend strategies to enhance their carbon sequestration potential. Such an approach will not only deepen our understanding of reservoir-influenced landscapes, but also support the broader agenda of climate change mitigation and sustainable rural development in Himachal Pradesh.

MATERIAL AND METHODS

Study area: This research was conducted in the vicinity of the Gobind Sagar Reservoir, situated within the upper sub-basin of the Satluj Basin (Code: 13) in Bilaspur district, Himachal Pradesh. Geographically, the district lies between latitudes 31°12′30″ and 31°35′45″ N and longitudes 76°23′45″ and 76°55′40″ E, encompassing a total area of 1,167 km², equivalent to approximately 2.1% of the state's geographical expanse (Sarvade et al., 2016a , 2016b). The terrain spans elevations from 290 to 1,980 m above mean sea level, with a substantial portion of the district lying below 650 m a. s.l.. The study area falls under the sub-mountain, low-hill tropical subtropical zone of the Himachal Pradesh. Based on 10-year averages (2005-2014), temperatures ranged from 3.53°C (January) to 23.20°C (July) for minimum and 19.38°C (January) to 36.19°C (May) for maximum. Monsoon rainfall varied between 104.49 mm (June) and 309.97 mm (August), with annual averages of 1,106.12 mm and marked inter-seasonal and inter-annual fluctuations, notably higher in 2006, 2007, and 2013 (Sarvade 2024).

A total of 25 sites were selected to address the study objectives, strategically distributed across seven concentric distance zones, each 2 km wide, surrounding the Gobind Sagar Reservoir designated as D1 (0-2 km), D2 (2-4 km), D3 (4-6 km), D4 (6-8 km), D5 (8-10 km), D6 (10-12 km), and D7 (12-14 km). These sites are located within SLJU020, SLJU021, SLJU022, and SLJU023 catchment. The distribution included six sites in D1 and D2, three sites in D3, D4, and D6, two sites in D5, and 2 in D7. Detailed site information is shown in Figure 1.

Sample collection and data analysis: In the agroforestry systems, biomass and carbon estimations were carried out through stratified quadrat sampling. For tree components, three quadrats of 15m × 15m were demarcated, while 1m × 1m quadrats were employed for crop components, following the guidelines of Muller-Dombois and Ellenberg (1974). The agroforestry systems in the study area were classified according to the structural attributes and spatial arrangement of the constituent plant species. Tree measurements were recorded once during the study period, whereas crop sampling was performed at the harvest stage of the growing season to capture the maximum biomass accumulation.

Biomass estimation: The biomass of all vegetation strata (trees and crops) was assessed to estimate aboveground biomass (AGB), belowground biomass (BGB), and total biomass (TB) in all identified agroforestry systems. A destructive sampling method was employed for crops. All individuals occurring within the designated quadrats were harvested, separated by species, and partitioned into shoot and root components. Plant parts were oven-dried at 70 ± 5°C to a constant weight, and biomass was expressed in tonnes ha^{-1}. Belowground herbaceous biomass was obtained by excavating a soil monolith of 25 cm × 25 cm × 30 cm, whereas shrub roots were extracted manually, washed thoroughly, and oven-dried for biomass determination (Gupta et al., 2009). Diameter at breast height (DBH) and total height were recorded using tree calipers and Spiegel Relaskop, respectively. Tree volume was estimated using species- and region-specific volume equations (FSI 2006, 2012). The aboveground tree biomass was calculated by multiplying the stem volume by species-specific wood density and biomass expansion factors (Dixon et al., 1993; 1994; IPCC, 2007), whereas belowground biomass was derived as 25% of the aboveground biomass following IPCC (1996).

Carbon storage estimation: Carbon storage in the different vegetation layers was calculated using biomass-derived

values. For herbaceous, crop, and shrub species, both aboveground and belowground carbon densities were estimated by multiplying the respective biomasses with a carbon conversion factor of 0.45 (Woomer 1999). For trees, aboveground carbon stock was obtained by applying factors suggested by the IPCC (2007), whereas belowground tree carbon was estimated using a conversion factor of 0.45 (Woomer 1999).

Statistical analysis: To evaluate the variations among land use systems and distance classes from the reservoir across the 25 study sites, two-way analysis of variance was performed. Post-hoc comparisons were carried out using the least significant difference at significance threshold of $P < 0.05$. All statistical analyses were conducted using SPSS software package version 23 (IBM Corp 2015).

RESULTS AND DISCUSSION

Aboveground biomass (AGB): Among the systems, the highest aboveground biomass was under HG (90.14 t ha^{-1}), which was significantly superior to all other systems (Table 1). In contrast, the lowest value was observed under AS (48.56 t ha^{-1}), which remained statistically comparable (P =

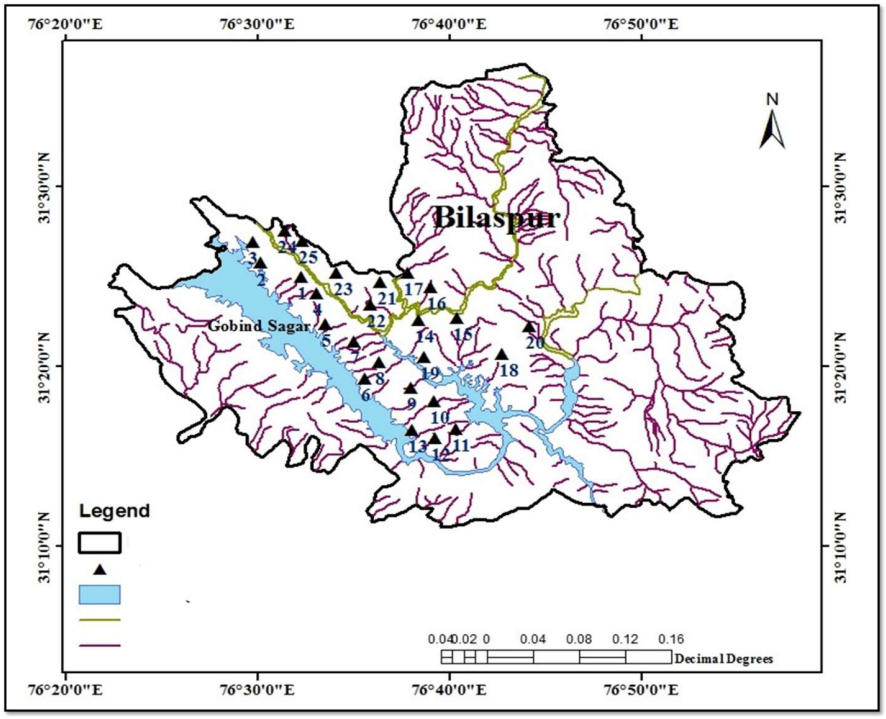

Fig. 1. Study sites selected in upstream catchment area of Gobind Sagar reservoir

Table 1. Aboveground biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	61.90 ±7.97	72.55 ± 8.57	64.10 ± 8.63	67.04 ± 15.30	111.76 ± 15.80	75.47
D2	54.55 ± 13.39	64.66 ± 12.88	53.50 ± 11.51	72.69 ± 2.09	95.80 ± 11.24	68.24
D3	48.36 ± 4.81	47.60 ± 7.97	43.17 ± 1.14	59.29 ± 7.06	94.55 ± 10.00	58.59
D4	43.70 ± 5.98	54.68 ± 7.04	55.04 ± 6.28	58.48 ± 10.39	90.17 ± 2.14	60.41
D5	48.90 ± 7.55	59.58 ± 0.93	55.64 ± 8.60	62.63 ± 0.89	92.53 ± 1.32	63.86
D6	42.08 ± 2.55	48.90 ± 8.79	52.96 ± 2.15	48.33 ± 3.61	75.17 ± 11.81	53.49
D7	40.44 ± 4.16	47.76 ± 3.39	47.10 ± 5.18	41.70 ± 3.48	71.04 ± 5.18	49.61
Mean	48.56	56.53	53.07	58.59	90.14	61.38
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

DFR = Distance from Reservoir; AFs = Agroforestry systems; AS = Agri-silviculture; AH = Agri-horticulture; ASH = Agri-silvi-horticultre; AHS = Agri-horti-silviculture; HG = Home gardens

0.212) with ASH (53.07 t ha^{-1}). Across distance classes, aboveground biomass peaked significantly at D1 (75.47 t ha^{-1}) and showed a gradual decline with increasing distance from the reservoir, following the order: D2 (68.24 t ha^{-1}) > D5 (63.86 t ha^{-1}) > D4 (60.41 t ha^{-1}) > D3 (58.59 t ha^{-1}) > D6 (53.49 t ha^{-1}) > D7 (49.61 t ha^{-1}). The significant interaction was also observed between agroforestry systems and distance classes, with the maximum biomass observed under HG at D1 (111.76 t ha^{-1}) and the minimum under AS at D7 (40.44 t ha^{-1}).

These findings highlight the synergistic role of tree-crop integration in enhancing aboveground biomass productivity. Improved soil fertility under agroforestry conditions coupled with complementary spatial arrangements of tree and crop components facilitates better utilization of available light, water, and nutrients. Furthermore, site-specific factors, such as slope and soil texture, modulate biomass accumulation, thereby reinforcing the ecological advantages of agroforestry systems (Das et al., 2008, Gera et al., 2011, Holzmueller and Jose 2012, Kanime et al., 2013).

Belowground biomass (BGB): The HG system exhibited the maximum BGB (19.83 t ha^{-1}), which was significantly higher than that of the other systems (Table 2). Conversely, the AS system showed the minimum BGB (11.28 t ha^{-1}), which remained statistically comparable with ASH (12.16 t ha^{-1}). Across distance gradients, D1 recorded the highest BGB (17.48 t ha^{-1}), while the lowest was obtained at D7 (11.32 t ha^{-1}), statistically similar to D3 (13.18 t ha^{-1}) and D6 (12.10 t ha^{-1}). The significant interaction effect between system types and distance classes was evident, with the maximum BGB under HG at D1 (25.36 t ha^{-1}) and the minimum under AS at D7 (9.35 t ha^{-1}). The highlight that root biomass dynamics in agroforestry systems are not only system-dependent but also strongly influenced by proximity to water sources. Higher root proliferation under HG may be attributed to efficient resource capture and favorable soil microenvironments, whereas lower values in AS reflect limited rooting capacity and reduced belowground allocation. Variations along distance gradients suggest that soil moisture availability, fertility status, and microclimatic conditions governed by the reservoir play a decisive role. Additionally, tree-crop interactions, inherent soil characteristics, and management interventions, such as spacing and pruning, significantly contribute to the observed differences in BGB (Das et al., 2008, Kanime et al., 2013, Sarvade et al., 2016b, Sarvade 2024).

Total biomass (TB): The analysis revealed that both main effects were highly significant, with a notable interaction effect (Table 3). Among the systems, HG accumulated the maximum total biomass (109.97 t ha^{-1}), followed by AHS, AH and ASH, whereas the minimum was in AS (59.84 t ha^{-1}). Across distance gradients, TB was highest at D1 (92.95 t ha^{-1}) and lowest at D7 (60.92 t ha^{-1}). The interaction of system and distance further demonstrated that HG at D1 stored the greatest amount of biomass (137.12 t ha^{-1}), while AS at D7 registered the least (49.79 t ha^{-1}). The observed variation in biomass across systems and distances underscores the role of management interventions that improve soil fertility, reduce interspecific competition, and enhance overall system productivity (Swarup et al., 2000; Hati et al., 2006). Biomass accumulation in agroforestry is further shaped by the type and proportion of tree-crop components, planting geometry, and availability of critical growth resources, such as soil moisture and light (Das et al., 2008, Das and Das 2010, Gera et al., 2011, Holzmueller and Jose 2012, Kanime et al., 2013). ASH systems contributed substantially (72.92%) to fruit and fodder tree components, a trend consistent with the findings of Singh (2014) in the Giri watershed of Himachal Pradesh. More broadly, system productivity is the outcome of interacting ecological factors,

Table 2. Belowground biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	14.56 ± 2.05	17.28 ± 2.82	14.77 ± 2.01	15.44 ± 3.69	25.36 ± 4.92	17.48
D2	12.74 ± 3.17	14.91 ± 3.40	12.34 ± 2.65	16.85 ± 0.84	20.96 ± 2.92	15.56
D3	11.14 ± 1.24	10.95 ± 1.53	9.85 ± 0.40	13.39 ± 1.46	20.55 ± 2.19	13.18
D4	10.23 ± 1.30	12.40 ± 1.42	12.50 ± 1.34	12.99 ± 2.17	19.62 ± 0.43	13.55
D5	11.20 ± 1.62	13.43 ± 0.14	12.73 ± 1.94	13.99 ± 0.35	19.96 ± 0.35	14.26
D6	9.75 ± 0.53	11.04 ± 1.87	12.09 ± 0.50	11.05 ± 0.93	16.55 ±2.13	12.10
D7	9.35 ± 1.12	11.04 ± 0.80	10.83 ±1.27	9.60 ± 0.60	15.78 ± 0.48	11.32
Mean	11.28	13.01	12.16	13.33	19.83	13.92
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

including climate, soil properties, floristic diversity, and species phenology, as emphasized by Bahar (2003).

Above ground carbon (AGC): There was significant effect of both factors with HG recording the maximum AGC (55.88 t ha^{-1}), significantly higher than all other systems (Table 4). The lowest value was under AS (24.28 t ha^{-1}), which statistically comparable with ASH (26.54 t ha^{-1}). Across distance gradients, AGC was highest at D1 (37.73 t ha^{-1}) and declined progressively with increasing distance, reaching its minimum at D7 (24.80 t ha^{-1}). The significant interaction effect was also observed, with the maximum AGC recorded under HG at D1 (55.88 t ha^{-1}) and the minimum under AS at D7 (20.22 t ha^{-1}). Greater AGC accumulation under HG highlights the synergistic role of tree-crop interactions supported by favorable soil and climatic conditions (Das et al., 2008, Gera et al., 2011, Jose and Bardhan 2012). Declining AGC at greater distances from the reservoir may be linked to enhanced soil erosion and associated fertility loss, which adversely affects the carbon storage capacity (Mahmoudi et al., 2010). Singh (2014) also reported similar system-specific variations, with the agri-silvi-horticulture system showing the highest aboveground carbon (31.56 t C ha^{-1}), followed by agri-horti-silviculture, agri-silviculture and agri-horticulture . These findings collectively emphasize that system composition, resource availability, and site conditions act in concert to regulate aboveground carbon dynamics in agroforestry landscapes.

Below ground carbon (BGC): The agroforestry systems and distance classes from the reservoir exerted a significant influence with the maximum BGC recorded under HG (8.97 t ha^{-1}) (Table 5). The minimum was in AS (5.14 t ha^{-1}), which remained statistically comparable with ASH (5.53 t ha^{-1}). Across distance gradients, the highest BGC was observed at D1 (7.95 t ha^{-1}), while the lowest was recorded at D7 (5.14 t ha^{-1}), which did not differ significantly from D3, D4, D5 and D6. The interaction effect was also significant with HG at D1 accumulating the maximum BGC (11.52 t ha^{-1}) and AS at D7 recording the least (4.26 t ha^{-1}). The decline in the BGC with increasing distance from the reservoir indicates the influence of soil degradation, declining fertility, harsher microclimatic conditions, and higher anthropogenic pressures (Mahmoudi et al., 2010, Gera et al., 2011, Kanime et al., 2013). The

Table 3. Total biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	76.46 ± 9.99	89.82 ± 11.36	78.87 ± 10.64	82.47 ± 18.92	137.12 ± 20.52	92.95
D2	67.30 ± 16.55	79.56 ± 16.22	65.84 ± 14.17	89.54 ± 2.74	116.75 ± 14.14	83.80
D3	59.50 ± 6.04	58.55 ± 9.49	53.02 ± 1.52	72.68 ± 8.52	115.10 ± 12.17	71.77
D4	53.93 ± 7.28	67.08 ± 8.46	67.54 ± 7.63	71.48 ± 12.55	109.79 ± 2.48	73.96
D5	60.10 ± 9.17	73.01 ± 1.07	68.37 ± 10.54	76.62 ± 1.24	112.49 ± 1.67	78.12
D6	51.83 ± 3.05	59.94 ± 10.65	65.05 ± 2.65	59.39 ± 4.54	91.72 ± 13.93	65.59
D7	49.79 ± 5.28	58.80 ± 4.19	57.93 ± 6.44	51.30 ± 4.08	86.82 ± 5.66	60.92
Mean	59.84	69.54	65.23	71.92	109.97	75.30
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

Table 4. Aboveground carbon storage (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	30.95 ± 3.98	36.27 ± 4.28	32.05 ± 4.31	33.52 ± 7.65	55.88 ± 7.90	37.73
D2	27.28 ± 6.69	32.33 ± 6.44	26.75 ± 5.76	36.34 ± 1.05	47.90 ± 5.62	34.12
D3	24.18 ± 2.41	23.80 ± 3.98	21.58 ± 0.57	29.65 ± 3.53	47.27 ± 5.00	29.30
D4	21.85 ± 2.99	27.34 ± 3.52	27.52 ± 3.14	29.24 ± 5.20	45.08 ± 1.07	30.21
D5	24.45 ± 3.78	29.79 ± 0.47	27.82 ± 4.30	31.32 ± 0.45	46.27 ± 0.66	31.93
D6	21.04 ± 1.27	24.45 ± 4.39	26.48 ± 1.08	24.17 ± 1.81	37.59 ± 5.91	26.74
D7	20.22 ± 2.08	23.88 ± 1.70	23.55 ± 2.59	20.85 ± 1.74	35.52 ± 2.59	24.80
Mean	24.28	28.27	26.54	29.30	45.07	30.69
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

superior BGC under HG suggests that system composition and management practices can enhance belowground carbon allocation through improved rooting depth and soil resource capture. Singh (2014) also observed that agri-silvi-horticulture systems stored the maximum belowground carbon (9.43 t C ha^{-1}), followed by agri-horti-silviculture agri-silviculture and agri-horticulture (6.86 t C ha^{-1}). These results underline the pivotal role of system design, soil conditions, and distance-induced ecological gradients in regulating belowground carbon storage in agroforestry landscapes.

Total carbon (TC): The total carbon stock (AGC + BGC) from the crop and tree components was markedly influenced by both the agroforestry systems and the distance gradients from the reservoir, and interaction also had a significant impact on TC (Table 6). Among the systems, the home garden (HG) accumulated the maximum TC (54.05 t ha^{-1}), followed by AHS , AH, ASH and the lowest in AS (29.42 t ha^{-1}). Across the spatial classes, the highest TC stock was observed at the nearest distance D1 (45.69 t ha^{-1}), declining progressively with distance, reaching the minimum at D7 (29.95 t ha^{-1}). The interaction pattern highlighted that the HG system at D1 stored the maximum carbon (67.40 t ha^{-1}), whereas the lowest was in AS at D7 (24.48 t ha^{-1}). These variations can be attributed to system-specific management interventions that enhance soil fertility, reduce tree-crop competition, and subsequently promote higher biomass accumulation and carbon retention (Swarup et al., 2000, Hati et al., 2006, Murthy et al., 2013). Singh (2014) also reported that agri-silvi-horticulture systems achieved the highest TC stock (40.99 t C ha^{-1}), followed closely by agri-horti-silviculture (39.49 t C ha^{-1}), while agri-silviculture (31.57 t C ha^{-1}) and agri-horticulture (30.29 t C ha^{-1}) stored relatively lower carbon. The grand total carbon stock in agroforestry systems is modulated by factors such as tree-crop combinations, planting geometry, site edaphic characteristics, and prevailing climatic conditions (Maikhuri et al., 2000, Das and Chaturvedi 2005, Das and Chaturvedi 2008, Gera et al., 2011, Nair 2012, Kanime et al., 2013). Supporting this, Roshetko et al. (2002) demonstrated that tree-based land use sequesters substantially more carbon than croplands or grasslands under comparable ecological settings. Similarly, Saha and Jha (2012) reported a wide variation (12 to 228 Mg ha^{-1}) with a median of 95 Mg ha^{-1}

Table 5. Belowground carbon storage (t ha^{-1}) in agroforestry systems (AFs) at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	30.95 ± 3.98	36.27 ± 4.28	32.05 ± 4.31	33.52 ± 7.65	55.88 ± 7.90	37.73
D2	27.28 ± 6.69	32.33 ± 6.44	26.75 ± 5.76	36.34 ± 1.05	47.90 ± 5.62	34.12
D3	24.18 ± 2.41	23.80 ± 3.98	21.58 ± 0.57	29.65 ± 3.53	47.27 ± 5.00	29.30
D4	21.85 ± 2.99	27.34 ± 3.52	27.52 ± 3.14	29.24 ± 5.20	45.08 ± 1.07	30.21
D5	24.45 ± 3.78	29.79 ± 0.47	27.82 ± 4.30	31.32 ± 0.45	46.27 ± 0.66	31.93
D6	21.04 ± 1.27	24.45 ± 4.39	26.48 ± 1.08	24.17 ± 1.81	37.59 ± 5.91	26.74
D7	20.22 ± 2.08	23.88 ± 1.70	23.55 ± 2.59	20.85 ± 1.74	35.52 ± 2.59	24.80
Mean	24.28	28.27	26.54	29.30	45.07	30.69
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

Table 6. Total carbon storage (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	37.59 ± 4.92	44.15 ± 5.59	38.77 ± 5.23	40.54 ± 9.30	67.40 ± 10.10	45.69
D2	33.08 ± 8.14	39.11 ± 7.97	32.36 ± 6.96	44.01 ± 1.35	57.38 ± 6.95	41.19
D3	29.25 ± 2.97	28.78 ± 4.66	26.06 ± 0.75	35.72 ± 4.19	56.56 ± 5.99	35.27
D4	26.51 ± 3.58	32.97 ± 4.16	33.20 ± 3.75	35.13 ± 6.16	53.95 ± 1.21	36.35
D5	29.54 ± 4.51	35.89 ± 0.53	33.61 ± 5.18	37.66 ± 0.61	55.28 ± 0.82	38.39
D6	25.48 ± 1.50	29.46 ± 5.24	31.97 ± 1.31	29.19 ± 2.23	45.07 ± 6.84	32.24
D7	24.48 ± 2.60	28.90 ± 2.06	28.47 ± 3.17	25.21 ± 2.01	42.67 ± 2.77	29.95
Mean	29.42	34.18	32.06	35.35	54.05	37.01
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

in the carbon sequestration potential of different agroforestry systems across the North-Eastern Hill Regions, reinforcing the high potential of diversified systems for long-term carbon storage.

CONCLUSION

The study reaffirm that agroforestry systems hold immense potential as nature-based solutions for climate change mitigation, while simultaneously supporting rural livelihoods. Home gardens, with their multi-strata structure and high species diversity, have emerged as the most effective model for maximizing carbon sequestration, while agri-silviculture systems have demonstrated relatively lower storage potential. Importantly, the proximity effect observed near the reservoir highlights the role of microclimatic conditions, soil moisture regimes, and landscape position in influencing carbon accumulation, suggesting that site-specific factors must be integrated into agroforestry planning. For broader applicability, this study emphasizes that diverse, well-managed agroforestry models should be prioritized across various ecological and socioeconomic settings worldwide. Incorporating multipurpose trees, shrubs, and crops in a scientifically designed planting geometry not only enhances carbon storage, but also delivers co-benefits such as soil conservation, biodiversity enrichment, and food and nutritional security. Therefore, governments, policymakers, and development agencies should promote home gardens, agri-horti-silviculture, and similar diversified systems as part of climate-smart land management strategies. In a global context, these results suggest that reservoir catchments, river basins, and other ecologically fragile zones can be rehabilitated effectively through agroforestry interventions. Scaling up such practices contributes to achieving international climate commitments (Paris Agreement, SDGs 13 and 15) and also address the livelihood needs of local communities. Thus, agroforestry represents a win-win pathway to reconcile climate mitigation with sustainable rural development worldwide.

AUTHOR's CONTRIBUTION

SS, DRB, and BG initiated and conceptualized the study, wrote, and reviewed the manuscript. PP, DK, and PS contributed to data evaluation, writing, and reviewing the manuscript. MK and VA contributed to the field data collection and laboratory work.

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Economic Feasibility of Finger Millet (*Eleusine coracana*) under Multitier Agroforestry Systems in South Gujarat

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Abstract: Economics of Finger Millet Eleusine coracana Gaertn. under the multi-tier bamboo-malabar neem (*Melia dubia*) and bamboo–mahogany (*Swietenia mahagoni*) agroforestry system was evaluated during *kharif* – 2022 and 2023 at Hill Millet Research Station, Waghai, Dang's, Navsari Agricultural University, Gujarat. The two multi-tier agroforestry systems namely bamboo-malabar neem (M_1) and bamboo-mahogany (M_2) were considered as main plot treatments and four finger millet varieties GN-5 (V_1), GNN-7 (V_2), GN-9 (V_3), and GN-10 (V_4) were selected as sub-plot treatments. The experiment followed in a split-plot design, with three replicates. Agroforestry system bamboo-malabar neem-GN-7 was the best multi-tier agroforestry combination achieving the highest grain yield (2,659 kg ha^{-1}), straw yield (4,279 kg ha^{-1}), gross return (₹1,62,878 ha^{-1}), net return (₹82,550 ha^{-1}) and benefit to cost ratio (2.03). The lowest economic gains were from bamboo-mahogany-GN-9, with a grain yield of 1,860 kg ha$_{-1}$ and B:C ratio of 1.45.

Keywords: Finger millet, Economics, Multi-tier agroforestry, Bamboo, *Melia dubia, Swietenia mahagoni*

Increased demand for food, fuel, and fodder to fulfill the need for rapidly increasing human and livestock population requires enhanced productivity per unit area. In regions with limited resources, such as hilly areas, including scarce good-quality land and water, this task becomes more challenging. Agroforestry is a viable alternative for land utilization to achieve the National Forest Policy (1988) goal that 33 per cent of the country's geographical area under forest and tree cover. For short-to medium-term benefits, timber trees and bamboos can be intercropped with food or cash crops and livestock to design and test agroforestry systems in such areas. Integration of bamboo in a multi-tier agroforestry systems can maximize its functionality with other productive crops. The bamboo-based agroforestry models improve the ecological parameters of the highly degraded basaltic tracts (Behari et al., 2000). Bamboo is a group of beautiful and useful woody plants belonging to the sub-family Bambusoideae of the family Gramineae. Bamboo is a valuable alternative because of its multiple uses and short rotation (3-5 years). Known to be fast-growing, bamboo can reach its maximum height in four to six months with a daily increment of 15 to 18 cm. Among the different tree species, *Melia dubia* is one of the best alternative pulpwood species (Bharti 2006, Dhaka et al., 2020, Thakur et al., 2021). It belongs to the family *Meliaceae* and is commercially known as “Malabar neem”. It is a fast-growing short-rotation multipurpose deciduous tree indigenous to India, Southeast Asia, and Australia, growing to a height of 30 m with a spreading crown and clear bole of 9 m. It is found scattered in natural forests of south Gujarat region and framers have adopted it as multifarious species without any deleterious effect on associated crops and soil (Parmar et al., 2019, Sukhadiya et al., 2021, Thakur et al., 2023,). *Swietenia mahagoni* (L.) Jacq. is a tall tree, up to 30 m high, with a short buttressing base, up to 1 m in diameter, and a spherical crown. The bark is smooth gray on young trees, turning to scaly dark reddish-brown on large trees. Although bamboo and *M. dubia* are short rotation components as compared to *S. mahagoni* even then to make these species based agroforestry systems economically viable there is need to develop cash crop based systems for early returns. Among several compatible intercrops, millets too can be viable option to resolve this issue.

Millets are warm-weather grasses belonging to the C_4 group of plants and are considered to be physiologically efficient. Their cultivation in India extends from sea level up to 2000 m above the mean sea level and often grows in diverse soils, climates, and harsh environments. India is considered one of the major millet producers in the world. The predominant millets grown in India are sorghum, pearl millet, finger millet, kodo millet, proso millet, little millet, foxtail millet and barnyard millet of which barnyard millet, little millet and kodo millet are endemically domesticated in Indian subcontinent. Finger millet (*Eleusine coracana* Gaertn.), is an important crop and a major food source in many parts of the dry farming region in India. It is grown in a dry farming region, where the annual rainfall ranges between 400 mm and 1000 mm. In India, finger millet ranks third among millets, after sorghum and pearl millet. In Gujarat, finger millet is the most important traditional millet crop grown over an area of 11,000 hectares with a productivity of 1335 kg/ha and provides food and nutritional security to marginal farmers in

rainfed dry lands and hilly tribal areas. In Gujarat, it is mainly cultivated as a rainfed crop in the less fertile hilly soils of the Dangs, Valsad, and Navsari districts of South Gujarat and Panchmahal district of middle Gujarat in kharif season (Patil et al., 2016). Therefore, this study reports the economic feasibility of finger millet under bamboo, *M. dubia* and mahogany in hilly district of south Gujarat The Dangs.

MATERIAL AND METHODS

The research area is located in the southeastern part of Gujarat state and northern zone of Western Ghats situated at 20.7737 ^{0} North latitude, 73.4976 ^{0} East longitude, and at an altitude of 122.11 meter above the mean sea level (Fig. 1). The climate is typically tropical subhumid, characterized by a fairly hot summer, moderately cold winter, and warm humid monsoon. Generally, the monsoon in this region commences during the second week of June and ends in September. The total annual rainfall in this region is approximately 2134 mm and the number of rainy days is 65 - 70 days. The lowest temperature of the season was recorded in either December or January (10 °C to 23.8 °C). Gujarat Nagli - 5 (GN - 5), Gujarat Navsari Nagli - 7 (GNN - 7), Gujarat Nagli - 9 (GN - 9) and Gujarat Nagli - 10 (GN-10) varieties of finger millet were selected. These varieties were developed by Hill Millet Research Station, Waghai, Dang's, Gujarat. Seeds of Finger millet [*E. coracana*] varieties were procured from Hill Millet Research Station (HMRS), Waghai, Dang's, Gujarat treated with thiram 2 g/kg of seed for 24 hours before sowing and sown by line sowing method in the open space of field for each variety separately than after 30 DAS plants were transplanted under Bamboo-Malabar neem and Bamboo-Mahogany multi-tier plots as an intercrop at spacing of 22.5 x 10 cm in 12 plots each of 1.8 x 3.0 m in size during kharif season of 2022 and 2023. Observations on grain yield and straw yield were recorded, and economics in terms of cost of cultivation (Table 1), gross return, net return, and benefit-to-cost ratio were determined.

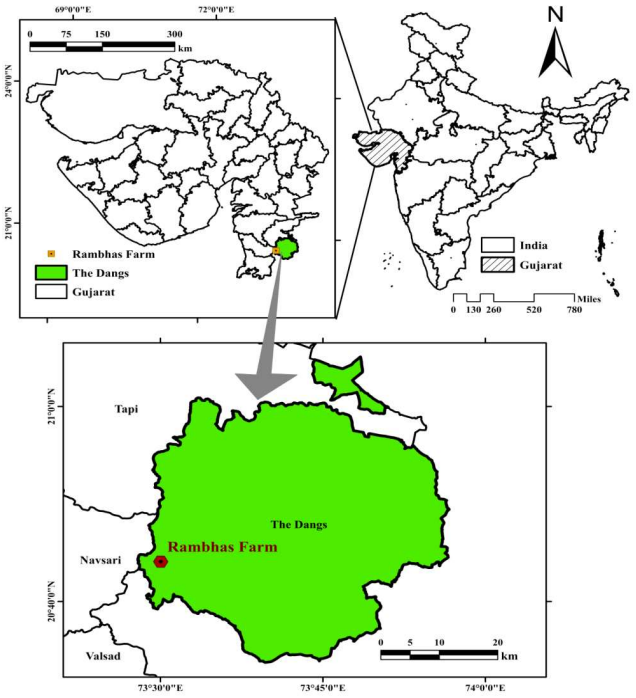

Fig. 1. Study area

RESULTS AND DISCUSSION

Economic analysis of multi-tier combinations in the agroforestry system showed considerable variation in grain yield, straw yield, gross return, net return, and benefit–cost (B:C) ratio (Table 1). Across all multi-tier combinations, the highest grain yield (2659 kg ha^{-1}) was obtained under bamboo-malabar neem-GNN-7 system, which fetched gross returns from grain of ₹ 132,927 per hectare. The corresponding straw yield (4279 kg ha^{-1}) contributed an additional gross returns of ₹ 29,951 per hectare, resulting in the maximum gross return (₹ 1,62,878 ha^{-1}). After deducting the cost of cultivation (₹ 80,328 ha^{-1}), the net return was ₹ 82,550 per hectare, with the highest B:C ratio of 2.03, indicating superior economic viability.

Other promising multi-tier combinations were bamboo–malabar neem-GN-10 and bamboo–mahogany-GNN-7, both yielding gross benefits above ₹ 1,32,000 per hectare and net return exceeding ₹ 52,000 per hectare, with B:C ratios of 1.66 each. In contrast, the lowest economic returns were from bamboo-mahogany-GN-9, which had the lowest grain yield (1860 kg ha^{-1}), net return (₹ 36,207 ha^{-1}) and B:C ratio (1.45).

These results suggest that bamboo, tree species and crop varieties significantly influenced system profitability, and malabar neem–based agroforestry systems generally outperformed mahogany-based agroforestry systems. The superior performance of M_1V_2 can be attributed to higher grain and straw yields due to more availability of light under malabar neem–based agroforestry system. Malabar neem have sparse crown which allow more sunlight as compared to Mahogany. Moreover, higher returns in V_2 (GNN-7) might be due to genetic makeup of the variety which allow it to grow under multi-tier agroforestry system as compared to other varieties. The higher B:C ratios in M_1V_2, M_1V_4, and M_2V_2 highlight the potential of these combinations for sustainable and profitable agroforestry adoption.

Economic feasibility of other intercrops (pulse and fodder grasses) under *M. dubia* based agroforestry systems (*M. dubia*-hybrid napier/Sorgham Sudan grass) evaluated by

Table 1. Cost of cultivation of finger millet (₹ ha^{-1})

Particular	Unit	Rate	Cost (₹)
A. Land preparation			
Ploughing with tractor (hrs)	6	@ ₹ 600 hr^{-1}	3600
Cultivator with tractor (hrs)	6	@ ₹ 600 hr^{-1}	3600
Bed preparation (labours /day)	10	@ ₹ 268 $labour^{-1}$ day^{-1}	2680
		Total (A)	9880
B. Planting material			
Seeds cost (4 varieties) (4kg)	4	@ ₹ 120 kg^{-1}	480
Seed sowing (labours/day)	2	@ ₹ 268 $labour^{-1}$ day^{-1}	536
Transplanting (labours/ 2 day)	15	@ ₹ 268 $labour^{-1}$ day^{-1}	8040
		Total (B)	8788
C. Manures and fertilizers			
FYM (tonne) or (₹5/kg)	10	@ ₹ 500 t^{-1}	5000
Neem cake (kg)	500	@₹ 35 kg^{-1}	17500
Vermicompost (kg)	1000	@ ₹ 7 kg^{-1}	7000
Application of manures / compost / neem cake (Labours/day)	15	@ ₹ 268 $labour^{-1}$ day^{-1}	4020
		Total (C)	33520
D. Intercultural operations			
Weeding (labours/day) x 3 times	15	@₹ 268 $labour^{-1}$ day^{-1}	12060
		Total (D)	12060
E. Harvesting, threshing and marketing			
Harvesting of ear heads (labours/day) x 2 times	10	@ Rs. 268 $labour^{-1}$ day^{-1}	5360
Threshing (labours/day) x 2	10	@ Rs. 268 $labour^{-1}$ day^{-1}	5360
Harvesting of straw (labours/day) x 2 times	10	@ Rs. 268 $labour^{-1}$ day^{-1}	5360
		Total (G)	16080
		Total fixed cost (A+B+C+D+E)	80328
		Gross Total	80328

Table 2. Economics of finger millet under bamboo-malabar neem and bamboo-mahogany based multi-tier agroforestry system

Multitier AFS	Grain yield (kg/ha)	Gross returns from grain (₹/ha)	Straw yield (kg/ha)	Gross returns from straw (₹/ha)	Cost of cultivation (₹)	Total gross return (₹)	Total net return (₹)	B:C Ratio
M_1V_1	1929	96451	3331	23314	80328	119764	39436	1.49
V_2	2659	132928	4279	29951	80328	162878	82550	2.03
V_3	1965	98245	3471	24296	80328	122541	42213	1.53
V_4	2144	107223	3712	25984	80328	133207	52879	1.66
M_2V_1	1932	96599	3289	23026	80328	119625	39297	1.49
V_2	2191	109556	3417	23921	80328	133477	53149	1.66
V_3	1860	93025	3359	23511	80328	116535	36207	1.45
V_4	1978	98896	3325	23278	80328	122175	41847	1.52

AFS= agroforestry systems, M_1V_1= Bamboo-malabar neem-GN-5, M_1V_2= Bamboo-malabar neem-GNN-7, M_1V_3= Bamboo-malabar neem-GN-9, M_1V_4= Bamboo-malabar neem-GN-10, M_2V_1= Bamboo- mahogany-GN-5, M_2V_2= Bamboo- mahogany-GNN-7, M_2V_3= Bamboo- mahogany-GN-9, M_2V_4= Bamboo- mahogany-GN-10

The price of grain was ₹ 50/kg and of straw was ₹7/kg per kg

Prajapati et al., (2020, 2022) in this region and are in line with present economic analysis. Bioeconomic compatibility of pulse crop based Malabar neem systems profitable in south Gujarat (Bhusara et al., 2018a, 2018b). Similarly, trend was observed by Hemalatha et al. (2023) in cluster bean variety MDU1 under *M. Dubia* and Mehta et al. (2024) in finger millet under Bhimal and Mulberry and these findings are in agreements with present agroforestry systems.

These findings align with previous studies conducted by Banerjee et al. (2009) in Bamboo with black gram, groundnut, cowpea and paddy; Kumar et al. (2010) in safedmusli under tamarind (*Tamarinus indica*); Anusha (2012) in finger millet under *M. dubia*; Anusha et al. (2015) in finger millet under *M. dubia*; Himshikha et al. (2017) in wheat + millet under poplar, Bhaskar et al. (2019) in finger millet under *M. dubia*; Batham et al. (2020) in finger millet under guava, Dalvi et al. (2020) in finger millet and black gram under cashew. Meshram et al. (2020) recorded highest BC ratio in the cashew + black gram, followed by cashew + finger millet, while the lowest ratio was seen in the cashew + proso millet.

CONCLUSION

The bamboo-Malabar neem-based multi-tier agroforestry system, especially with variety GNN-7, offered the highest profitability due to superior grain and straw yields, resulting in the highest gross and net returns with the highest B:C ratio. The bamboo-malabar neem-GNN-7 is the most productive and profitable multi-tier agroforestry combination with a higher B:C ratio.

AUTHORS' CONTRIBUTION

Patel, H. S.- Research implementation, data compilation; Tandel, M. B.-Planning, management of trials and manuscript writing, Jayesh Pathak-Management of research trial; Patel, S. M.-Data analysis and cost of cultivation; Vadodariya, G. D.-data collection and management; Prajapati, D. H. - filed operations management.

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Economics of *Senegalia catechu* based Agroforestry Systems of Samba and Kathua Districts in Jammu and Kashmir

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Abstract: The present study examined the economics of agroforestry systems involving *Senegalia catechu* (*khair*) and compares its performance with conventional cropping practices in the rainfed areas of Samba and Kathua districts of Jammu and Kashmir (J&K), India. A total of 100 *khair*-growing farmers were randomly selected from lists provided by the forest department, and data on production, management, and marketing were collected through personal interviews using a pre-tested questionnaire. For comparison, 30 farmers practicing conventional farming without trees were also surveyed. The analysis employed standard cost concepts to estimate costs and returns, and the Cobb–Douglas production function to assess resource-use efficiency. Results indicated that the predominant cropping pattern consisted of maize, paddy, and blackgram during the kharif season, and wheat, mustard, and *toria* (*Brassica campestris* var. toria) during the *rabi* season. The average cost of cultivation was 52,979.25 for maize, ₹58,795.21 for paddy, ₹46,367.06 for wheat, ₹41,232.21 for blackgram, and ₹44,787.77 for mustard, with corresponding benefit–cost (B:C) ratios of 1:1.32, 1:1.90, 1:1.07, 1:1.97, 1:2.64, and 1:2.13, respectively. Comparative analysis revealed that although yields were marginally higher under sole cropping, agroforestry systems generated substantially greater net returns, with an overall B:C ratio of 1:6.14 compared to 1:1.88 in non-agroforestry systems. The Cobb–Douglas regression further showed that the cost of *S. catechu* trees and the quantity of DAP (Diammonium Phosphate) fertilizer were highly significant determinants of gross profit, with the model explaining 78% of the variation in returns . These findings demonstrate that *S. catechu*-based agroforestry is more profitable and sustainable than conventional cropping alone, providing both short-term agricultural benefits and long-term income from trees in rainfed regions of J&K.

Keywords: Economics, Resource use efficiency, *Senegalia catechu*, *Khair*, Agroforestry

Agroforestry refers to a diverse set of land-use systems and technologies in which woody perennials such as trees, shrubs, palms, and bamboos are intentionally integrated with agricultural crops and/or livestock, either spatially or temporally (FAO 2015). It is increasingly recognized for its multiple ecological, economic, and livelihood benefits. Beyond providing timber, fuelwood, medicines, tannins, dyes, and fodder, agroforestry contributes to improved soil fertility, reduced erosion, and enhanced long-term sustainability of farming systems. Commonly adopted tree species in agroforestry systems include *Populus* (poplar), *Senegalia*, *Pinus* (pine), *Eucalyptus*, *Santalum* (sandalwood), and *Terminalia* species (Luna et al., 2009b, 2011).

Among these, *Senegalia catechu* (L.f.) P.J.H. Hurter & Mabb., previously known as *Acacia catechu* Willd. (*khair*), holds a special place due to its multiple uses. It is a deciduous tree that yields catechu, tannins, dye, firewood, and nectar for bees (Orwa et al., 2009). The heartwood, bark, and extract are extensively used in traditional medicine due to the presence of natural compounds such as Catechin and epicatechin (Peng et al., 2015), while the extract also serves in dyeing, leather tanning, preservation of fishing nets, and viscosity regulation in oil drilling (Kumari et al., 2022). Studies have highlighted its pharmacological (anti-ulcer) properties (Khare et al., 2018), antioxidant (Verma and Pandey 2014), nutritional, anti-fungal (Ahmed 2020), anti-microbial and UV-protection (Samant et al., 2020), and anti-diabetic (Pandey et al., 2020). Its medicinal relevance also includes applications in dermatology, sore throat, asthma, and constipation (Rout et al., 2021). From an agronomic and ecological perspective, Kabir et al.,. (2016) observed that *S. catechu* performs well in rainfed and unirrigated areas, especially in small landholdings where density tends to be higher. Research on growth regulators (Thakur et al., 2018) has further demonstrated its potential for vegetative propagation, while studies on related Acacia species highlight sustainable plantation management practices (Huong et al., 2020) and financial viability under taungya systems (Nigussie et al., 2020). Cochard et al. (2021) also documented farmer-driven expansion of Acacia plantations in Vietnam, emphasizing its economic role in land-use change and rural livelihoods. Also, the carbon storage potential of *S. catechu* can be utilized for harnessing the intangible benefits (Mahajan et al., 2023)

In India, the significance of *S. catechu* has also been shaped by policy interventions. The Indian Forest Act, 1927 (Section 51A) empowered states to regulate forest produce, including *S. catechu*. In Jammu and Kashmir, this authority

led to the formulation of The Jammu and Kashmir Non-Forest Land Khair Trees (*Acacia catechu*) Management Plan Rules, 2016 (SRO 111 of 2016). These rules permit private cultivation, regulated felling, conversion, and transportation of *khair*, as well as the establishment of *katha* manufacturing units, subject to inspection and licensing. This policy shift has opened new avenues for farmers to cultivate *S. catechu* on private lands. Farmers in the lower Himalayan region, in particular, continue to retain khair trees within traditional agroforestry systems, which serve as a sustainable and dependable source of income (Thakur et al., 2005, Thakur et al., 2008, Luna et al., 2009a).

Despite its diverse applications and supportive policy framework, limited systematic research has been conducted on the economic evaluation of Senegalia catechu-based agroforestry compared to traditional cropping systems in Jammu and Kashmir. Consequently, the present study was undertaken to assess the economics and profitability of *S. catechu* in the rainfed areas of Samba and Kathua districts, in comparison with alternative cropping systems without trees. Additionally, the study examines resource-use efficiency through the Cobb–Douglas production function, providing insights into the economic viability of *S. catechu*-based agroforestry systems.

MATERIAL AND METHODS

The present study was conducted in the Union Territory of Jammu and Kashmir to assess the economics of agroforestry systems involving *S. catechu*, compared to alternative cropping systems without trees. Kathua and Samba districts were purposively selected for data collection, as they represent rainfed conditions where *S. catechu*-based agroforestry is commonly practiced. A comprehensive questionnaire was designed to capture information on production, management, and marketing aspects of *S. catechu*. The schedule was developed in line with the study objectives and pre-tested with a small group of farmers to ensure clarity, reliability, and relevance. Necessary modifications were incorporated based on the feedback from pre-testing, making the instrument practical and effective for field conditions.

Primary data for the study were collected through personal interviews with the respondent farmers. Face-to-face interactions ensured accuracy of responses and enabled the collection of detailed information on costs incurred, outputs obtained, and marketing channels utilized. To obtain a representative sample, a list of *S. catechu*-growing farmers was obtained from the Forest Department of Jammu and Kashmir, from which 100 farmers were randomly selected for the survey. These respondents provided comprehensive data on plantation management, input use, harvesting, and income generation from S. catechu. For comparative analysis, an additional group of 30 farmers from neighboring areas, not practicing *S. catechu* cultivation, was also surveyed. These farmers followed conventional cropping systems without trees, and information was collected on their crop inputs, yields, costs, and incomes. This comparative group served as a benchmark to analyze the relative profitability of S. catechu-based agroforestry versus traditional crop-based systems.

The cropping patterns followed by farmers in the study area were documented to understand seasonal cultivation practices. During the *kharif* season, maize, paddy, and blackgram were commonly grown, while wheat, mustard, and *toria* predominated in the *rabi* season. This information provided insights into how the integration of *Senegalia catechu* influenced crop selection and farming practices across seasons. To assess the cost of cultivation and returns, the cost concepts recommended by the Commission for Agricultural Costs and Prices (CACP) were applied. These included: Cost A_1 (paid-out costs such as hired labour, bullock and machinery charges, seeds, fertilizers, irrigation, and repairs); Cost A_2 (Cost A_1 plus rent paid for leased-in land); Cost B_1 (Cost A_2 plus interest on fixed capital); Cost B_2 (Cost B_1 plus rental value of owned land); Cost C_1 (Cost B_1 plus imputed value of family labour); Cost C_2 (Cost B_2 plus imputed value of family labour); and Cost C_3 (Cost C_2 plus 10% managerial cost). Incomes were evaluated in terms of Gross Income (total value of output) and Net Income (Gross Income minus Cost C_3).

The profit efficiency was estimated using “Cobb-Douglas” or “Translog” functional specifications as per the suitability of data. The Cobb-Douglas functional form employed in the presented study is presented as equation 'I'.

$$Y_i = f(X_i;\beta)e^{V_i - U_i} \text{ ---------- I}$$

where

Y_i= Profit of the i^{th} farmer

X_i= (1 × K) vector of input quantities used by i^{th} farmer

β = (K × 1) vector of parameters to be estimated

V_i = random variations due to factors outside farmer's control, it is an independently and identically distributed random error component (statistical noise), and usually assumed to follow the standard normal distribution with zero mean and constant variance σ_v^2.

U_i = error due to inefficiency i.e. profit inefficiency (within the control of farmer)

The explicit forms of Cobb Douglas model is expressed in equation as:

$$\ln Y = \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \beta_3 \ln X_3 + (V_i - U_i) \text{-------- II}$$

The profit inefficiency effects model using the various socio-economic variables is given as equation III.

$$U_i = \delta_0 + \delta_1 \ln(\text{Cost of } Senegaliacatechu \text{ trees}) + \delta_2 \ln(\text{urea applied}) + \delta_3 \ln(\text{seed used}) + \delta_4 \ln(\text{Labour}) + \delta_5 \ln(\text{MOP}) + \delta_6 \ln(\text{DAP}) + \delta_7 \ln(\text{Age}) + \delta_8 \ln(\text{Farming experience}) \quad \text{---------- III}$$

Profitability analysis: Profitability analysis of agroforestry system was assessed using the following concepts:

Net Present Value

Where

$$\sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

R_t= Net cash inflow-outflows during a single period t

i = Discount rate or return that could be earned in alternative investments

t = Number of time periods

Internal rate of return

$$0=NPV= \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_o$$

Where

C_t = Net cash inflow during the period t

C_0 = Total initial investment costs

IRR = The internal rate of return

t = Number of time periods

Cropping system resource use efficiency: The marginal physical product (MPP) of inputs was obtained by taking derivatives of production function. The estimated production function underlying crop production was used to assess the efficiency of factor proportions.

The Marginal value of product (MVP) was computed by multiplying the coefficients of the given resource with the ratio of the geometric means of the output to the geometric mean of given resource.

$$MVP\ (X_i) = b_i \frac{\text{Geometric Mean } \bar{Y}}{\text{Geometric Mean } \bar{X}_i}$$

Where

MVP = Marginal Value of Product

bi = Corresponding elasticity of

Xi (G.M.) = G.M. of i^{th} resource

Y (G.M.) = Computed value of Y at G.M. levels of resources

The MVP helps in assessing the efficiency of resource use in production economics as given below:

- MVP > 1: Indicates underutilization of resources (more of the resource can be profitably used)
- MVP < 1: Indicates overutilization of resources (excess use is reducing efficiency)
- MVP = 1: Indicates optimal utilization of resources (resources are being used most efficiently)

RESULTS AND DISCUSSION

Concentration of *Senegalia catechu:* The spatial distribution of *S. catechu* plantations in the Jammu region exhibited considerable variation across villages. The blue-shaded areas on Figure 1 represent zones of low concentration (0.1-7 ha), indicating scattered plantations, often maintained as boundary trees or in small patches within farmlands. Yellow-shaded areas (7.1-25 ha) denote medium concentration zones, where farmers have adopted *S. catechu* plantations on a relatively larger scale, integrating them with seasonal crops under an agroforestry model. Red-shaded zones, representing high concentration areas (above 25 ha), highlight clusters where *S. catechu* cultivation has become a dominant land-use practice and serves as a significant source of income. Green boundaries depict village limits, helping to demarcate the spread of *S. catechu* across the study area.

This distribution pattern indicated that adoption of *S. catechu*-based agroforestry is uneven, concentrated in pockets where soil, rainfall, and farmer preferences are favorable. High-concentration zones, in particular, suggest the emergence of localized production hubs, which could facilitate collective marketing, establishment of katha-processing units, and enhanced bargaining power for farmers. Conversely, the prevalence of low-concentration areas reflects that many farmers are still experimenting with *S. catechu* or remain reliant on conventional crops. These findings underscore the importance of policy support, extension services, and market linkages to promote wider adoption of *S. catechu* plantations in the region.

Cropping pattern: The farmers predominantly cultivate a mix of cereals, pulses, and oilseeds across the kharif and rabi seasons (Table 1). During the *kharif* season, maize emerged as the major crop, grown by 79 farmers over 42.20 ha, reflecting its importance as both a staple food and fodder

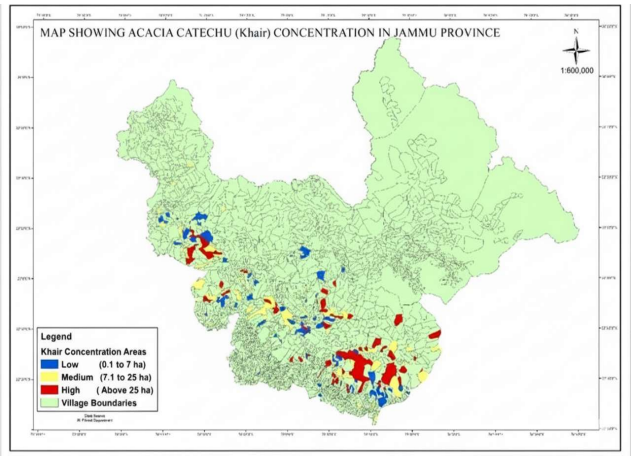

Fig. 1. Concentration of *S. catechu* in Jammu region

under rainfed conditions. Paddy was the second most prominent crop, cultivated by 63 farmers on 29.20 ha, primarily in areas with relatively better water availability. In contrast, blackgram was grown by only 4 farmers on 2.00 ha, highlighting its marginal role in the regional cropping system. In the *rabi* season, wheat dominated, with 89 farmers cultivating it on 57.60 ha, underscoring its significance as the primary winter staple. Oilseeds also featured in the rotation, with mustard grown by 25 farmers on 9.35 ha and *toria* by 11 farmers on 2.30 ha, indicating that farmers diversify their cropping system with short-duration oilseed crops for both subsistence and market purposes.

Overall, cereal crops, particularly maize and wheat, form the backbone of the farming system in the sampled districts, while pulses and oilseeds occupy relatively smaller areas. This pattern reflects farmers' preference for food security through cereals, supplemented by cash income from mustard and, to a lesser extent, blackgram and toria. The relatively low area under pulses and oilseeds also points to potential opportunities for crop diversification and nutritional security interventions. Furthermore, when integrated with *Senegalia catechu* plantations, this cropping pattern provides a balanced mix of food, cash, and tree-based products, enhancing both farm income and overall resilience.

Economics of *kharif* crops: The cost structure, returns, and profitability vary across crops, with labour emerging as the most significant cost component in all cases (Table 2). For maize, the cost of cultivation was estimated at ₹52,979.25/ha, with human labour, including both hired and family labour accounting for the largest share (₹11,672/ha), followed by seed expenses (₹4,171.47/ha). This underscores that maize production in the study area is highly labor-intensive and requires a relatively high seed rate. The gross return from maize was ₹70,081.53/ha, resulting in a net return of ₹17,102.28/ha and a benefit–cost (B:C) ratio of 1:1.32. Rana et al. (2018) also highlighted the labor-intensive nature of maize cultivation under rainfed conditions.

For paddy, the cost of cultivation was slightly higher at ₹58,795.21/ha. Labour remained the dominant input, with farmers spending ₹27,604.81/ha on human labour-nearly half of the total cost. Herbicide application was the second-largest expense, averaging ₹4,864.52/ha, reflecting the crop's high requirement for weed management. Gross returns were estimated at ₹112,125.31/ha, significantly augmented by by-product returns of ₹32,429.46/ha from straw. This resulted in a net return of ₹53,329.96/ha and a benefit–cost (B:C) ratio of 1:1.90, indicating that paddy cultivation under the agroforestry system is highly remunerative. These findings are consistent with Srinivasan (2012), where paddy is among the most labor-intensive crops, often requiring twice the labour input compared to other cereals.

In blackgram, the cost of cultivation was estimated at ₹41,232.21/ha. As with other crops, labour constituted the largest share of expenditure (₹14,700.00/ha), followed by herbicide costs (₹650.00/ha). The gross return was ₹81,585.00/ha, yielding a net return of ₹40,352.79/ha and a benefit–cost (B:C) ratio of 1:1.97-the highest among the *kharif* crops studied. The blackgram, despite being cultivated over a relatively smaller area, is a highly profitable crop under S. catechu-based agroforestry systems. Mohiuddin et al.

Table 1. Cropping pattern of *S. catechu* growing farmers in Jammu region

Season/Crops	Total area (ha)	No. of farmers
Kharif		
Maize	42.20	79
Paddy	29.20	63
Blackgram	2.00	04
Rabi		
Wheat	57.60	89
Mustard	9.35	25
Toria	2.30	11

Table 2. Economic return of *Kharif* crops under Agroforestry system involving *S. catechu* trees

Particulars	Maize	Paddy	Blackgram
Seed (₹)	4171.47	3183.06	405.00
Manure (₹)	2680.77	2012.90	450.00
Urea (₹)	3326.92	529.41	62.50
DAP (₹)	289.62	1017.20	0.00
MOP (₹)	596.92	264.59	160.00
Herbicide (₹)	381.54	4864.51	650.00
Hired Labour (₹)	3460.00	8467.74	4550.00
Family Labour (₹)	8212.00	19137.07	10150.00
Interest on working capital (₹)	521.75	711.87	219.71
Depreciation (₹)	11671.15	1915.32	7350.00
Rental Value (₹)	15000.00	15000.00	15000.00
Interest on fixed capital (₹)	2667.11	1691.53	2235.00
Total cost (₹)	52979.25	58795.21	41232.21
Yield of main product (quintal)	36.78	27.58	12.95
Price of main product ((₹/q)	1870	2889.62	6300.00
Returns from main product (₹)	68778.60	79695.80	81585.00
Returns from by-product (₹)	1302.93	32429.46	0.00
Gross return (₹/ha)	70081.53	112125.31	81585.00
Net return (₹/ha)	17102.28	53329.96	40352.79
Cost-benefit ratio	1:1.32	1:1.90	1:1.97

(2018) also reported that blackgram is labor-intensive but capable of generating substantial net returns, based on their study in the Sherpur and Jamalpur districts of Bangladesh. Comparative analysis indicates that paddy and blackgram outperformed maize in terms of profitability under *S. catechu*-based agroforestry systems. While maize continues to serve as an important subsistence crop in rainfed conditions, farmers in the study area achieved higher economic gains from paddy and blackgram, particularly when accounting for by-product returns in paddy and favorable market prices for blackgram. These results suggest that integrating *S. catechu* plantations with high-value or input-efficient crops can enhance overall farm income, improve labour utilization, and increase resource-use efficiency.

Economics of *Rabi* crops: The economic returns of *Rabi* crops under the *S. catechu*-based agroforestry system indicated that wheat cultivation incurred a cost of ₹46,367.06/ha, with labour as the dominant input (₹17,657.30/ha) followed by seed (₹4,940.53/ha), reflecting its highly labor-intensive nature (Table 3). The crop generated a gross return of ₹51,367.44/ha and a net return of ₹5,000.38/ha, resulting in a modest benefit–cost (B:C) ratio of 1:1.07. These findings are consistent with Kharel et al. (2021), who similarly reported wheat as a labor-intensive crop with relatively low profitability. Mustard exhibited stronger economic performance, with a cost of cultivation of ₹44,787.77/ha, dominated by labour expenditure (₹13,550.80/ha) followed by DAP fertilizer (₹2,267.38/ha). The gross return from mustard was ₹118,581.87/ha, yielding a net return of ₹73,794.10/ha and a B:C ratio of 1:2.64, indicating its high economic viability under the agroforestry system.

Sonvanee and Pathak (2016) also identified mustard as a profitable crop with favorable input–output ratios. Toria, despite having the highest cultivation cost (₹60,002.85/ha), demonstrated considerable profitability. Labour remained the largest cost component (₹19,478.20/ha), followed by DAP fertilizer (₹5,269.56/ha). The crop generated a gross return of ₹128,106.65/ha and a net return of ₹68,103.80/ha, resulting in a benefit-cost (B:C) ratio of 1:2.13. Thakuria et al., (2025) also reported B:C ratio of 2.07 for toria. Overall, the results indicate that while wheat continues to serve as a staple crop, oilseeds such as mustard and toria offer substantially higher returns under S. catechu-based agroforestry, making them more suitable for enhancing farm income and improving resource-use efficiency in the study area.

Economics of *S. catechu* agroforestry and non-agroforestry interventions: The crop yields were slightly higher under the non-agroforestry system-for example, maize (30.20 q/ha vs. 28.58 q/ha), paddy (28.64 q/ha vs. 27.58 q/ha), wheat (20.60 q/ha vs. 18.39 q/ha), and mustard (24.15 q/ha vs. 23.31 q/ha) (Table 4). This modest reduction in yield under agroforestry is expected due to tree–crop competition for light, moisture, and nutrients. However, when net returns and benefit–cost (B:C) ratios were compared, the agroforestry system clearly outperformed sole cropping. Although the net return from mustard was slightly lower under agroforestry (₹73,794.10/ha) compared to conventional cultivation (₹80,477.10/ha), the inclusion of *S. catechu* significantly enhanced overall farm income, contributing ₹48,63,485 and achieving a very high B:C ratio of 1:32. As a result, the average B:C ratio of farms with agroforestry reached 1:6.14, compared to only 1:1.88 in the conventional system. These findings establish agroforestry as a more profitable and sustainable land-use strategy, despite marginal reductions in annual crop yields. Shode and Amanuel (2016) also demonstrated that tree-based agroforestry systems provide substantially higher net benefits than monocropping, primarily due to the complementary role of trees in enhancing farm income and long-term productivity.

S. catechu is financially viable when harvested at 22 years of age, with a positive net present value (NPV) of ₹9,18,956.40 at an 8% discount rate, ₹5,41,450.97 at 10%,

Table 3. Economic returns of *Rabi* crops under *S. catechu* based agroforestry systems

Particulars	Wheat	Mustard	Toria
Seed (Rs.)	4940.53	1124.92	4317.39
Manure (Rs.)	247.35	545.45	86.95
Urea (Rs.)	709.43	599.67	1108.69
DAP (Rs.)	821.12	2267.38	5269.56
MOP(Rs.)	265.16	1874.33	2652.17
Herbicide (Rs.)	2624.71	761.49	560.86
Hired labour (Rs.)	5517.41	3219.25	6086.95
Family labour (Rs.)	12139.88	10331.55	13391.30
Interest on working capital	529.39	363.73	702.89
Depreciation (Rs.)	1883.70	6545.45	8478.26
Rental Value (Rs.)	15000.00	15000.00	15000.00
Interest on fixed capital	1688.37	2154.54	2347.82
Total cost	46367.06	44787.77	60002.85
Yield of main product	18.39	23.31	26.54
Price of main product/q	1975.00	4650.00	4650.00
Returns from main product	36320.25	108391.50	123411.00
Returns from by-product	15047.19	10190.37	4695.65
Gross return/ha	51367.44	118581.87	128106.65
Net return/ha	5000.38	73794.10	68103.80
Cost-benefit ratio	1:1.07	1:2.64	1:2.13

and ₹2,96,702.52 at 12% (Table 5). The internal rate of return (IRR) for this rotation age was estimated at 13%, exceeding the assumed discount rates and confirming profitability. However, extending the harvest age beyond 22 years reduced economic viability, as reflected by negative NPVs at higher discount rates and a sharp decline in IRR (8% at 32 years, 5% at 42 years, and 2% at 52 years). This attributable to increased opportunity costs and diminishing incremental returns over time, highlighting the importance of timely harvesting for maximizing profitability in *S. catechu*-based agroforestry systems. Pitigala and Gunatilake (2002) also reported that species such as mahogany, teak, jackfruit, and eucalyptus yielded positive NPVs at moderate discount rates, but values turned negative at higher rates, underscoring the significance of selecting an appropriate economic rotation for forestry species.

The estimates of the Cobb–Douglas regression model) provide insights into the factors influencing gross profit under the *S. catechu*-based agroforestry system in Samba and Kathua districts (Table 6). The coefficient of determination indicate that 78% of the variation in gross profit was explained by the selected explanatory variables, thus reflecting a good fit of the model. The cost of *S. catechu* (0.30*), quantity of seed (0.18**), labour (0.33**), and DAP (0.23*) had positive and statistically significant effects on gross profit. This implies that a 1% increase in these inputs would increase gross profit by 0.30, 0.18, 0.33, and 0.23%, respectively. These findings highlight the critical role of both tree and crop inputs, particularly labour and fertilizers, in enhancing profitability under agroforestry systems.

The urea (-0.05) exhibited a negative, though statistically non-significant, relationship with gross profit, suggesting that excessive or imbalanced application may not contribute positively to returns. Similarly, MOP (0.008), age of respondents (0.03), and farming experience (0.05) had positive but non-significant coefficients, indicating that while these factors tend to enhance gross profit, their impact was not strong in this study. Marginal Value Product (MVP) analysis further revealed that resources such as the cost of *S. catechu* (₹3.28), seed (₹299.59), labour (₹838.83), and DAP (₹31,924.70) were underutilized, suggesting potential for better allocation to improve returns. Phuge et al., (2020) also

Table 6. Estimates of Cobb Douglas regression model

Dependent variable: Gross profit (₹)

Variables	Regression coefficients	Standard error	MVP
Constant	2.849*	0.419	-
Cost of *S. catechu* (₹)	0.30*	0.09	3.28
Quantity of urea (q)	-0.05	0.93	-5999.81
Quantity of seed (₹)	0.18**	0.07	299.59
Quantity of labour (q)	0.33**	0.13	838.83
Quantity of MOP (q)	0.008	0.04	2847.02
Quantity of DAP (q)	0.23*	0.48	31924.70
Age of respondent (year)	0.03	0.17	168.79
Farming experience (year)	0.05	0.12	441.85

Coefficient of determination (R^2) = 0.78
*, **Significant at 1 % and 5% level of significance

Table 4. Comparative economics of agroforestry with non-agroforestry system

Crops	With agroforestry intervention			Without agroforestry intervention		
	Yield (q/ha)	Net return (₹/ha)	B.C ratio	Yield (q/ha)	Net return (₹/ha)	B.C ratio
Maize	28.58	17102.28	1:1.32	30.20	18443.13	1:1.34
Paddy	27.58	53329.96	1:1.90	28.64	55569.91	1:1.95
Wheat	18.39	5000.38	1:1.07	20.60	7005.16	1:1.14
Blackgram	12.95	40352.79	1:1.97	13.42	43572.50	1:1.99
Mustard	23.31	73794.10	1:2.64	24.15	80477.1	1:2.68
Toria	26.54	68103.80	1:2.13	27.10	76455.00	1:2.22
Senegalia catechu	1000	4863485	1:32	-	-	-
Total	-	5121168.31	1:6.14	-	281522.80	1:1.88

Table 5. Feasibility analysis of *S. catechu* under agroforestry systems

Particulars	Age of trees: 22 years	Age of trees: 32 years	Age of trees: 42 years	Age of trees: 52 years
NPV@8%	₹ 9,18,956.40	₹ 3,16,296.19	₹ -3,35,663.60	₹ -5,35,371.70
NPV@10%	₹ 5,41,450.97	₹ 1,02,637.05	₹ -3,53,899.57	₹ -4,57,493.20
NPV@12%	₹ 2,96,702.52	₹ -5,277.03	₹ -3,30,187.69	₹ -3,87,370.45
IRR	13%	8%	5%	2%

reported that human labour, fertilizer, and irrigation had significant positive effects on farm income. The study highlights that efficient management of S. catechu, labour, and fertilizer inputs plays a critical role in enhancing the profitability of agroforestry systems.

CONCLUSION

The highest concentration of commercially exploitable *Senegalia catechu* was located in Kathua district, followed by Samba district in the Jammu region of J&K. The farmers adopting *S. catechu*-based agroforestry systems achieved a substantially higher benefit–cost under sole cropping, highlighting agroforestry as a more profitable and sustainable land-use practice. The gross profit was positively influenced by the costs of *S. catechu* seed, labour, MOP, DAP, as well as farmer age and experience/These findings underscore the importance of balanced input use and efficient management for maximizing profitability under agroforestry. The optimum marketable age of *S. catechu* is 22 years, corresponding to an average tree diameter of 30 cm; beyond this age, the Net Present Value (NPV) becomes negative, rendering delayed harvesting economically unviable for farmers. The study concludes that *S. catechu*-based agroforestry not only enhances farm-level income and resource use efficiency but also provides long-term sustainability in rainfed areas of Jammu and Kashmir. It offers a viable model for integrating trees with crops to secure both economic and ecological benefits.

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Agroforestry Systems in the North-Western Himalayas: A Nexus of Biodiversity Conservation, Livelihood Enhancement, and Ecosystem Services

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***Abstract*:** The North-Western Himalayn Region (NWHR) spanning Uttarakhand, Himanchal Pradesh and Jammu & Kashmir supports diverse agroecological zones and traditional agroforestry systems thereby conserving biodiversity, enhancing livelihood and improving other ecosystem services. Agroforestry systems emerge as a multifunctional land use strategy in these fragile landscapes offering various provisioning, regulating, supporting and cultural services. Integrating trees, crops and livestock in these systems enhances food and fodder security, sequesters carbon, regulates hydrology and buffer communities against climate variabilities. In Garhwal Himalayas, agroforestry provides 0.5-0.68 kg of fuelwood per capita daily and 4.70-5.57 kg fodder per animal unit reducing the reliance on natural forests. Traditional agroforestry systems ranging from Homesteads and Silvipastoral models to Sea buckthorn-based agroforestry demonstrates deep cultural integration and resilience. However, challenges such as land fragmentation, land tenure issues, restrictive forest laws etc. constraints its wider adoption. Supportive framework and policies like National Agroforestry Policy, Nationally Determined Contributions, Convention on Biodiversity, Land Degradation Neutrality etc. helps to strengthen agroforestry in North Western Himalayan Region.

Keywords:

The North-Western Himalayan Region (NWHR) comprising regions of Indian states of Uttarakhand, Himanchal Pradesh and Jammu & Kashmir have varying agroecological conditions. It not only supports rich biodiversity but also helps to sustain a large population depending on the existing natural resources for their livelihood (Rawat 2023) including food, fodder, fibre, timber, medicine as well as drinking water (Sharma and Chettri 2021). Agroforestry systems in this context emerge as a multifunctional and multipurpose land use strategy which contributes to diverse ecosystem services including provisioning, regulating, supporting and cultural services by maintaining ecological stability, food and fodder security, climate resilience, carbon storage etc. (Borelli et al., 2018). This region consists of various traditional and evolved agroforestry systems over time ranging from silvipastoral and agrisilvicultural combinations to home gardens and alley cropping models developed through indigenous knowledge and community adaptation to wide range of physical and socio-cultural conditions (Verma et al., 2024). It acts as dynamic link between conservation and development offering different pathways to reduce increasing pressure on natural forests and enhance sustainability of agricultural farming systems (Nair et al., 2022). As the world is facing issues like global warming, climate change, food insecurity, biodiversity and land degradation etc., agroforestry acts as a mitigation and adaptation strategy to restore ecosystems, ensure and support environmental sustainability while maintaining the land use productivity (Saikia et al., 2017). This review aims to provide the information regarding currently existing agroforestry systems in NWHR analysing their ecological functions, livelihood implications, biodiversity conservation and other ecosystem services contribution. It also reviews the prevailing challenges faced by the or practitioners of the agroforestry systems outlining policy gap and research constraints for strengthening agroforestry as a sustainable land use strategy in NWHR.

Agroforestry systems across varying agroclimatic zones of the North-Western Himalayan region: The NWHR encompasses a wide range of agroclimatic zones (Table 1), covering an area of approximately 0.33 million km^2 varying from subtropical foothills to temperate mid-hills and alpine highlands lying above 3000 m amsl and shaped by diverse climatic conditions, soil types and altitudinal gradients (Sharma et al., 2017). It significantly influences the local farming systems and land use practices leading to depletion of resources and reduced productivity. In this context, agroforestry systems in these regions have naturally evolved as an adaptive strategy for sustaining productivity, ensure resource conservation while maintaining the ecological balance. Over centuries, it has evolved to address food insecurity, forest degradation, and climate issues

(Verma et al., 2024). Despite modernization and pressure of land fragmentation, many traditional systems persist and offer solutions for developing climate resilient agroforestry models.

Diverse agroforestry systems prevalent across North-Western Himalayan region: The NWHR region exhibits rich indigenous knowledge systems that foster sustainable land use practices. Local communities have developed region-specific agroforestry models like homestead in Garhwal and Himanchal including multilayered planting of vegetables, fruit trees, medicinal plants and fodder trees reflecting biodiversity conservation and household food security (Kumar 2022) while the silvi-pastoral systems are common in high altitude and slopy areas where these systems integrate fodder trees (eg. *Bauhinia variegata, Grewia optiva*) with grazing lands, supporting livestock and preventing soil erosion (Rawat 2023). The major prevalent agroforestry systems in North-Western Himalayan region have been summarized in the Table 2 and some traditional agroforestry systems have been shown in Table 3.

Agroforestry based Ecosystem services in the North Western Himalayan Region: Ecosystem services are the set of diverse ecological purposes or the direct and indirect contributions of an ecosystem to the human well-being (TEEB 2010). The Millennium Ecosystem Assessment (MES) provides a globally recognized classification into four types, viz. provisioning services, regulating services, supporting services and cultural services (Tallis and Kareiva 2005, Haines-Young and Potschin 2012) (Fig. 1). The following are some significant ecosystem services that NWHR agroforestry systems offer:

Agroforestry for biodiversity conservation: Agroforestry as a natural habitat ensures in-situ conservation of native flora and fauna offering a sustainable land use model. Mountain regions are rich source of biodiversity due to their diverse gene pools. However, several anthropogenic activities such as hunting, timber extraction, extensive grazing, forest conversion, and climate change, pose a danger to these ecosystems' biodiversity. By reducing anthropogenic pressure, agroforestry mitigates forest degradation while providing protection for a variety of species. Well integrated agroforestry landscapes serve as ecological corridors that facilitate habitat connectivity and species movement across fragmented Himalayan topography. Various fruit trees like *Malus, Prunus, Pyrus,* and *Morus* species and fodder tree species like *Grewia, Grevillea,* and *Gmelina* are frequently planted in lower elevations. Another significant tree species in the higher altitude Himalayan region is *Hippophae salicifolia*, which is grown for its fruit, which can be utilized locally as fuelwood,

Table 1. Zonal classification of agro-climatic zones of the North-Western Himalayan states

States	Agro-climatic zones	Altitudinal ranges (m amsl)	Districts/ Part of the state
Jammu and Kashmir	Low altitudinal subtropical zone	≤1000	Jammu, Kathua, Udhampur, and parts of Doda and Rajouri districts
	Mid to high altitude intermediate zone	1000-2000	Poonch and major part of Rajouri, Anantnag, Pulwama, part of Doda district
	Valley temperate zone and mid to high altitude zone	2000-3000 (<1200 Kashmir valleys)	Srinagar, Baramulla, Kupwara and part of Anantnag, Pulwama, Budan, and Poonch
	Cold arid zone	>3000	Kargil, Leh, upper parts of Doda, Anantnag, Baramulla and Kupwara districts
Himanchal Pradesh	Low altitudinal subtropical zone	≤1000	Una, Hamirpur, Bilaspur and parts of Kangra, Chamba, Mandi, Sirmour, and Solan districts
	Mid-hills subhumid zone	1000-2000	Part of Chamba, Solan, Shimla, Mandi, Sirmour districts
	High hills temperate wet zone	2000-3000	Parts of Chamba, Kangra, Mandi, Sirmour, Shimla, and Kullu districts
	High hills dry temperate zone	>3000	Kinnaur, Lahaul Spiti, and parts of Kangra and Chamba districts
Uttarakhand	Babhar and tarai zone and subtropical low hills zone	<1000	Haridwar, Udham Singh Nagar, and parts of Nainital, Dehradun, Pauri Garhwal districts
	Hill zone Mid-hill subhumid zone	1000–2000	Parts of Garhwal, Nainital, Dehradun, and Champawat districts
	High hills temperate zone	2000–3000	Almora, Bageshwar, Tehri Garhwal, parts of Chamoli, Champawat, Rudraprayag, Nainital, and Uttarkashi districts
	High hill dry temperate zone	>3000	Parts of Chamoli, Rudraprayag, Pithoragarh, and Uttarkashi districts

Source: Ghosh (1981), Kashyap et al. (2013)

fodder and nutraceutical properties providing farmers with a high income. Because of the ability to endure the shock and strain of environmental and climatic change, agroforestry has been recognized as one of the resilient farming systems to guarantee food security (Panda 2025). Nair et al. (2022) emphasizes the role of these strategically located agroforestry systems in maintaining ecological continuity and enhancing biodiversity conservation outside recognized protected areas. One of the main international initiatives to emphasize the advantages of biodiversity and the rising costs of ecosystem degradation and biodiversity loss is the Economics of Ecosystems and Biodiversity (TEEB). All ecosystem services are regulated by biodiversity, but it can also function as a service in and of itself (Mace et al., 2012). As it offers resilience against present or upcoming changes in ecosystems and the benefits they offer, biodiversity is sometimes thought to have insurance value.

Climate resilience and other ecosystem services: Agroforestry systems affect climatic patterns and absorb carbon from the atmosphere. Climate regulation describes how ecosystems affect the earth's temperature by releasing greenhouse gases (GHGs) into the atmosphere. These systems enhance soil processes and properties, which are crucial for regulating the climate by lowering GHGs emissions and sequestering carbon, as well as for supplying water by controlling soil properties. The potential for agroforestry systems to reduce climate change and global warming has been estimated at around 26 million metric tons of carbon, which will rise to 45 million metric tons by 2040 as they include woody species that develop quickly (IPCC 2001). Furthermore, in both low-lying and high-altitude regions, agroforestry serves as a substitute for the traditional farming system in order to lessen deforestation and CO_2 emissions and slow down climate change and global warming (Mbow et al., 2014). The World Agroforestry Centre (WAC) states that agroforestry systems can boost yield up to 50% and can help sequester as much as 3.5 tons of C ha^{-1} yr^{-1}. The various agroforestry types found in NWHR are capable of capturing and storing carbon in soil and vegetation, with values ranging from 0.02-54 Mg C ha^{-1}. In agriculture-based agroforestry systems, the majority of the biomass is removed for human consumption resulting in a lesser vegetation carbon compared to horticulture agroforestry since plant parts extraction is limited. However, differences in elevation, agroforestry components, and management strategies led to variances in carbon stock in both vegetation and soil (Chisanga et al., 2018, Vikrant et al., 2020). In addition to these, the age and growth pattern of plants, as well as the

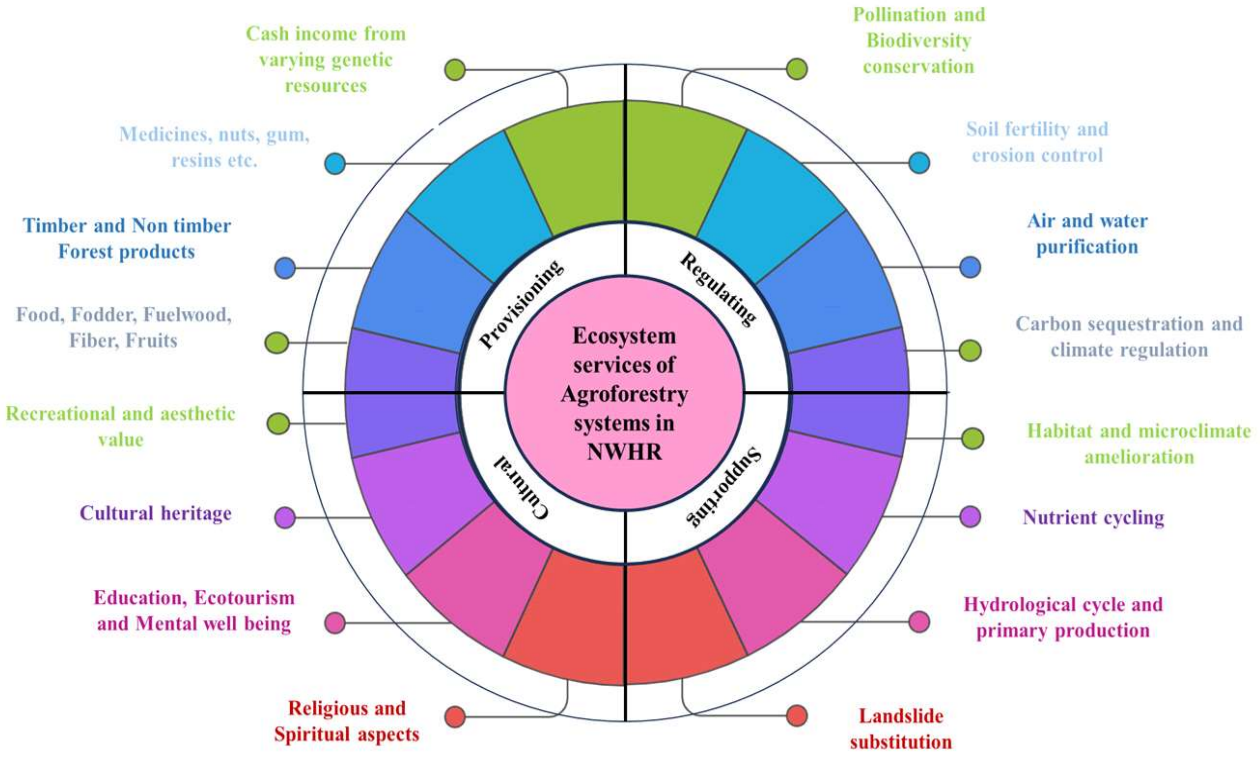

Fig. 1. Major Ecosystem services provided by agroforestry systems in North-Western Himalayan Region

interactions between crops and trees, affect the carbon stock and biomass accumulation in agroforestry systems (Kanime et al., 2013). This helps to lock in more carbon and improve CO_2 mitigation. Data indicates that by taking appropriate mitigation measures, soil carbon emissions might be lowered by 50% by 2050 compared to 2010 levels (Xu et al., 2020). Agroforestry techniques can reduce farmers' susceptibility to climate change, according to a study conducted in the Western Himalayan region (Pandey et al., 2017). This is because agroforestry is a sustainable land-use system for the mountains because it is self-regulating, adaptive, and incorporates a variety of crops and livestock.

Culture and Supporting services: Agroforestry systems in the North Western Himalayas play a critical role in enhancing ecosystem services and bolstering climate resilience. In addition to the primary services listed above, it also offers supporting and cultural ecosystem services. The integration of trees with crops and livestock improves carbon sequestration potential, acting as a natural sink and aiding in climate change mitigation (Pandey and Ghosh 2023). These systems contribute significantly to soil health by promoting organic matter accumulation and microbial diversity, thus enhancing nutrient cycling (Rawat et al., 2023). Furthermore, agroforestry helps regulate the hydrological cycle by enhancing water infiltration, reducing surface runoff, and facilitating spring recharge in the ecologically fragile Himalayan terrain (Sharma et al., 2024). Himalayan region's agroforestry systems provide an increase in pollinator species (Sharma et al., 2020), provide fodder for livestock, conserve water and improve water use efficiency (Chauhan et al., 2013), regulate nutrient cycling, provide aesthetic value, and provide ritual plants. Furthermore, various ethnic communities that live in the mountains consider the mountain landscapes, including the agroforestry systems of the Himalayan region, to be sacred and culturally significant because they offer spiritual and recreational services (Sharma et al., 2007). Additionally, agroforestry systems have helped certain communities preserve their traditional

Table 2. Prevalent agroforestry systems and species diversity in NWHR (Modified from Sharma et al. 2024)

Region	Agroforestry systems	Species composition
Himanchal Pradesh	Agri-silviculture, Agri-horticulture, Silvi-pastoral, Pastoral-silviculture, Pastoral-Horti silviculture, Horti-agriculture, Horti-pastoral, Agri-Horti silviculture, Agri-Silvi horticulture, Agrisilvopastoral	Forest trees: *Abies pindrow, Acacia catechu, Ailanthus altissima, Albizia chinensis, Bauhinia variegata, Cedrus deodara, Celtis australis, Dalbergia sissoo, Diospyros kaki, Grewia optiva, Melia composita, Picea smithiana, Pinus gerardiana, Pinus wallichiana, Populus alba, Populus ciliata, Quercus semecarpifolia, Quercus ilex, Robinia pseudoacacia, Salix alba, Toona ciliata, Ulmus villosa*
		Fruit trees: *Carica papaya, Citrus spp., Juglans regia, Litchi chinensis, Malus domestica, Mangifera indica, Morus alba, Phyllanthus emblica, Prunus amygdalus, Prunus armeniaca, Prunus domestica, Prunus persica, Psidium guajava, Punica granatum, Pyrus communis*
		Crops: *Abelmoschus esculentus, Allium cepa, Allium sativum, Avena sativa, Beta vulgaris, Brassica juncea, Brassica oleracea, Capsicum annuum, Cicer arietinum, Glycine max, Hordeum vulgare, Oryza sativa, Phaseolus vulgaris, Pisum sativum, Solanum lycopersicum, Solanum lycopersicum, Solanum smithiana, Triticum aestivum, Vigna mungo, Zea mays*
Uttarakhand	Agrisilviculture, Agrisilvihorticulture, Agrisilvopastural, Silvipastoral, Agrihorticulture, Agrihortisilviculture, Silvi horticulture, Hortipastoral	Forest trees: *Cedrus deodara, Celtis australis, Ficus auriculata, Ficus palmata, Grewia oppositifolia, Melia azedarach, Pinus roxburghii, Pinus wallichiana, Quercus leucotrichophora, Rhododendron arboretum, Toona ciliata,*
		Fruit trees: *Carica papaya, Citrus spp., Emblica officinalis, Juglans regia, Malus domestica, Mangifera indica, Morus serrata, Musa paradisiacal, Myrica esculenta, Prunus armeniaca, Prunus cerasoides, Prunus domestica, Prunus spp., Psidium guajava, Punica granatum, Pyrus pyrifolia*
		Crops: *Abelmoschus esculentus, Amaranthus caudatus, Amaranthus spinulosa, Brassica campestris, Brassica juncea, Cajanus cajan, Eleusine coracana, Glycine max, Hordeum vulgare, Lens culinaris, Lycopersicon esculentum, Oryza sativa, Phaseolus vulgaris, Pisum sativum, Spinacea oleracea, Triticum aestivum, Vigna mungo, Vigna umbellate, Zea mays*
Jammu and Kashmir	Agrisilviculture, Agrihorticulture, Horti agriculture, Horti-silviculture, Horti-silvipastoral, Horti-agrisilviculture, Silvipastoral, Hortipastoral, Agrisilvipastoral, Agri-Horti silviculture, Homesteads	Forest trees: *Abies pindrow, Acacia catechu, Aesculus indica, Ailanthus altissima, Albizzia lebbeck, Cedrus deodara, Dalbergia sissoo, Picea smithiana, Pinus wallichiana, Populus deltoids, Populus nigra, Robinia pseudoacacia, Salix alba, Ulmus wallichiana*
		Fruit trees: *Cydonia oblonga, Juglans regia, Malus spp., Morus alba, Prunus amygdalus, Prunus avium, Prunus persica, Punica granatum*
		Crops: *Abelmoschus esculentus, Allium cepa, Allium sativum, Brassica juncea, Brassica oleracea, Brassica rapa, Cucumis sativus, Daucas carota, Glycine max, Lagenaria siceraria, Oryza sativa, Phaseolus vulgaris, Pisum sativum, Raphanus sativus, Solanum lycopersicum, Solanum tuberosum, Triticum aestivum, Vigna radiata, Zea mays*

knowledge and germplasm of native and heirloom crop and tree species, as well as culturally significant plants including *Ocimum sanctum, Ficus reliogiosa*, and *Thysanolaena maxima* (Islam et al., 2017). As climate variability intensifies, the adaptive capacity of agroforestry, through diversified land use and species richness, offers a buffer against extreme events and supports both ecological stability and sustainable livelihoods (Hussain et al., 2024).

Livelihood and socio-economic benefits: The socio-economic status of a society is determined by combining its social and economic standing in relation to others, having a broad impact on the availability of resources, the pattern of social livelihood, food security, etc. (Roy et al., 2013). Ignoring socioeconomic issues causes various developmental programs to suffer, thus, knowledge of these factors is crucial for farming systems and aids in the formulation of policies for the welfare of society (Sood et al., 2008). Agroforestry and socioeconomic factors are interlinked as these encourage tree integration on farms while improving livelihoods, especially benefitting vulnerable groups including marginal and small farmers, women, and children emphasizing its potential to enhance society (Murthy et al., 2016). Numerous studies conducted nationwide demonstrate its beneficial effects on the socioeconomic status of farmers in terms of women welfare, advancement of marginalized groups, food security, enhanced financial resilience, decreased crop failure, consistent employment and income, increased land productivity etc. Agroforestry can generate around 5.76-million-man days annually, spanning 75,500 hectares, demonstrating the potential for employment as well as a rural development in the tough Himalayan terrains (Arunachalam et al., 2020). Agroforestry contributes directly to household provisioning of fodder, fuelwood, and non-timber forest products (NTFPs). In Garhwal Himalaya, agroforestry was found to supply 0.5−0.68 kg fuelwood per capita per day and 4.70-5.57 kg fodder per animal unit per day, depending on altitude, fulfilling substantial proportions of household energy and livestock feed needs, while reducing dependency on natural forests (Nagar et al., 2018). Crucially, agroforestry systems also buffer households against climate and market shocks. This correlation between socio-economic indicators and the extent of agroforestry adoption reinforces its role as a risk mitigation strategy amid climatic variability and market fluctuations.

Challenges and research gap: India has surpassed China as the most populated nation, and while the agricultural sector employs about half of the workforce, its contribution to GDP has decreased since independence to roughly 17.8% (Sharma and Raina 2021). NWHR ecosystems are delicate due to its steep and rocky terrain, geological dangers, biodiversity, land degradation, land use and land cover, and topography (Saha and Kumar 2019). However, inconsistency in its adoption arises due to different land tenure systems, market access and changing socio-economic priorities across different agroecological zones of the NWHR (Gyau et al., 2014, Kumar et al., 2024). In addition, a several anthropogenic activities, such as deforestation, excessive resource use, poor farming techniques, etc., have led to land fragmentation (Shukla et al., 2018), soil erosion, the depletion of land resources, decreased productivity, etc. NWHR's biophysical

Table 3. Traditional agroforestry systems of NWHR

Agroforestry systems	Description	Species
Homesteads or Kyaroo in Kangra, Hamirpur and Jammu districts	Farm unit or multitier canopy structure that raises a variety of species for fuelwood, timber, and fodder etc, primarily to meet the fundamental needs of the farmers.	Upper storey: Fodder trees like *Celtis australis*, *Bahaunia variegata*, *Grewia optiva*, and bamboo species particularly *Dendrocalamus hamiltonii* and *D. strictus* Middle storey: Bushes like medicinal *Adhatoda vasica*, *Vitex negundo*, etc. Fruit trees: pear, plum, lemon, citrus, etc., are grown along with *Colocasia esculanta*, *Dioscoria spp*, and *Curcuma domestica* grown for domestic uses.
Plantation crop combination	Generation of national economy by value added products for different international markets by growing species on waste and marginal lands.	Tea is the important plantation crop of the Himalayan region. Traditionally, it is grown with indigenous species. In Himachal Pradesh, tea gardens in Kangra, Palampur, and Baijnath valleys are managed under *Albizia chinensis.*
Sea-Buck-Thorn Based Agroforestry Systems in Cold Desert Areas	Sea-buck-thorn is a fast-growing shrub accounting for <5% plantation cover which fixes 180 kg ha^{-1} yr^{-1} ofnitrogen and has calorific value of 4,785 calories kg^{-1}.	*Hippophae rhamnoides* renowned for restoring land in cold and dry fragile ecosystems, preventing desertification.
Bamboo groves	Cultivation is done to utilize it for making a variety of domestic products such as fishing rods, baskets, mates, cow huts, miniature farmhouses, and water conveyers etc. Additionally, it is used as feed for the cattle in winter season.	*Dendrocalamus hamiltonii, D. structus,* and *Bambusa nutans* are cultivated in high rainfall subtropical and mid-hill moist regions (Himachal Pradesh regions of Palampur, Hamirpur, Una, Bilaspur, Jammu, J&K and Dehradun, Uttarakhand).

characteristics' susceptibility, sustainable land use practices are crucial for ecosystem resilience. Agroforestry can aid in stabilizing these landscapes but its full potential appears to be constrained by the available area as the average size of land holdings has decreased, averaging around 1 hectare. So, there is less opportunity for farmers with small land areas to include trees as an overabundance of agriculture. The cold desert region in NWHR makes the area more vulnerable to climatic fluctuations (Tewari and Kapoor 2013). However, as the population grows, people are also cultivating sloppy areas, which has harmed the ecology. The ecological rehabilitation requires integrated land use and management strategies for which agroforestry appears to be the solution to all issues. Despite their ecological and socio-economic significance, substantial challenges occur in scaling and institutionalization. The implementation of National Agroforestry Policy (2014) in the hilly terrains remains constrained due to issues such as unclear land tenure, restrictive forest laws, and fragmented holdings. Decentralized forest governance mechanisms such as Van Panchayats, Joint Forest Management Committees (JFM), and the Forest Rights Act (FRA) and schemes like MNREGA, RKVY, and PMKSY include provisions for agroforestry components have not been effective and have limited field level impact (Pandey and Ghosh 2023). Institutions such as ICAR, ICFRE, and State Forest Departments play a crucial role in research and policy implementation, yet region-specific data, participatory models, and adaptive technologies are still lacking (Hussain et al., 2024). Several other policies like Convention on Biological Diversity (CBD), Nationally Determined Contributions (NDCs) under the Paris agreement (2015), and Land Degradation Neutrality (LDN) and UN Sustainable Development Goals have reinforced its importance in addressing land degradation, climate change and alleviating rural poverty etc. (Gichuki et al., 2019). Addressing these multifaceted challenges calls for enhanced institutional coordination, inclusive policy reforms, improved extension services, and recognition of the role of smallholders and women in sustaining traditional agroforestry landscapes across the Himalayas.

CONCLUSION

Agroforestry systems in NWHR represent different ecologically sound and socio-economically viable land use strategies, harmonizing biodiversity conservation with rural livelihoods and other associated ecosystem services. The region's unique agroecological gradients have nurtured a diversity of traditional agroforestry practices ranging from silvipastoral and home gardens and alley cropping are deeply rooted in local knowledge system and are adaptive to site-specific conditions. Despite its potential, the systems remain under recognized in policy and land use planning frameworks with implementation barriers like insecure land tenure, restrictive forest regulations, poor market access and limited region-specific research continues to hinder its wider adoption. However, different policies like National Agroforestry Policy, Nationally Determined Contributions, Land Degradation Neutrality etc. strengthen the participation to some extent. A holistic and integrated approach is thus needed to mainstream agroforestry for sustainable development, climate resilience and biodiversity conservation in this fragile landscape.

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Evidences versus Claims on Deep Rootedness in Planted Eucalyptus

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***Abstract*:** Eucalyptus has been grown in India since its introduction in 1790. It is a prominent tree which has been planted both within and outside forests in the greater geographical area of the country. The tree started attracting hate from some quarters around 1980's and continues till date from some parts of the country. The major claim by its opponents is related to its root system which is repeatedly quoted penetrating very deep in the soil to exploit groundwater table leading to land degradation. Though there are many other claims made by its opponents and proponents, this paper reviews Eucalyptus root spread from the exiting reports. The paper also includes four case studies with pictorial evidences exhibiting actual root spread of some Eucalyptus species. The tree is currently grown under short production cycles 2 years onward. Based on the available information on its root spread, it is inferred that the tree does not grow a deep root system which could be held responsible for exploiting the deep ground water table especially on degraded and stressed sites.

***Keywords*:** Eucalyptus, Tap root, Root length, Root spread, Water use controversies

Eucalyptus is the top planted, top wood producer, and the backbone of at least the paper and panel industry in India. The tree is gradually attaining the status of common-man tree as its wood is locally available at low cost, is durable, and is now being used in numerous utilities including construction in many parts of the country. Eucalyptus is now a torch bearer of the clonal forestry with highest number of clonal plants for a single tree species being planted in the country. According to an estimate around 50 Crore clonal Eucalyptus plants were planted during 2024-25 (Dhiman 2025a). Dozens of its fast growing and site matched clones have been developed by different organizations which are grown by farmers on their farmland.

The tree is significantly contributing towards the livelihood of millions of people who are directly and indirectly engaged in its nursery and plantation production; logistic support in plantation works including harvesting of trees; transportation and trading of its wood; and wood processing and making its products. There are a large number of economical activities happening around its value chain from growing and trading of its nursery plants; trade and handling of wood between production and consumption centres, trading and marketing wood products and finally their end-use in different utilities. According to an estimate Rs. 48,000 Crore worth of its wood was traded during 2023-24 in the country which is transforming the economical conditions of engaged stack-holders (Dhiman et al., 2023). The tree has indirectly helped in conservation of native forest and tree resources by diverting the pressure to non-forest land where it is being grown. Controversies against the tree invariably surface which creates confusion among its stake-holders whose livelihood is now closely linked with it. This paper reviewed the root spread of Eucalyptus which is seldom reported as its major controversy.

Controversies against Eucalyptus

In India the hate against some trees, both the native and exotic ones, has perpetuated for quite some time. There are at least 3 contrasting cases of hating trees which surfaced during the last over 5 decades and include native Chir pine (*Pinus roxburghii*) in the Himalayas, Poplars (*Populus* species) in Kashmir valley, and Eucalyptus (*Eucalyptus* species) in some states. These hate drives have been very strong and were pushed up with a lot of speculative environmental concerns without supportive scientific evidences and explanations. Each case study is unique and had involved local public, environment lobby, political and even legal ecosystems. At times, the issue became so emotive, sensitive and concerning that the highest legal institutes like state high courts were carried away with these drives and issued virtual removal of Poplar in Kashmir valley and banned planting Eucalyptus in Karnataka (Nautiyal et al., 2021).

There is a long history of growing both the native and introduced Poplars in Kashmir valley for centuries and the tree has been well integrated in the local social, industrial, forestry and agriculture ecosystems for its immense values to the locals. The tree was especially targeted during the last over 1.5 decades period when it was virtually made a villain for its floss which is cotton like fine fibrous element attached with seed to help its dispersal for natural regeneration. Initially it was claimed that the tree's pollen (floss was mistaken as pollen) is causing numerous health hazards

including pollen allergy and respiratory problems (Dhiman 2014). The matter was taken up in the Hon'ble J&K High Court to address the claims that it is causing a serious public health disorder.

By the time, the scientific and technical evidences provided were being seriously debated against this false narrative of pollen allergy, COVID epidemic was spread throughout the glove including India and Kashmir valley. The Poplar floss thereafter was deliberately and ignorantly connected with the spread of COVID virus during the peak of this epidemic with claims of the imminent danger to the public health. The Court accordingly ordered immediate harvest and removal of all those Poplar trees which produce floss and avoid its further planting in the valley. The state administrative and forestry establishments initiated the action and a few Lakh of such trees were immediately felled out of estimated number of 15 million Poplar trees in the valley. The author *suo-moto* filed an affidavit in the Hon'ble High Court with scientific facts that Poplar and its floss cannot be held responsible for spreading COVID infection. The Court directed the state forest department to constitute an expert committee to give opinion on this matter. The Court, based on the recommendations of the committee, issued the final order amending its original perception and saved the millions of remaining trees with further accepting the recommendation of the committee to plant Poplar of male clones to avoid “Floss Problem”. This man-made controversy was finally put to rest and Poplar culture is now thriving well and supporting a huge economic activity in wood based industry and farmer's income support (Rizvi 2025, Dhiman 2025b).

Chir pine hate in the Himalayas was somewhat similar to Poplar controversy and was also man-made on speculative environmental concerns. Chir pine occurs in the low and mid Himalayas from Pakistan to Nepal and Bhutan and is a native tree to this region which has naturally evolved over the long period of time and got established. The tree was in the focus for research during the early phase of establishing research infrastructure and many of the original research findings in India were related to this tree which also includes the one named as “Longifolene” that was extracted from Chir pine turpentine and was named after the original and old name *P. longifolia* syn. to *P. roxburghii* of this tree. Chir pine was considered so important tree in those days that its cone was made the official logo of the Forest Research Institute, Dehradun which still exists after so many changes in the Indian forestry research establishment in the country.

A few environmentalists had raised the issue that the fires and degradation in lower Himalayas are associated with Chir pine with further claims that this tree was introduced by Britishers in the locality for commercial wood and resin production. The tree was claimed to destroy the native flora especially that of oak (*Quercus leucotrichophora*) forests though there are reports that such changes, if any, may be associated with climate change (Nautiyal 2015). Oak is reported as people's-friendly tree for providing much needed fuel and fodder compared to Chir pine trees. With moratorium on green felling in the Himalayas post-Indian Forest Policy 1988, the tree is now thriving and expanding well even without making much of its plantations and the controversy has gradually disappeared.

While the controversies surrounding Poplar and Chir pine have by and large ended, it still surrounds Eucalyptus in the country. There are numerous claims in favour and against Eucalyptus. A large number of its proponents and opponents invariably make claims and counter claims many of which are based on speculative environmental concerns without authentic scientific explanations. The main claims against the tree have been its excessive use of water and nutrients leading to dried conditions around its growing locations, and creating shade and allelopathy in and around agriculture fields leading to crop failures (Shyam Sunder 1994). Some other narratives include it being invasive; have adverse social and environment effects, native biodiversity and birds and animals; and many others (NewGen Eucalyptus 2019). Many of these claims are false narratives created by its critic opponents to push their agenda to hate the tree.

Claiming Eucalyptus as invasive tree is not true by any technical, scientific and practical realities. Eucalyptus an introduced tree has been continuously grown since its introduction in 1790 in the country. For any species to be invasive, it needs to expand and replace the native vegetation; should have natural reproduction for such an invasion, and enough breeding population to sustain odd stresses. The tree has been extensively planted within and outside natural forests over a very large geographical area of the country and produces viable seed which does not get natural germination and regeneration. It therefore failed to expand beyond planted spots to any forest areas and other ecologically sensitive ecosystems. However, the tree often coppices well if it is harvested at right age, season, and appropriate height from ground level. The coppice potential of the tree reduces over the subsequent coppicing cycles and hence the coppiced Eucalyptus fails to expand and sustain after a few cycles.

Eucalyptus does not have genetically related/sister species in India. It therefore does not outcross/breed with any of the native trees and does not interfere with the genetic makeup of the native trees and their genetic pool. The tree is therefore no threat to our native ecosystem, species and

gene level diversity. It is a safe introduced tree from biodiversity perspective provided it is not deliberately planted by harvesting the native forests. The tree on the other hand is effectively and efficiently helping in conserving and protecting the diversity & ecology of native forests by shifting a huge wood production pressure to non-forest areas where it is grown. In the absence of Eucalyptus, it would have been extremely difficult to protect the natural forests and their biodiversity against heavy demand for tree based needs of the country. According to Poore (1987) the proliferation of Eucalyptus plantations in India, arouses strong feelings both for and against and the arguments by its opponents and supporters, have often been based more on prejudice/wrong perception than the balanced scientific considerations.

This paper reviews the root spread in the planted Eucalyptus with summaries of 4 relevant case studies in addition to inputs from others to substantiate, with photographic evidences and scientific datasets, how deep and wide is its root spread. There are many other debatable claims against Eucalyptus which could not be discussed here due to the paucity of space. The main goal to write this paper is not to promote Eucalyptus plantations but to make the readers aware of the scientific reasoning for better understanding of such claims and disclaims and also to enable them to make their own rational judgment about the correctness of such claims.

Case Studies

Four case studies, two from India and two from other countries- one each from Ethiopia and Laos are summarized from the original publications which are in the public domain and are related to root spread of planted Eucalyptus. These studies are pertinent in the present context as they are related to 2 main tree species namely *E. camaldulensis* and *E. tereticornis* which are extensively grown in India. A couple of these studies are reported from the agroforestry production system which is also the main land-use for Eucalyptus production in India. Summaries predominantly present the root spread related traits for better connect with the title of this paper and its space economy by ignoring other studied traits. Most of the datasets from these studies were reworked from the original ones to suite the theme whereas pictures are presented in original and are duly acknowledged.

Case study 1. *E. camaldulensis* in forest stand, Ethiopia (Source: Schume et al., 2022)

This study was conducted in Ker Jarso site which is located near Durbete Town in Achefer District, Ethiopia. The site is located at 1945 m a.m.s.l. which receives a mean annual precipitation of 1499 mm and the mean annual temperature as 17.7°C. *E. camaldulensis* stand was 10 years old and had 4881 trees/ha with 24.3 m dominant height and 408 m^3/ha standing GS (ob). The forest stand had a sparse layer of herbaceous plants which covered approximately 20% of the soil surface. Roots were examined by excavating 39 m^3 soil/tree in the form of 2 semi-circular rings and side trenches. The root spread was studied up to 3.10 m soil depth and up to 3.50 m horizontal distance from the tree base. Though maize crop was grown 80 cm away from the tree rows during the start of 10^{th} year growth, datasets were given for only crop growth and yield in agroforestry plots.

82.7% of all water and nutrient absorbing fine roots (< 2 mm) were concentrated within the first 1 m from trees and within 60 cm soil depth whereas the share of very coarse roots (> 50 mm) was 84% in this soil section within 1 meter from tree base. Regardless of the distance to the trees, 70.5% of the fine root mass was found in the top 60 cm depth, the remaining 29.5% was in higher depths. The penetration depth of the tap roots varied between 1 and 1.9 m and all tap roots had fallen <4 cm below 70 cm soil depth. The fresh root

Source: Schume et al., 2022

Fig. 1. Excavated root system of *E. camaldulensis* with wide spreading lateral roots. Two white arrow marked roots moving upward into the top soil

Table 1. Dry root biomass (g m^{-2}) of roots of different thickness at different distances from trees

Distance from trees (cm)	Diameter class (mm)					
	<2	2-<5	5-<10	10-<50	>50	Total
50-150 cm	25.1	109.3	156.1	185.8	76.8	553.1
250-350	21.8	48.6	49.6	56.8	31.1	208.0
Average	23.5	79.0	102.9	121.3	54.0	380.6

mass density of the experimental trees was highest in the top1 m soil horizon (0–10 cm) distance from the stem with 1164 g m^{-3} across all root diameter classes. In 3 meters distance from the stem the respective value was only 313 g m^{-3}. Root mass distribution in different soil depths is surprisingly similar between 1 and 3 m distances from the tree base with 62.9% and 57.6% in the top 60 cm of the soil.

One of the datasets presented in this study also includes tap root traits of 9 trees which include tree dbh (7 to 18 cm), tap root diameter at 10 cm of stump (4.8 to 14.7 cm), tap root length (100 to 190 cm), and tap root fresh weight (803-3900 g). Regression equations were developed by the author (me) for predicting tap root No., tap root length and tap root fresh weight based on dbh and dbh^2 of trees. Out of the developed regression equations, Fresh wt (g) = - 564 + 19777*D with R (adj.) of 71% and P= 005 was better predicted whereas tap root diameter= 1.93 + 55.1 D with R^2 (Adj.) 57 and P=0.18 has relatively low prediction. The predictions of tap root length based on dbh and dbh^2 were highly unreliable as its R^2 (Adj.) was just in single digit. It also had low and non-significant coefficient of correlation r^2 as 0.14 between tree dbh and tap root length. The regression equations for tap root No. and tap root fresh weight in *E. camaldulensis* provided some

Table 2. Root biomass per tree at different soil depths from ground surface

Soil depth (cm)	Root dry biomass (g m^{-2})		Root dry biomass (%)	
	50-150	250-250	50-150	250-350
0-60	347.6	119.8	63.9	57.6
60-110	116.3	53.4	21	25.7
110-210	56.8	24	10.3	11.5
210-310	32.3	10.9	5.8	5.2
Total	558.1	208	100	100

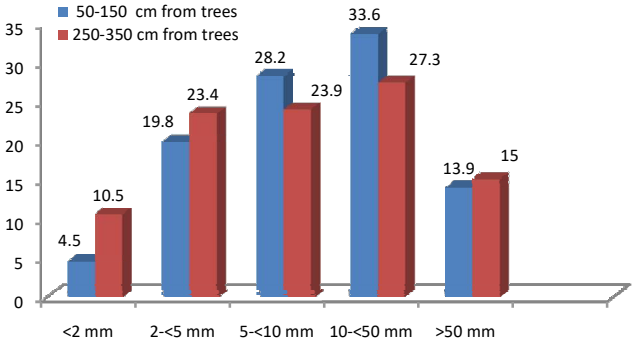


Fig. 3. Percent roots of different thickness away from trees (Drawn from datasets given by Schume et al., 2022)

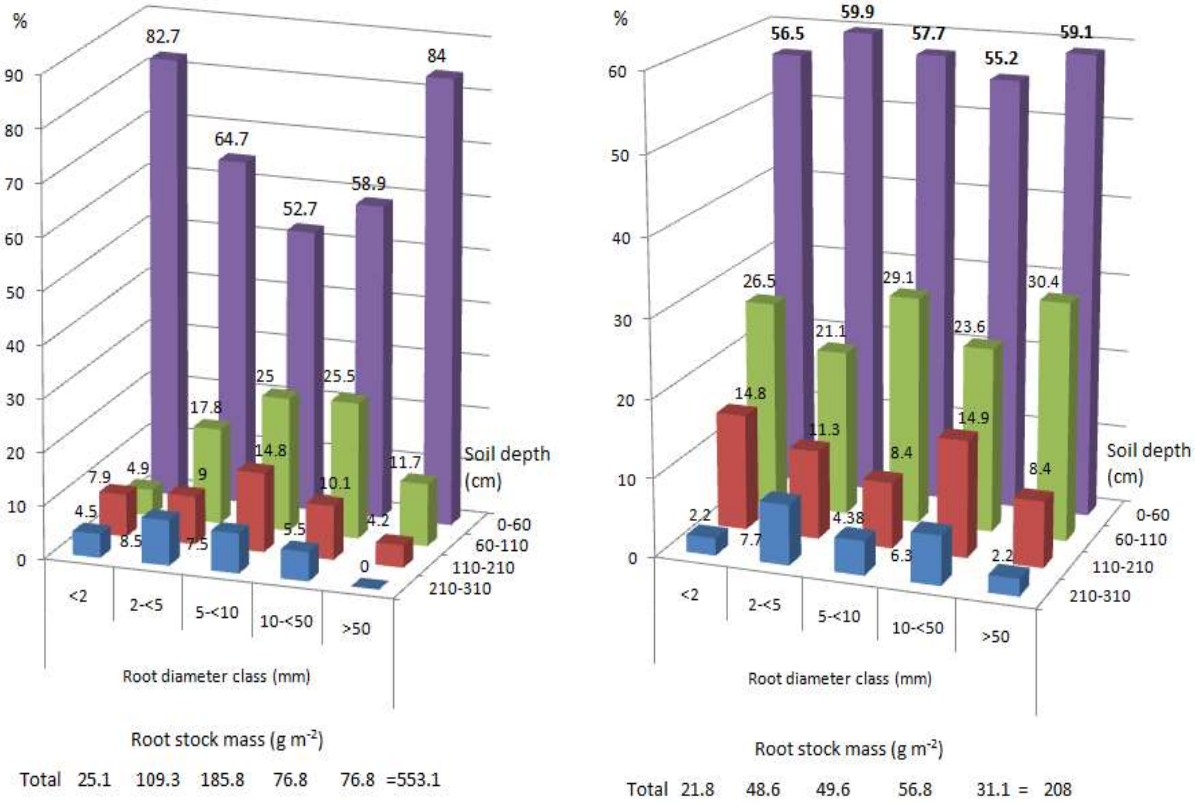


Fig. 2. Root spread at different soil depths of 50-150 cm away from trees (left) and 250-350 cm away from trees (right) (Drawn from datasets given by Schume et al., 2022)

ready reference for estimating these traits using tree dbh for future studies which could gradually be refined with more datasets.

Case study 2. *E. camaldulensis* with and without intercropping, Laos (Source: Edberg et al., 2022)

This study was conducted at 4 different sites in Saravanh and Savannakhet provinces, South Laos. Studies on root spread and some other traits were conducted in 2 and 7 years *E. Camaldulensis* stands which were established in 2 spacing models of 9 X 1 m and 5 X 2 m without and with intercropping involving rice and cassava under similar silviculture protocols. Annual precipitation of these sites varied from 1800-2500 mm with mean temperature from 14-35°C. The root studies were conducted using the manual excavation of trenches and stainless steel soil cores (100 mm internal tube diameter). The study was conducted up to 60 cm depth with segregation of root samples in 0-20 cm, 20-40 cm, and 40-60 cm soil depths and in distances from tree base up to 275 cm in 5 X 2 m stand and up to 450 cm in 9 X 1 m stand.

The effect of age, spacing and intercropping on the root system of *E. camaldulensis* existed in the shallow depths and well spread horizontally in both pure and intercropped stands with further no significant effect of intercropping rice and cassava, and plantation model (9 x 1 m and 5 x 2 m spacing model). The main lateral roots were confined to shallow depths and along horizontal distances from tree base in both pure and intercropped stands. The root system of 2-year-old *E. camaldulensis* trees in the 9 x 1 m spacing stands had 4-6 main lateral roots (>5 mm) in both pure and intercropped stands with 4-5 in intercropped and 5-6 in pure stand. The corresponding number of secondary lateral roots (<5 cm) was 12-22 in pure Eucalyptus and 12-13 in intercropped stands. Intercropping in 7-year old 5 x 2 m and 9 x 1 m

Source: Edberg et al., 2022

Fig. 4. Typical root system of 2-year old E. camaldulensis trees in monoculture (A) and intercropped (B)

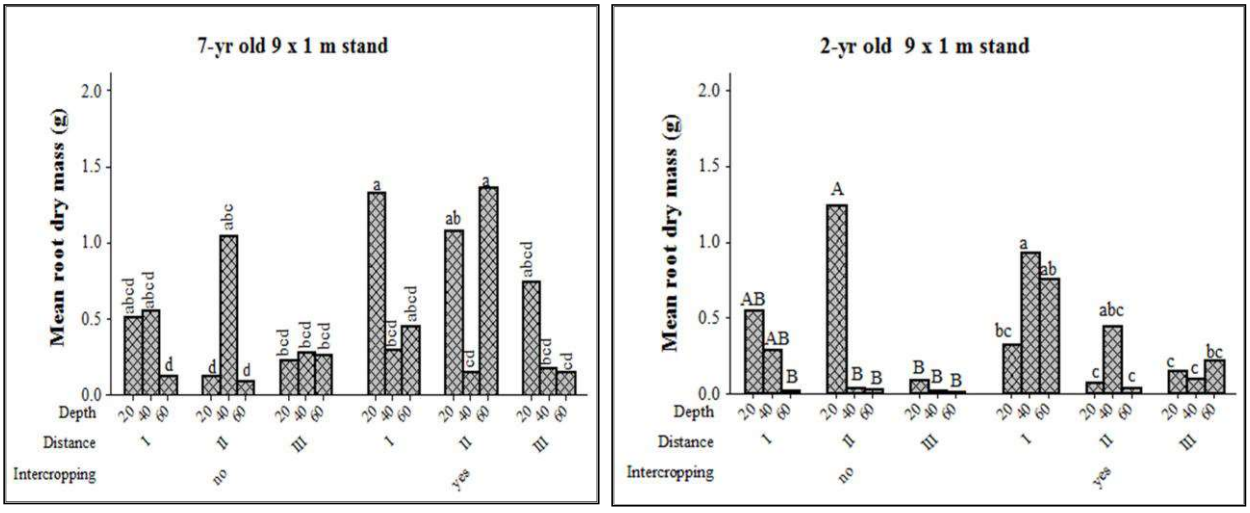
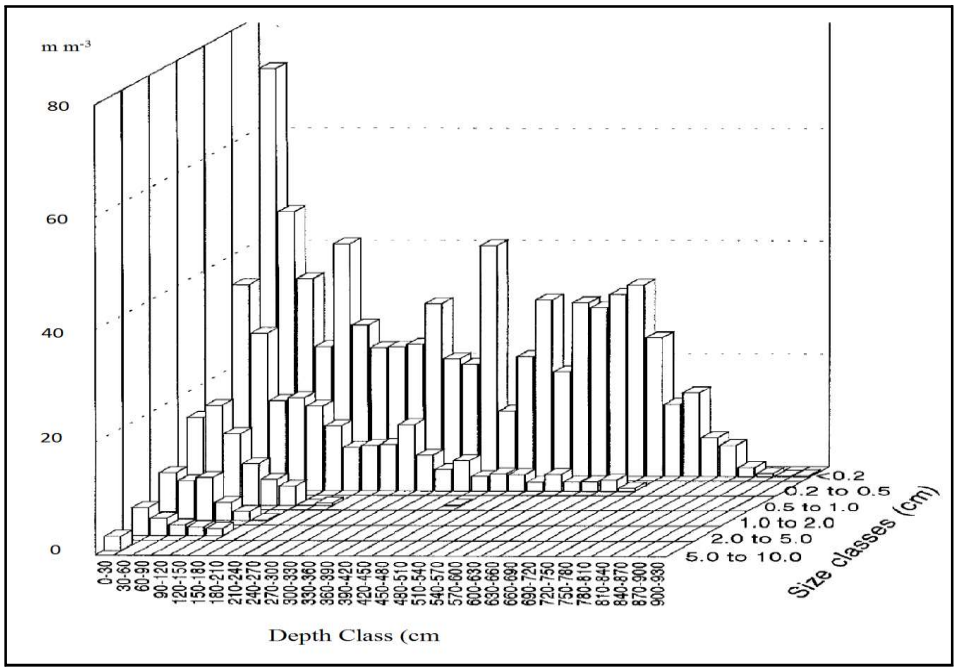


Fig. 5. Root spread traits in 7-year old and 2-year old *E. camaldulensis* stands with and without intercrops (Reproduced from Edberg et al., 2022)

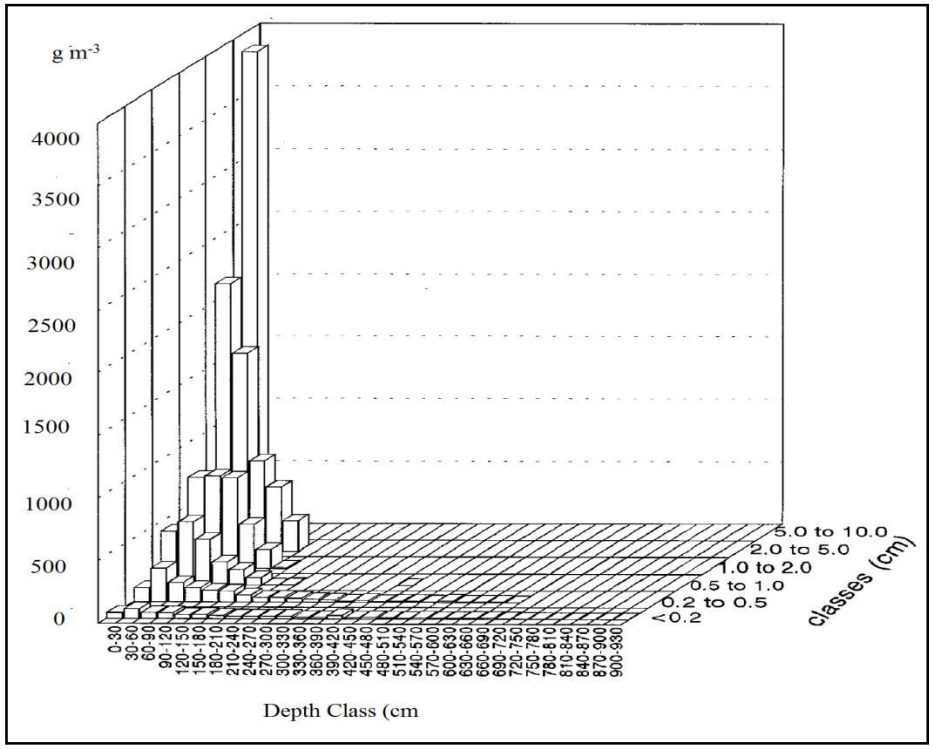
spaced plantations produced no significant differences on total root dry mass whereas it was significantly different in young plantation at 9 x 1 m spacing which significantly decreased with increasing distance from the tree base but was non-significant between intercropped and pure stands.

Root dry mass was lower (0.33 g) in young 2-year old compared to old 7-year old stand (0.64 g). Mature stands had higher root dry mass at 60 cm depth and at 275 cm distance



Source: Kallarackal and Somen 1968

Fig. 6. Root length density (m m-3) in *E. tereticornis*



Kallarackal and Somen 1968

Fig. 7. Root weight density in *E. tereticornis*

compared to young stands where it was higher at both the 20 cm and 40 cm depth within 275 cm distance compared to other depths and distances from tree base. The root dry mass at 40 cm soil depth was significantly higher in 5 x 2 m spaced stand and for 9 x 1 m stand at the middle distances from the tree base whereas root dry mass at 20 cm and 60 cm depths was higher in 9 x 1 m stand compared to other spacing at 275 cm from the tree base.

Root dry mass at 60 cm soil depth was higher for pure stand than for intercropped stand at 275 cm distance from the tree base. The mean root dry mass in 7-year old 9 X 1 m stand was higher in 20 cm and 60 cm soil depths for the intercropped stand compared to pure stand. Root dry mass in 2-year pure 9 X 1 m stand at 20 cm depth was higher at 275 cm distance compared to 450 cm across all other soil depths and at 60 cm depth in the first 100 cm from the tree base at nearly all soil depths compared to other distances from tree base.

Case study 3. *E. tereticornis* in research trial, KFRI, Kerala, India (Kallarackal and Somen 1968)

This case study is based on 20 years old 6 Eucalyptus species namely *E. tereticomis, E. camaldulensis, E. urophylla, E. brassiana, E. pellita* and *E. deglupta* which were grown in an experimental plot of 14 Eucalyptus species at the sub-centre of the Kerala Forest Research Institute at Nilambur located at 50 m a.m.s.l. This trial was planted at 2 X 2 m spacing. The locality receives average rainfall of 2817 mm per year with an average temperature from 24°C to 31°C during the monsoon season. The phreatic aquifer in the locality was reported between 9.0 and 12.0 m during the summer season.

The root spread was based on the datasets of one *E. tereticornis* tree and its results were applied to support findings of all the 6 studied Eucalyptus species. The vertical extent of the root system in *E. tereticornis* was studied from two excavations made around the tree up to 9.5 m depth. Classification of the roots was done according to Bohm (1979) as central root bole of stem (>100 mm diameter), Coarse structural root (50-100 mm), Very large structural root (20-50 mm), Large structural root (10-20 mm), Medium structural root (5-10 mm), Small structural root (2-5 mm), Fine roots (<2 mm). The root length density and dry biomass density in different soil depths is given in Fig.6 and Fig.7 respectively.

The root length density and root weight density had much variation in different layers of the soil. The study recorded the traceability of roots up to 9.3 m soil depth. Roots of larger size classes (structural roots) were found to a depth of about 2.0 m from ground level. At depths lower than 2 m, only roots with a diameter <5.0 mm were found. Maximum density of roots with diameter <2.0 mm was found in the upper 30 cm of the soil. Roots of lower size classes were found in all the soil layers. The root length density and root weight density was maximum in the upper 2 m depth of soil and was contributed by all the root thickness classes. Only select fine and light weight roots could penetrate deeper than 2 m depth with a few of them reaching up to 7 m and only a select one up to 9.3 m depth.

Case study 4. Eucalyptus hybrid under water logged and alkaline conditions, Haryana, India (Jeet ram et al., 2008).

The study reported root spread and related parameters from two sites as follow:

Site-1: Dhob-Bhali plot is located 6 km from Rohtak city. Eucalyptus hybrid plantation was of 18 years age having 807 trees/ha with average height of 22.6 m and average girth at breast height of 102 cm. The average annual rainfall of the site is 490 mm and the main source of irrigation is canal. The area has high pH values.

Observations recorded in a dug up open well indicated that the sinker roots reached up to a depth of 4.4 m below the ground level. The depth of ground water table was 4.70 m and the zone of capillary fringe above the ground water table

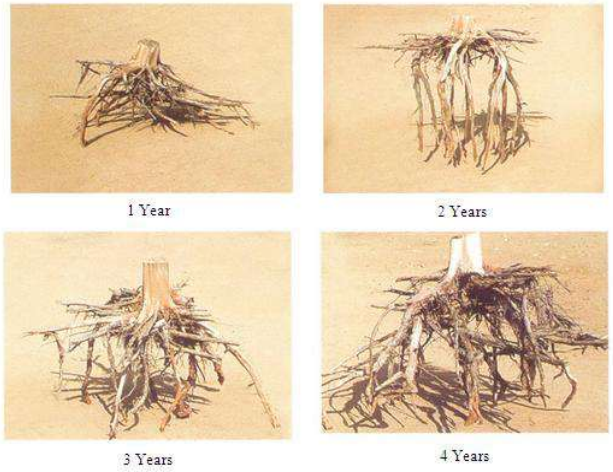


Fig. 9. Root system of 1 to 4 years age clonal Eucalyptus trees

Source: Jeet Ram et al., 2008

Fig. 8. Root length of Eucalyptus hybrid in Site-1 Dhob-Bhali, Rohtak(left); and Site-2: Puthi Village, Hisar (Right).

was between the depths of 2.50 m - 4.70 m. It was inferred that the Eucalyptus trees were absorbing capillary water of the ground water table.

Site-2: Puthi Village Hissar District had 5 year and 4 months old trees with average girth of 56 cm, and average height 18 m. Plantation was raised at 50 cm ridge. The average rainfall is 212 mm. It faces sub-surface water-logging during the whole, and surface as well as sub-surface water logging during the rainy season. The main causes of water-logging are seepage from canals, brackish ground water and absence of natural drainage.

An open well was dug up to observe the root zone in this strip plantation. The roots reached up to 3.35 m soil depth from the top of 0.50 m high ridge and 2.85 m from the ground level.

Root Spread In Eucalyptus

Woody plants on an average are more deeply rooted than herbaceous ones (Kutschera and Lichtenegger 1997). Schenk and Jackson (2002) studied the average rooting profiles of 15 terrestrial biomes in different latitudes and reported that the soil depths of 1.1 m, 0.7 m, and 0.4 m correspond to cumulated root proportions of 95%, 90%, and 80%, respectively. According to Canadell et al. (1996) the rooting depths of herbaceous plants, shrubs, and trees are globally in the range of 2.6 ± 0.1m, 5.1 ± 0.8m, and 7.0 ± 1.2m, respectively. There is no precise definition of deep rootedness in any species, as such 4 m is assumed as the reference depth for mature Eucalyptus trees which is equivalent to approximately half that of 7.0 ± 1.2 m mentioned for trees.

Table 3 presents root spread of some Eucalyptus species from the existing studies. The four case studies presented above were based on physical excavating soil by making trenches and holes around the trees to study root spread. A few others reported in the Table 3 may have been done the same way, yet many others may be based on the inferences and experience of the professionals and scientists reporting as some of them do not mention age of the studied trees.

Major Eucalyptus culture has now shifted to farmland where millions of farmers grow Eucalyptus to produce wood for wood based industry. The current Eucalyptus production systems could be divided into 3 types namely long production cycles of 8+ years grown at wider spacing for timber production, moderate production cycles of 4-8 years at moderate spacing for peeling log production, and short production cycles of 3- 4 years at close spacing for chip wood production used in paper, MDF, PB factories; and poles (Dhiman et al., 2023). Most farmers grow it for a very short production cycles whereas a few of them grow it for 6-7 years. State forest departments grow Eucalyptus for longer rotations. The old Eucalyptus trees planted in the past are gradually harvested as a result such trees which could produce long and deep roots are gradually declining. Young Eucalyptus harvested at 3-4 years produce root system largely located in the upper soil layers, for example root system of 1 to 4 years age of clonal eucalyptus is reported a vertical spread up to 2.5 m depth (Kulkarni 2012).

Table 3. Root spread in Eucalyptus species

Species	Age (Years)	Soil depth (m)	Lateral spread (m)	Reference
E. tereticornis		3	3.5	Davidson 1985
E. tereticornis	20	9.3		Kallarackal and Somen 1968
E. camaldulensis	10	1.9	84% up to 1	Schume et al., 2022
Eucalyptus spp.		3.5		Rajan et al., 1987
Euca. hybrid	18	4.4		Jeet ram et al., 2008
Euca. hybrid	5.4	2.85		Jeet Ram et a.,l 2008
Clonal Euca.	14	1.47		Dhiman et al. 2020
Clonal Euca.	1 to 4	1.5 to 2.5		Kulkarni 2012
Clonal Euca.	9	Top <0.25	53%	Bouillet et al., 2022
Euca. hybrid	40	3.5		Dhiman et al., 2020
6 genotpes	2	Top< 0.3	50%	Shah et al., 2020
E. globulus		3.08		Mathur et al., 1986
E. globulus	9	1.3		Herrero 2014
E. grandis	7	8-10	20	Robinson et al., 2006
E. grandis	9	28		Dye 1996
E. grandis	7	8-10	20	Robinson et al., 2006

Eucalyptus is a major plantation tree in Haryana, Punjab and many other states. Hoshiarpur with 14.11% of total Eucalyptus trees (>10cmdbh) in Punjab (FSI 2006) and Ambala with 24.16% of Eucalyptus trees (>10 cm dbh) in Haryana (HFD 2023) are the leading districts with maximum share of planted Eucalyptus in these states. Major area of the Hoshiarpur in Punjab lies in Deep Water Level category (20-40 m depth) with some area under Very Deep Level Category of >40m depth (CGWB 2023a). Similarly Ambala district of Haryana falls under 2 categories of Deep Water Table (20-40 m depth) and Moderate Water Table (10-20 m depth) (CGWB 2023b). Root studies from clonal field trial reported above have shallow root spreads mainly restricted to 3 m soil depths. It was 9.3 m in 20 years old tree in KFRI study. Water table in Case study 4 from Haryana was 4.7 m against root spread up to 4.4 m in water-logged locations. Eucalyptus was planted there for bio-drainage purpose as water level existing in relatively upper soil layers.

Agroforestry is a different land use in which the competition around the trees is from shallow rooted agriculture crops compared to forest stands where other associated trees and bushes compete with trees with their longer and wider root spreads. Jourdan et al. (2018) advocated that *E. camaldulensis* based agroforestry adds a lot of crop residues and creates nutrient “hot-spots” in the upper soil layers (even at 60 cm depth) which facilitates production of more lateral roots, high root biomass, and specific root lengths in nutrient rich patches to acquire more soil nutrients. Based on the above, it can safely be assumed that the major Eucalyptus production system is for a short period during with its root system hardly elongating to deeper layers and in such cases the tree largely meets its water requirements from rain and irrigation water provided to agriculture crops. According to Mrdeiris et al. (2025), it is a hasty conclusion that some Eucalyptus species can contribute to reduced soil water.

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Influence of Plant Growth Regulators and Cutting Types on Sprouting and Growth of Henna (*Lawsonia inermis* L.) in Arid and Semi-Arid Regions of Western Rajasthan

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***Abstract*:** The experiment was carried out to observe the effects of plant growth regulators (PGRs) *viz*., indole-3-acetic acid (IAA), indole-3-butyric acid (IBA), and naphthalene acetic acid (NAA) on the vegetative propagation of henna (*Lawsonia inermis* L.) on hardwood, semi-hardwood, softwood, and twigs cuttings. Significant variations were observed in sprouting percentage (%), shoot and leaf growth, root development, and biomass across cutting types and PGR treatments. Hardwood cuttings recorded the highest mean sprouting rate (81.63%), with maximum sprouting (98.14%) achieved under IAA at 1500 and 2000 ppm, followed by IBA 1000 ppm and IAA at 500 and 1000 ppm. Semi-hardwood cuttings showed moderate sprouting (66.79%), best under IAA 1000 ppm (88.33%), while high IAA (2000 ppm) showed reduced sprouting. Softwood and twig cuttings showed relatively lower sprouting rates (48.58 and 46.40%, respectively), with IAA at 500–1000 ppm yielding the best results. In hardwood cuttings, IAA at 500 ppm showed the maximum shoot length (38.33 cm) and leaf number (6.00), while IBA at 1500 and 1000 ppm also enhanced growth significantly. IBA 500-1500 ppm consistently enhanced root number and biomass, especially in hardwood (29.6) and semi-hardwood cuttings (15.6), whereas IAA was more effective in promoting root elongation. NAA generally resulted in lower sprouting and root formation, particularly at higher concentrations. The study highlights the superior effectiveness of IBA and IAA for rooting and growth in henna cuttings, emphasizing the importance of cutting type and auxin concentration for optimizing propagation. These findings provide a valuable basis for developing efficient, sustainable propagation protocols to support large-scale cultivation of henna in arid and semi-arid regions.

***Keywords*:** Henna, *Lawsonia inermis*, Plant Growth Regulators, Vegetative propagation, Stem cuttings

Lawsonia inermis L, is a drought-tolerant shrub belonging to the family Lythraceae, widely cultivated in the arid and semi-arid regions of Rajasthan. It is an important cash crop valued for its natural dye, traditionally used for coloring hair, palms, and feet since ancient times (Singh et al., 2015). Henna cultivation thrives under low rainfall conditions, offering a reliable source of income with minimal input costs, making it well-suited for drought-prone areas. The plant begins yielding economically valuable leaves from the third year, with production continuing for 15 to 30 years. Annual harvesting typically involves cutting shoots 10-15 cm above ground level during October-November (Chand and Jangid 2007). The crop's low fertilizer requirement, high establishment success, and resistance to pests and diseases make it an ideal candidate for promoting economic and ecological development in hot, arid regions. India plays a major role in the global henna market, exporting substantial quantities yearly, with cultivation concentrated mainly in the Pali district of Rajasthan, where Sojat is recognized as the primary processing and trading centre (Chand and Jangid 2007, Jyotshna et al., 2017).

Despite its commercial importance, there has been limited research on the vegetative propagation of henna particularly in semi-arid and arid region of Rajasthan. Generally, henna is propagated through seeds but it exhibits poor germination due to dormancy. The vegetative propagation by stem cuttings is vital for rapid multiplication of genetically uniform plants, which is essential for large-scale cultivation (Hartmann et al., 2002). Rooting success in cuttings is strongly influenced by plant growth regulators (PGRs), particularly auxins, which play a key role in inducing adventitious root formation (Davis and Haissig 1990, Thakur et al., 2021). However, the interaction between different PGRs and the physiological age or size of henna cuttings remains underexplored. Since responses to PGRs vary according to the genetic makeup of the plant species, understanding these species-specific effects is critical to developing efficient propagation methods. While some plants root naturally without treatment, many require exogenous application of auxins such as indole-3-butyric acid (IBA), indole-3-acetic acid (IAA), or naphthalene acetic acid (NAA) to enhance rooting (Syros et al., 2004). Additionally, the physiological maturity of cuttings, which affects endogenous carbohydrate reserves and hormone levels, plays an important role in rooting potential. With this background the present study was undertaken to standardize and optimize suitable type of cutting and to study the effect of different plant growth regulators for better rooting and sustainable propagation method in Henna.

MATERIAL AND METHODS

The study was carried out at Central Arid Zone Research Institute (CAZRI), Regional Research Station, Pali-Marwar (Rajasthan) during February, 2022-23 which is located between 25°47'- 25°49' E and 73°17'-73°18' N at 217-220 m above mean sea level and receives 460 mm annual average rainfall with annual maximum mean temperature 42°C and minimum 7°C. The experiment was conducted at nursery conditions in completely randomized block design with three replications.

To evaluate the effect of three plant growth regulators *viz*., indole-3-acetic acid (IAA), indole-3-butyric acid (IBA) and naphthalene acetic acid (NAA) with a control, across four cutting sizes: hardwood (woody portion of the basal area of stem), semi hard wood (Partially woody portion of the middle area of the stem), softwood (younger portion of upper part of the stem) and twigs (thin or tip of the stem typically less than 10 mm) were considered. Cuttings were collected from healthy, uniform mother plants using one-year-old shoots. Each cutting measured approximately fifteen centimeter in length and included 3-4 nodes. Before treatment, all cuttings were soaked in a Bavistin solution for five minutes to prevent fungal infection. Following this, the treated samples were dipped in different ppm solutions of IAA, IBA or NAA. The control group consisted of cuttings only treated with Bavistin (no PGR application). The plants were planted in each treatments in polybags consisted of a mixture of sand, soil, and farmyard manure (FYM) in a 1:2:1 ratio and kept it in shade net condition.

The sprouting percentage (%) was recorded from 7th day in seven days interval. The seedling growth parameters *viz*., shoot length (cm), number of leaves, leaf length and width (cm) were recorded. At the end of the observation period, five randomly selected cuttings were uprooted without causing any damage to confirm root development and root parameters *viz*., root length (cm) and numbers of root were recorded. Then the shoot and root portions were separated and leaf, shoot and root dry weight (gm) was determined.

RESULTS AND DISCUSSION

The results indicated significant variations based on both the type of cutting and the applied PGR treatment and the differences among treatments were statistically significant.

Sprouting percentage (%): Among all cutting types, hardwood cuttings recorded the highest mean sprouting percentage (81.63%). Maximum sprouting (98.14%) was observed under IAA at 1500 ppm and 2000 ppm, followed by IBA 1000 ppm and IAA at 500 and 1000 ppm (96.29%). NAA at 1500 ppm exhibited the lowest survival rate (35.18%) (Table 1). These findings suggest that IAA, particularly at moderate to high concentrations, is most effective in enhancing sprouting in hardwood cuttings, likely due to its role in promoting cell elongation and root initiation. Quainoo et al., (2014) also observed that hardwood cuttings outperformed semi-hardwood and softwood cuttings of henna across all measured parameters.

Semi-hardwood cuttings exhibited a moderate average sprouting rate of 66.79%. The highest sprouting (88.33%)

Table 1. Effect of plant growth regulators and different types of cuttings on sprouting (%) of Henna (*L. inermis*)

Treatments (Concentrations in ppm)	Cutting type and sprouting (%)			
	Hardwood	Semi hardwood	Softwood	Twigs
IAA 500	96.29	83.33	91.66	63.33
IAA 1000	96.29	88.33	90.00	65.00
IAA 1500	98.14	70.00	75.00	58.33
IAA 2000	98.14	43.33	70.00	35.00
IBA 500	94.44	63.33	76.66	41.66
IBA 1000	98.14	66.66	41.66	55.00
IBA 1500	98.14	73.33	41.66	26.66
IBA 2000	83.33	66.66	55.00	38.33
NAA 500	83.33	50.00	28.33	50.00
NAA1000	74.07	43.33	10.00	60.00
NAA 1500	35.18	75.00	8.333	40.00
NAA 2000	40.74	85.00	21.66	41.66
Control	65.00	60.00	21.66	28.33
Mean	81.63	66.79	48.58	46.40
CD (p=0.05)	9.25	11.87	6.89	8.54

was observed with IAA at 1000 ppm, followed by NAA at 2000 ppm (85.00%) and IAA at 500 ppm (83.33%). Lowest sprouting rate was with the application of IAA 2000 ppm (43.33%) and NAA 1000 ppm (43.33%) (Table 1). These results indicated that semi-hardwood cuttings respond best to lower concentrations of IAA and higher concentrations of NAA. Excessively high levels of IAA, however, may have a detrimental effect, possibly due to hormonal imbalance.

Softwood cuttings recorded a relatively lower mean sprouting percentage (48.58%). The highest sprouting was with IAA at 500 ppm (91.66%) and 1000 ppm (90.00%), while IAA at 1500 ppm yielded a sprouting rate of 75.00%. In contrast, NAA treatments were markedly less effective, with sprouting as low as 8.33% under NAA at 1500 ppm. IBA treatments also resulted in lower sprouting rate (41.66% at 1000 and 1500 ppm). This pattern underscores the superior efficacy of IAA in promoting rooting and survival in softwood cuttings, particularly at lower concentrations.

Twig cuttings showed the lowest average sprouting rate (46.40%) across all cutting types. The best performance was observed under IAA at 1000 ppm (65.00%) and 500 ppm (63.33%). Moderate sprouting was also recorded under NAA 1000 ppm (60.00%). However, sprouting rates declined significantly with higher concentrations of IBA and NAA, with IBA 1500 ppm resulting in only 26.66% sprouting and IAA 2000 ppm in 35.00%. These findings reaffirm the preference for lower concentrations of IAA for softer, less lignified cuttings such as twigs . IBA is widely recognized as the most effective auxin due to its low toxicity and broad efficacy (Hartmann et al., 2002) and the role in enhancing rooting and survival in cuttings has been well-documented (Melgarejo et al., 2000, Henrique et al., 2006, Soundy et al., 2008, Kaur 2024).

Shoot and leaf parameters: In hardwood cuttings of henna, IAA 500 ppm produced the longest shoots (38.33 cm) and a higher number of leaves (6.00), followed by IBA 1500 ppm (28.40 cm) and IBA 1000 ppm (27.40 cm). The enhanced shoot growth under IAA 500 ppm suggests improved apical dominance and nutrient mobilization. Leaf length ranged between 2.20 cm (control) and 3.10 cm (IBA 500 ppm), while the maximum leaf width (1.60 cm) was observed under r IAA 1500 ppm (Table 2). This indicated that lower to moderate concentrations of IAA and IBA improve leaf expansion, likely due to enhanced cell elongation and nutrient uptake in hardwood cuttings. Siva et al., (2018) also reported an increased number of leaves in hardwood cuttings treated with higher concentrations of IBA. This suggests that IBA, at optimal concentrations, enhances shoot vigor by stimulating both cell division and nutrient assimilation. This suggests that hardwood cuttings produce more shoots compared to semi-hardwood and softwood cuttings in henna, likely due to their higher carbohydrate reserves (Dick 2001). Being more physiologically mature, hardwood cuttings also appear to respond more effectively to NAA treatment (Noor Camellia et al., 2009).

Shoot length varied significantly across treatments in semi hard wood cuttings. The longest shoots were under IAA 1000 ppm (19.43 cm), followed by IAA 2000 ppm and IAA 500

Table 2. Effect of plant growth regulators on growth parameters of Henna (*L. inermis*) Hard wood cuttings

Treatments (Concentrations in PPM)	Shoot length (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	No. of roots	Root length (cm)
IAA 500	38.33	6.00	3.0	1.5	29.0	9.33
IAA 1000	25.50	4.33	3.0	1.3	17.3	13.1
IAA 1500	23.56	5.33	2.8	1.6	20.6	5.40
IAA 2000	26.93	6.00	3.0	1.2	22.6	3.00
IBA 500	24.93	5.00	3.1	1.2	25.3	11.4
IBA 1000	27.40	5.00	3.0	1.2	24.6	9.66
IBA 1500	28.40	5.00	2.9	1.3	29.6	5.30
IBA 2000	19.10	8.66	2.3	0.5	17.3	3.86
NAA 500	23.23	6.00	2.7	1.4	28.0	7.63
NAA1000	19.46	3.33	3.0	1.1	17.0	6.46
NAA 1500	19.00	3.66	2.8	1.2	18.0	4.00
NAA 2000	19.00	3.00	2.8	1.1	15.0	3.86
Control	15.06	3.33	2.2	0.9	8.0	2.03
Mean	23.83	4.97	2.8	1.1	20.9	6.54
CD (p=0.05)	2.69	0.57	0.32	0.13	2.25	0.87

ppm in semi hard wood cuttings. The shortest shoot length (7.60 cm) was observed in the control. This suggests that IAA at 1000 ppm is particularly effective in promoting apical growth in semi-hardwood cuttings. The number of leaves per cutting ranged from 2.00 (NAA 1000, NAA 1500, and control) to 3.00 (IBA 500, IBA 1500, and IBA 2000 ppm). While leaf number showed moderate variation, IBA-treated semi hard wood cuttings generally produced more leaves than IAA or NAA treatments. Leaf length ranged from 2.03 cm (control) to 3.00 cm (IBA 1000 ppm), while maximum leaf width (1.56 cm) with IBA 1000 ppm, suggesting that IBA at moderate doses promotes healthier foliage development (Table 3). Soni et al. (2016) also observed improved leaf production in guava cuttings treated with auxins.

Among the treatments in softwood cuttings, IBA at 500 ppm produced the longest shoots with an average length of 21.93 cm, followed by IBA 1000 ppm and IAA 1000 ppm and these showed significant increases compared to the control (5.50 cm). The control treatment had the lowest shoot length, indicating the crucial role of PGRs in stimulating shoot elongation. The number of leaves per cutting ranged from 2.33 to 4.33, with the highest number in IAA 2000 ppm and IBA 500 ppm (4.33 leaves each). Leaf length and width were similarly enhanced by PGR treatments, with IBA 1000 ppm showing the greatest leaf length (3.10 cm) and width (2.10 cm), indicating improved leaf expansion and overall vigor (Table 4).

In twigs, IBA at 1000 ppm resulted in maximum shoot length of 19.63 cm, followed closely by IBA 500 ppm and IAA 2000 ppm. These values were markedly higher than the control group, which showed a shoot length of only 8.70 cm (Table 5). This indicates that moderate concentrations of IBA are effective in stimulating shoot elongation in henna twigs. The number of leaves per cutting was highest in the control (7.00), although the leaves were smaller in size compared to treated cuttings, where leaf length and width were significantly improved by IBA and IAA treatments., IBA 1000 ppm recorded the highest leaf length (2.96 cm) and leaf width (1.40 cm), suggesting that PGRs enhance not just the quantity but also the quality of foliage development. Rao et al. (2020) and Tanwar et al. (2020) also reported that PGRs, particularly auxins, promoted shoot elongation and rooting in pomegranate cuttings. The improved growth observed in these cuttings could also be attributed to auxin-induced histological changes such as callus formation and vascular tissue differentiation, which support shoot and root development (Mitra and Bose 1954, Singh 2014). The overall enhancement of shoot growth and foliage parameters due to IAA and IBA aligns with earlier findings in fig (Pinheiro et al., 1971), lemon (Seran and Umadevi 2011), cape gooseberry (Moreno et al., 2009) and Bougainvillea (Anuradha and Parminder Singh 2024) reaffirming the efficacy of auxins in stimulating vegetative propagation responses across different plant systems.

Root parameters: In hardwood cuttings, the highest number of roots (29.6) were in response to IBA 1500 ppm, closely followed by IAA 500 ppm and NAA 500 ppm. The longest roots (13.13 cm) were observed under IAA 1000 ppm, while

Table 3. Effect of plant growth regulators on growth parameters of Henna (*L. inermis*) Semi hard wood cuttings

Treatments (Concentrations in PPM)	Shoot length (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	No. of roots	Root length (cm)
IAA 500	14.56	2.66	2.56	1.16	15.6	7.36
IAA 1000	19.43	2.66	2.70	1.23	13.3	7.70
IAA 1500	13.76	2.33	2.63	1.40	13.6	7.10
IAA 2000	14.93	2.33	2.70	1.23	11.0	7.53
IBA 500	14.16	3.00	2.76	1.20	15.6	9.86
IBA 1000	14.53	2.66	3.00	1.56	15.0	8.66
IBA 1500	14.73	3.00	2.66	1.33	11.6	9.33
IBA 2000	11.70	3.00	2.13	0.80	15.3	6.53
NAA 500	10.92	2.33	2.33	1.20	14.0	5.66
NAA1000	8.796	2.00	2.26	1.00	11.0	5.53
NAA 1500	8.543	2.00	2.36	1.06	9.10	4.00
NAA 2000	8.223	2.33	2.06	0.93	10.0	3.76
Control	7.600	2.00	2.03	0.86	6.00	2.50
Mean	12.45	2.48	2.47	1.15	12.3	6.58
CD (p=0.05)	1.47	0.28	0.27	0.12	1.41	0.77

the control produced lowest number of roots (8.0) with a mean length of 2.03 cm (Table 2). The results highlight a differential effect of PGRs on root number and root length, where IBA promotes root proliferation, and IAA enhances elongation. Both are crucial for nutrient absorption and overall plant establishment.

Among the treatments in semi hardwood cuttings, the number of roots per cutting were highest with application of IAA 500 ppm and IBA 500 ppm (15.6 each), closely followed by IBA 1000 ppm. IAA and IBA treatments at 500-1000 ppm significantly improved root proliferation compared to NAA and control. The longest roots were observed in IBA 500 ppm (9.86 cm), followed by IBA 1500 ppm and IBA 1000 ppm. The shortest root length (2.50 cm) was in the control. This indicates that IBA, particularly at 500-1500 ppm, is most effective in enhancing root elongation in semi-hardwood cuttings. Furthermore, hardwood cuttings recorded the longest roots followed by semi-hardwood cuttings with

Table 4. Effect of plant growth regulators on growth parameters of Henna (*L. inermis*) Soft wood cuttings

Treatments (Concentrations in PPM)	Shoot length (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	No. of roots	Root length (cm)
IAA 500	19.26	2.66	2.56	1.26	14.3	7.00
IAA 1000	19.86	3.00	2.90	1.33	18.6	6.63
IAA 1500	16.93	4.00	2.60	1.33	13.6	8.16
IAA 2000	19.20	4.33	3.00	1.40	8.33	5.66
IBA 500	21.93	4.33	3.06	1.36	26.6	14.1
IBA 1000	23.46	3.66	3.10	2.10	23.0	6.00
IBA 1500	11.33	3.66	2.30	1.23	19.3	6.36
IBA 2000	11.26	2.33	2.56	1.30	20.6	7.60
NAA 500	11.73	2.66	2.30	1.10	19.0	6.90
NAA1000	11.26	2.33	2.20	1.03	10.3	6.56
NAA 1500	9.400	3.00	2.20	1.10	8.33	4.90
NAA 2000	10.06	3.00	2.06	1.03	7.33	5.90
Control	5.500	3.33	2.36	0.80	6.66	3.80
Mean	14.70	3.25	2.55	1.25	15.0	6.89
CD (p=0.05)	1.81	0.37	0.29	0.14	1.77	0.87

Table 5. Effect of plant growth regulators on growth parameters of Henna (*L. inermis*) Twigs

Treatments (Concentrations in PPM)	Shoot length (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	No. of roots	Root length (cm)
IAA 500	8.466	5.66	2.23	0.80	10.3	7.80
IAA 1000	8.700	3.66	2.20	1.10	11.0	5.36
IAA 1500	9.900	3.66	2.56	1.33	14.6	7.80
IAA 2000	14.60	3.66	2.10	1.10	8.66	19.0
IBA 500	16.36	5.66	2.26	1.10	13.6	9.26
IBA 1000	19.63	3.33	2.96	1.40	10.3	13.7
IBA 1500	14.56	4.33	2.80	1.50	7.00	8.16
IBA 2000	12.00	3.00	1.63	0.80	13.6	3.80
NAA 500	7.466	3.66	2.03	1.16	11.3	3.03
NAA1000	5.733	4.33	1.60	0.96	12.3	6.13
NAA 1500	7.233	3.00	2.13	0.93	17.0	3.26
NAA 2000	5.333	4.33	1.40	0.76	19.6	2.06
Control	8.700	7.00	1.63	0.93	4.66	1.06
Mean	10.66	4.25	2.11	1.06	11.8	6.96
CD (p=0.05)	1.22	0.49	0.22	0.11	1.45	1.00

softwood cuttings with the least root length (Table 3). These increase in root length maybe due to an early initiation of roots at physiologically matured stage of hardwood cuttings and more utilization of the food materials due to early formation of roots.

In softwood cuttings, IBA 500 ppm induced the highest number of roots (26.6), followed by IBA 1000 ppm while the control recorded only 6.66 roots on average. Root length was also greatest (14.10 cm) under IBA 500 ppm, suggesting that this concentration is highly effective in promoting root elongation and development. In contrast, higher concentrations of IBA (1500 and 2000 ppm) and all concentrations of NAA showed a decline in both root number and length, indicating potential inhibitory effects of excessive auxin on root formation in henna softwood cuttings (Table 4).

In twigs, the highest number of roots (14.6) were with IAA 1500 ppm, suggesting that this auxin concentration favors root initiation. Conversely, NAA 2000 ppm resulted in the longest roots (19.6 cm) but minimum roots (7.33), indicating that while NAA may enhance root elongation at high concentrations, may not promote root initiation effectively. IBA treatments at 500 and 1000 ppm resulted in robust root development, with root numbers of 13.6 and 10.3 and root lengths of 9.26 cm and 13.76 cm, respectively (Table 5). These results highlight IBA's strong role in balancing root initiation and elongation, crucial for establishing healthy cuttings.

Among all treatments, IBA especially at 500 to 1500 ppm, consistently promoted the highest number of roots across hardwood, semi-hardwood, and softwood cuttings, confirming its superior rooting efficiency due to low toxicity and stability, as also supported by Hartmann et al. (2002). Hardwood cuttings showed the longest roots, followed by semi-hardwood and softwood cuttings, likely due to early root initiation at a more mature physiological stage and efficient utilization of stored nutrients. These findings were confirmed with the study of Sardoei et al. (2013) and Quainoo et al. (2014) in *L. inermis*.

IAA, in contrast, was more effective in enhancing root length, particularly in hardwood and twig cuttings, suggesting its role in cell elongation and vascular differentiation. Excessive concentrations of IBA and NAA negatively impacted root formation in softwood cuttings, indicating possible auxin overdose. These findings align with earlier study of Singh et al. (2013), emphasizing that optimal auxin concentration is critical for successful root initiation and elongation during vegetative propagation. Similar observations were made by Swamy et al. (2002) in *Grewia optiva* and *Robinia pseudoacacia*, Grewal et al. (2005) in *Dendranthema grandiflora* cv. Snowball, Singh et al. (2010) in *Bougainvillea glabra and* Singh et al. (2013) in *Cestrum nocturnum*..

Biomass parameter: In hardwood cuttings, the highest leaf dry weight was in IBA 1000 ppm (0.85 g), followed by IAA 500 ppm. Leaf dry weight was highest in IBA 500 ppm (0.48 g) in semi hardwood cuttings, followed by IAA 500 ppm, indicating enhanced photosynthetic potential and foliage development. In softwood cuttings, the maximum leaf dry weight was in cuttings treated with IBA 500 ppm (0.48 g), indicating enhanced photosynthetic tissue development. In twigs, the maximum leaf dry weight was observed in cuttings treated with IBA 500 ppm (0.41 g) and IBA 1000 ppm (0.40 g) (Fig. 1).

The shoot dry weight was also highest under IAA 500 ppm (0.78 g) in hardwood cuttings. The control treatment consistently recorded the lowest values across all growth and biomass parameters, confirming the beneficial effect of PGRs on rooting and overall plant vigour. In semi hardwood cuttings, shoot dry weight maximum under IAA 1000 ppm (0.48 g) and IAA 2000 ppm (0.48 g). Shoot dry weight highest at 0.256 g under the same treatment in softwood cuttings. Similarly, shoot dry weight peaked in these treatments (0.10 g and 0.09 g, respectively) in twigs, reflecting enhanced shoot vigor (Fig. 2).

In hardwood, the root dry weight peaked in IAA 1500 ppm (0.10 g), indicating a thicker or more developed root system, despite shorter overall length. Root dry weight was highest in IAA 1500 ppm (0.06 g) and IBA 500 ppm (0.05 g), suggesting well-developed, thick root systems in semi hardwood cuttings. Root dry weight in softwood cutting was also highest in IBA 500 ppm (0.07 g), reflecting better root system development and potential for nutrient uptake. Root dry weight was also higher in these treatments, with IBA 500 ppm

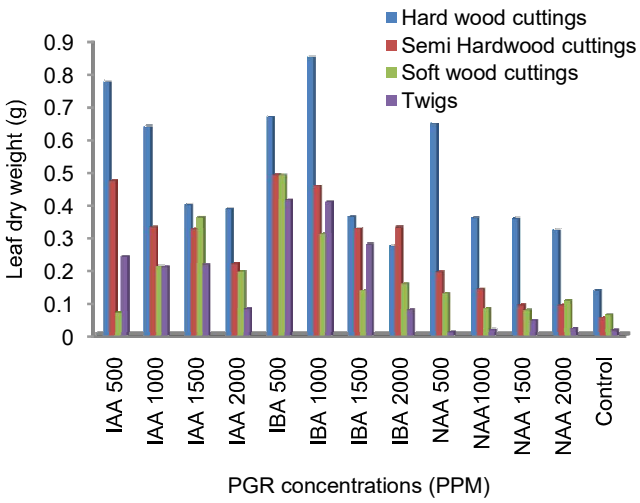

Fig. 1. Effect of plant growth regulators and cutting types on leaf dry weight of Henna (*L. inermis*)

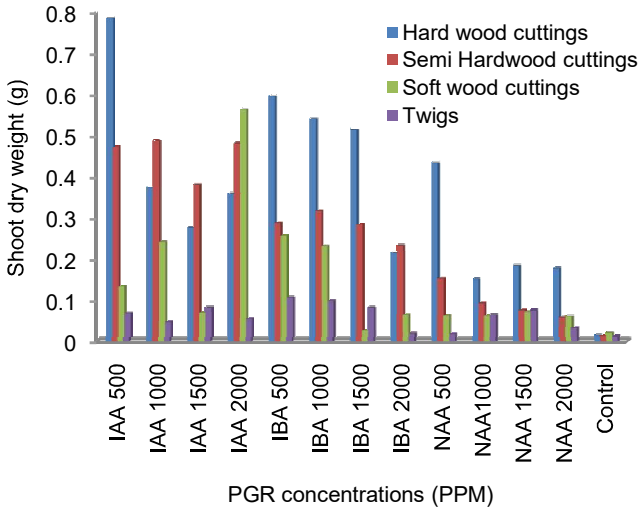

Fig. 2. Effect of plant growth regulators and cutting types on shoot dry weight of Henna (*L. inermis*)

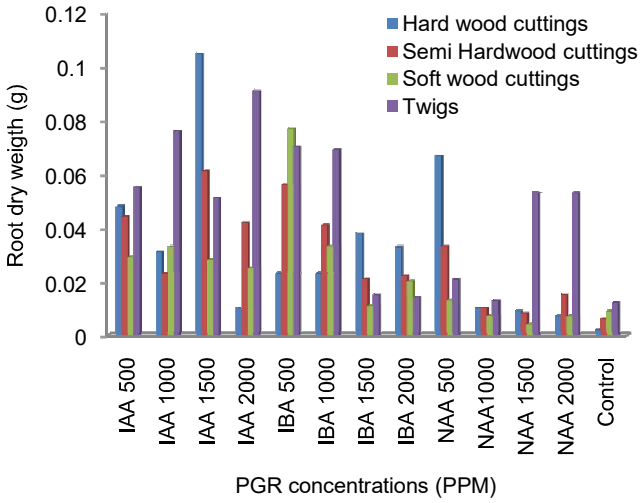

Fig. 3. Effect of plant growth regulators and cutting types on root dry weight of Henna (*L. inermis*)

(0.07 g) in twigs showing significant higher biomass compared to control (0.01 g), highlighting improved root system development (Fig. 3).

The superior dry matter accumulation in hardwood cuttings treated with auxins may be attributed to the higher stored carbohydrate content in these tissues, which, when combined with exogenous auxin application, promoted better root initiation and development. Camellia et al. (2009) in *Jatropha curcus*, reported higher root dry matter due to enhanced root proliferation. Similar outcomes were observed by Deb et al. (2009) in lemon, and Khapare et al. (2012) in fig, where PGR treatments significantly improved biomass accumulation through better root and shoot development.

CONCLUSION

The present study demonstrated that the type of cutting and the concentration of plant growth regulators (PGRs) significantly influence the survival, growth, rooting, and biomass accumulation in henna (*L. inermis*). Among the four types of cuttings evaluated, (hardwood, semi-hardwood, and softwood, and twigs) hardwood cuttings showed superior performance across all parameters, particularly when treated with IAA at 500 ppm or IBA at 1000-1500 ppm. These treatments resulted in the highest sprouting percentage, enhanced shoot length, increased number and size of leaves, maximum root development, and improved biomass accumulation. Semi-hardwood and softwood cuttings responded well to moderate concentrations of IBA (500-1000 ppm), showing satisfactory rooting and shoot growth, though slightly lower than hardwood cuttings. Twig cuttings exhibited the lowest survival and growth performance but still showed improvements under lower concentrations of IAA and IBA. Notably, higher concentrations of NAA were generally less effective or inhibitory, particularly in softwood and twig cuttings. Based on these findings, the use of hardwood cuttings in combination with IAA 500 ppm or IBA 1000 ppm is recommended as the most effective propagation method for henna, offering the best balance between sprouting, vigor, and biomass production. These findings offer a practical strategy to improve henna establishment and productivity in challenging agro-ecological zones.

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Effect of Storage Containers and Media on Germination of *Dysoxylum malabaricum* Bedd. In Hilly Zone of Karnataka

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Abstract**:** The primary objective of seed storage is to preserve viability with minimal loss. However, *ex-situ* storage of recalcitrant seeds is challenging, as they lose viability within days to a few months due to dehydration. This study aimed to extend seed longevity of *Dysoxylum malabaricum*, an endangered evergreen tree, by evaluating different storage containers and treatments. Seeds collected from natural populations were stored in three containers-polythene bags, poly pots and earthen pots-under seven treatments: control, carbendazim (0.5%), chlorpyrifos (2%), abscissic acid (0.005%), carbendazim (0.5%) + chlorpyrifos (2%), carbendazim (0.5%) + chlorpyrifos (2%) + abscissic acid (0.005%), and cow dung + ash. Poly pots were the most effective, and maintained viability for 45 days with 63.18% germination. Among remaining treatments, Chlorpyrifos (2%) was superior, retaining viability for 45 days with 94.81% germination. The highest germination (97.78%) was in seeds stored in polythene bags treated with chlorpyrifos (2%) for 45 days. Appropriate storage treatments and container selection can thus significantly prolong the viability of *D. malabaricum* seeds, aiding the conservation and sustainable use of this endangered species.

Keywords**:** *Dysoxylum malabaricum*, Recalcitrant seeds, Seed viability, Storage containers, Germination

Dysoxylum malabaricum Bedd. is an endangered tree species belonging to the family Meliaceae. The species is commonly called as “White cedar” and is endemic to Western Ghats, distributed in the evergreen forests from Uttar Kannada southwards up to Kerala at an elevation of 2000 m above mean sea level (Swaminath et al., 2003). The timber of the species is highly valued for its luster, aroma and durability. The species is an important ingredient in Ayurvedic medicines and the leaf extract is used to kill malarial vector (Nathan et al., 2005). The wood oil is remedy for ear, eye diseases and decoction of the wood is used in the treatment of rheumatism. The fruits ripen during May to July are food for many birds including the Malabar grey hornbill (Bachan 2006). The prime objective of storage is to preserve the seeds with their viability as little impaired as possible. Stored seeds are of very little value if on sowing they fail to produce healthy and vigorous plants. Ex-situ storage of recalcitrant seeds poses a major challenge, as they undergo dehydration during storage and rapidly lose viability, often within days to a few months. Unlike orthodox seeds, recalcitrant seeds cannot be stored using conventional methods because their germinability declines once the seed moisture content drops below relatively high critical levels. For *D. malabaricum*, an endangered and highly valued species, information on seed germination and storage is extremely limited. Nair et al. (2002) reported that freshly sown seeds of *D. malabaricum* exhibited only 20% germination without any pre-sowing treatments, and that the seeds lost viability within 7–10 days. Given this knowledge gap, the present study was undertaken to evaluate suitable germination and storage methods for *D. malabaricum* seeds, with the aim of improving their viability and conservation potential.

MATERIAL AND METHODS

The present study was carried out at nursery of College of Forestry, Ponnampet, located in the hilly zone (Zone 9), Kodagu district of Karnataka state. Nursery is situated at 12.142983°N latitude; 75.938617°E longitudes and at an altitude of 856 m above Mean Sea Level (MSL). The study area is under tropical humid climate with monthly mean maximum temperature varied from 31ºC to 37 ºC and mean monthly minimum temperature varying from 24 ºC to 27 ºC. *D. malabaricum* seeds were collected from natural populations of Western Ghats during May to July. The collected fruits were depulped and the depulped seeds were subjected to seven seed storage treatments. The treated seeds were stored in three different containers for four different storage periods (Table 1). The experiment was laid out in split-split plot experimental design by considering seed storage containers as main plot, seed storage treatment as sub plot and storage period as sub-sub plot in three replications (30 seeds per replication). The following observations were recorded in each treatment.

Daily germination count: Daily germination was recorded.

Germination per cent: The germination was recorded when cotyledons emerged out of sand on seed bed and expressed

in percentage. Germination per cent values were subjected to arc sine transformation.

Statistical analysis: The data were analysed in split-split plot design in SPSS ver. 27.

RESULTS AND DISCUSSION

No significant differences were observed among treatments (Table 2). However, the interaction effect of container and treatment indicated that the seeds without treatment (T1) when stored in poly pot (M2) gave maximum germination (87.22%) with a mean germination 56.19 per cent followed by seeds without treatment stored in earthen pot (79.44%) with a mean germination of 48.25 per cent. The interaction effect between storage containers and storage duration was non-significant (Table 3). However, the highest germination (63.18%) was when seeds were stored for 45 days (D4) in poly pots (M2), with a mean germination of 56.19%. Across all storage periods, poly pots consistently maintained higher germination compared to other containers, indicating their effectiveness in reducing seed viability loss. These findings suggest that recalcitrant seeds of *D. malabaricum* can be stored up to 45 days when appropriate pre-sowing treatments and suitable storage containers are adopted. Anilkumar (2009) also observed that freshly sown *D. malabaricum* seeds showed 50.87% germination, while seeds stored for 10 days exhibited only 20% germination. Studies on other recalcitrant species have also emphasized the role of storage conditions in prolonging seed viability. Priyanto et al. (2022) found that *Myristica fragrans* seeds stored for 12 days in plastic standing pouch packaging recorded 56.25% germination. Anandalakshmi et al. (2005) demonstrated that polybags of varying thickness, irrespective of pores, could prolong the viability of *Syzygium cuminii* seeds up to five months at 20°C.

The significant effect of different treatment and storage period and on germination per cent was observed in current study (Table 4). chlorpyrifos 0.5% resulted in maximum germination (94.81%) was recorded under D4 (seeds stored for 45 days) and least (8.89 %) was in D1 (seeds when sown fresh) when treated with carbendazim (0.5 %) + chlorpyriphos (2%). Maximum mean germination (79.44%) observed in control treatment (T1) and minimum mean germination (21.30%) was with cow dung + (T7).

The interaction effect of storage container, storage media and storage period on germination (percentage) of *D. malabaricum* seeds was also non-significant in differentiating the effects (Table 5). However, maximum germination (97.78 %) was observed in seeds stored in polythene bag (M1) and treated chlorpyrifos (2 %)] up to 45 days followed by seeds without treatment sown after 15 days of storage (93.33 %). No germination was recorded in seeds stored for 45 days in earthen pot after treated with carbendazim 0.5 %. Poly pots, in particular, proved to effective for *D. malabaricum*, allowing storage for up to 45 days without severe viability loss. Koppad and Umarbhadsha (2006) reported that carbendazim promoted proper seed emergence by controlling pathogens, while Sharma et al. (2004) observed that carbendazim provided up to 90% control of pre-

Table 1. Details showing different storage treatments

Main plot (storage container)	Sub plot (storage media)	Sub-sub plot (storage periods)
M1: Earthen pots	T1: Control	D1: Freshly collected seeds
M2: Poly pots	T2: Carbendazim (0.5%)	D2: 15 Days after collection
M3: Polythene bags	T3: Chlorpyrifos (2 %)	D3: 30 Days after collection
	T4: Abscissic acid (0.005%)	D4: 45 Days after collection
	T5: Carbendazim (0.5%) + Chlorpyrifos (2 %)	
	T6: Carbendazim (0.5 %) + Chlorpyrifos (2 %) + Abscissic acid (0.005%)	
	T7: Cow dung + Ash	

Table 2. Interaction effect of storage container and storage treatment on germination (percentage) of *D. malabaricum* seeds

Sub plot/ Main plot	T1	T2	T3	T4	T5	T6	T7	Mean T
M1	71.67 (57.84)	36.11 (36.94)	66.11 (54.40)	21.11 (27.35)	33.89 (35.60)	52.22 (46.27)	17.78 (24.94)	42.70 (40.80)
M2	87.22 (69.06)	42.78 (40.85)	61.11 (51.42)	52.22 (46.27)	48.33 (44.04)	70.00 (56.79)	31.67 (34.25)	56.19 (48.56)
M3	79.44 (63.04)	21.11 (27.35)	63.89 (53.06)	52.22 (46.27)	31.11 (33.90)	75.56 (60.37)	14.44 (22.34)	48.25 (44.00)
Mean M	79.44 (63.04)	33.33 (35.26)	63.70 (52.95)	41.85 (40.31)	37.78 (37.93)	65.93 (54.29)	21.30 (27.48)	
CD (p=0.05)				NS				

NS = Not significant at 5% level of significance

emergence mortality and 78% control of post-emergence mortality, contributing to improved germination. Similarly, in *Lophopetalum wightianum*, Maheswarappa et al (2020) demonstrated that a combination of carbendazim (0.25%) and chlorpyrifos (0.89%) treatment in earthen pot storage enhanced germination up to 64.61% after 60 days. In the present study, chlorpyrifos (2%) treatment was particularly effective in preventing pest infestation during storage, thereby enabling higher germination percentages in *D. malabaricum.* Similar results were reported for few recalcitrant seeds, like those of *Myristica malabarica*, remain viable for short periods under natural conditions but can be stored for up to a year in polythene bags at specific temperature and humidity levels (Kumar et al., 2002). Hosur et al. (2023) reported significant variation in seed germination (28.89–98.33%) among seven seed sources of *Dysoxylum binectariferum*, with seeds collected from Jog (Karnataka) exhibiting superior performance across all germination traits. Storage conditions, including container type, temperature, and duration, significantly impact seed germination and viability across different medicinal plant species (Tiwari et al., 2022).

The findings hold significant implications for the conservation of *D. malabaricum*, an endangered and ecologically valuable species. By identifying suitable storage containers and treatments to prolong seed viability, this study provides a practical method for short-term ex-situ conservation and nursery propagation. Such techniques can aid forest departments, and restoration programs in maintaining viable seed stocks for reintroduction and habitat rehabilitation. Moreover, these practices can be extended to other recalcitrant-seeded species of ecological and economic value, thereby strengthening in-situ and ex-situ conservation strategies and contributing to the long-term preservation of tropical forest biodiversity. The study faced certain limitations, including a short storage duration of 45 days and limited control over temperature and humidity under ambient conditions. Seed availability was restricted due to the endangered status and sporadic fruiting of *D. malabaricum*. Additionally, seeds were collected during a

Table 3. Interaction effect of storage container and storage period on germination (percentage) of *D. malabaricum* seeds

Storage period/Storage container	D1	D2	D3	D4	Mean D
M1	45.71 (42.54)	40.32 (39.42)	42.86 (40.89)	41.91 (40.34)	42.70 (40.80)
M2	50.16 (45.09)	56.51 (48.74)	54.92 (47.82)	63.18 (52.64)	56.19 (48.56)
M3	42.86 (40.89)	48.89 (44.36)	47.62 (43.64)	53.65 (47.09)	48.25 (44.00)
Mean M	46.24 (42.84)	48.57 (44.18)	48.47 (44.12)	52.91 (46.67)	
CD (p=0.05)			NS		

NS = Not significant

Table 4. Interaction effect of storage treatment and storage period on germination (percentage) of *D. malabaricum* seeds

Storage period/ Storage media	D1	D2	D3	D4	Mean D
T1	86.66 (68.58)	93.33 (75.03)	77.04 (61.37)	60.74 (51.20)	79.44 (63.04)
T2	50.37 (45.21)	34.07 (35.71)	31.85 (34.36)	17.04 (24.38)	33.33 (35.26)
T3	20.00 (26.56)	60.00 (50.77)	80.00 (63.43)	94.81 (76.84)	63.70 (52.95)
T4	46.67 (43.09)	62.96 (52.51)	23.70 (29.13)	34.08 (35.71)	41.85 (40.31)
T5	8.89 (17.35)	11.85 (20.14)	41.48 (40.10)	88.89 (70.53)	37.78 (37.93)
T6	84.44 (66.77)	60.74 (51.20)	68.15 (55.64)	50.37 (45.21)	65.93 (54.29)
T7	26.67 (31.09)	17.04 (24.38)	17.04 (24.38)	24.45 (29.63)	21.30 (27.48)
Mean T	46.24 (44.18)	48.57 (44.18)	48.47 (44.12)	52.91 (46.67)	
CD (p=0.05)			(23.92)		

Parenthetical values are arc sine transformed values; NS = Not significant

Table 5. Interaction effect of storage container, storage treatment and storage period on germination (percentage) of *D. malabaricum* seeds

Storage period	T1	T2	T3	T4	T5	T6	T7
Polythene bag (M1)							
D1	86.66 (68.58)	66.67 (54.74)	26.67 (31.09)	33.33 (35.26)	0.00 (0.00)	84.44 (66.77)	22.22 (28.12)
D2	93.33 (75.03)	42.22 (40.53)	60.00 (50.77)	26.67 (31.09)	6.67 (14.96)	46.67 (43.09)	6.67 (14.96)
D3	71.11 (57.49)	28.89 (32.51)	80.00 (63.43)	11.11 (19.47)	40.00 (39.23)	48.89 (44.36)	20.00 (26.57)
D4	35.56 (36.61)	6.67 (14.96)	97.78 (81.43)	13.33 (21.42)	88.89 (70.53)	28.89 (32.51)	22.22 (28.13)
Poly pot (M2)							
D1	86.66 (68.58)	42.22 (40.53)	11.11 (19.47)	55.56 (48.19)	26.67 (31.09)	84.44 (66.77)	44.45 (41.81)
D2	93.33 (75.03)	37.78 (37.93)	60.00 (50.77)	88.89 (70.53)	24.44 (29.63)	68.89 (56.10)	22.22 (28.13)
D3	84.45 (66.77)	46.67 (43.09)	80.00 (63.43)	33.33 (35.26)	53.33 (46.91)	64.45 (53.40)	22.22 (28.12)
D4	84.45 (66.77)	44.44 (41.81)	93.33 (75.04)	31.11 (33.90)	88.89 (70.53)	62.22 (52.07)	37.78 (37.93)
Earthen pot (M3)							
D1	86.66 (68.58)	42.22 (40.53)	22.22 (28.12)	51.11 (45.64)	0.00 (0.00)	84.44 (66.77)	13.33 (21.42)
D2	93.33 (75.03)	22.22 (28.13)	60.00 (50.77)	73.34 (58.91)	4.44 (12.17)	66.67 (54.74)	22.22 (28.12)
D3	75.56 (60.37)	20.00 (26.57)	80.00 (63.43)	26.67 (31.09)	31.11 (33.90)	91.11 (72.66)	8.89 (17.35)
D4	62.22 (52.07)	0.00 (0.00)	93.33 (75.04)	57.78 (49.48)	88.89 (70.53)	60.00 (50.77)	13.33 (21.42)
CD (p=0.05)				NS			

single season, and only a few chemical and traditional treatments were tested. Future research should focus on long-term storage conditions, optimization of moisture content and physiological and molecular responses influencing viability loss. Exploring eco-friendly bio preservatives and low-temperature storage methods may further enhance the conservation potential of *D. malabaricum* seeds.

CONCLUSION

This study demonstrated that appropriate storage conditions and treatments can effectively maintain the viability of recalcitrant seeds of *D. malabaricum*. Seeds treated with chlorpyrifos (2%) and stored in polythene bags achieved the highest germination even after 45 days, whereas stored in earthen pots with carbendazim (0.5%)did not germinate. These findings provide valuable insights for developing short-term conservation strategies and enhancing seedling availability for restoration initiatives.

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Modulation of Adventitious Root Formation in *Boswellia serrata* Stem Cuttings to Exogenous Application of different Root Promoting Hormones

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***Abstract*:** *Boswellia serrata* Roxb., commonly known as Salai in India and Indian frankincense globally, is widely distributed across 17 of the 28 Indian states. Despite its extensive range, the species is not having good status in India and at the same time it is Critically Endangered in Sri Lanka, primarily due to overexploitation and habitat loss. Given the species' current status, natural regeneration in the wild remains poor. Study was conducted to evaluate the rooting response of *B. serrata* cuttings treated with indole-3-butyric acid (IBA) and α-naphthalene acetic acid (NAA). In vegetative propagation trials, IBA at 5000 ppm produced 21.67% callusing and 11.67% rooting success, followed by IBA at 4000 ppm, with 18.33% callusing and 10.00% rooting. The highest sprouting rate (28.33%), number of roots (4.33), total mean root length (220.04 cm), and mean dry weight of roots (115.00 mg) were observed at IBA 4000 ppm. In contrast, NAA treatments showed peak rooting success (3.33%) at both 4000 and 5000 ppm, with lower concentrations (2000-3000 ppm) resulting in reduced rooting (1.67%). Control cuttings failed to produce any roots. This study highlights the efficacy of IBA, particularly at 4000 to 5000 ppm, in promoting effective vegetative propagation of *Boswellia serrata*, offering a promising approach to aid the conservation and sustainable management of this valuable species.

***Keywords*:** Overexploitation, Natural regeneration, Callusing, Sprouting, Rooting

Boswellia serrata Roxb., belongs to the family Burseraceae, commonly called Salai, is a species predominantly found in the dry deciduous forests of India. It is widely distributed across 17 of the 28 Indian states. The genus includes around 23 recognized species (Anonymous 2025). Globally, it is known as Indian Frankincense. The main non timber forest products obtained from this species is turpentine and resin. India is the world's sole exporter of Indian frankincense, having exported 74.56 metric tonnes in 2016-17 (Brendler et al., 2018). It is a medium-sized tree that can grow up to 15 meters tall (Brendler et al., 2018, Thulin 2020). It has imparipinnate compound leaves that fall in December. The tree remains leafless during its flowering and fruiting phase, which usually occurs from February to March. Bark is thin, papery, and yellowish, which eventually peels away to reveal green stems underneath.

Salai is known to be self-incompatible, a trait reflected in its low fruit set, with an average flower-to-fruit ratio of 18.5:1 (Sunnichan et al., 2005). Although the seeds are produced in large quantities ranging from 13,400 to 25,000 seeds per kilogram, however regeneration through seeds is surprisingly poor (Sharma et al., 2021), raising questions about seed viability under natural pollination conditions (Joshi et al., 1981). Besides seed propagation, the tree can also regenerate vegetatively through stem cuttings and root suckers (Thakur et al., 2021). Past research and experiences in this species advocated the planting of large cuttings (100-120 cm) resulted in significant effect on its rooting (Joshi 1981). Due to ecological and economic value of this tree and considering its poor natural regeneration status in India and critical endangerment in Sri Lanka (Anonymous 2012, Thulin 2020) vegetative propagation presents a promising conservation strategy to improve its chances of survival and ensure sustainable use. Therefore, this study is an attempt to find out the effect of different root promoting hormones on stem cuttings of *B. serrata.*

MATERIAL AND METHODS

The study was performed in the nursery unit of College of Forestry BUAT Banda in of July 2024 during the monsoon.

Field preparation: For the experiment nursery bed of size 10 m x 1.2 m was prepared**.** Soil was made light and pulverized by mixing adequate quantity of sand for easy rooting of the cuttings having sand and soil in ratio of 2:1.

Preparation of stem cutting: Stem cuttings of the Salai were taken from trees with dbh 30-40cm in Bahadurpura Forest Block of Banda Forest Division (Latitude: 25.03298, Longitude: 80.53363° and altitudinal range: 200m -300m) which falls within the Bundelkhand region of arid ecosystem. Size of the cuttings was in range of 20-25cm. Cutting was given a slanting cut to increase the surface area for the better absorption of the rooting hormone. Prepared cuttings were treated with 0.25% mancozeb for one hour. Each replication having 20 cuttings were eventually planted out. These cuttings

were kept in bed for 60 days and regular monitoring was done in this period. The experiment was treated weekly with mancozeb fungicide (0.25%) and chlorpyrifos insecticide (0.2%) to prevent fungal and termite infestation. The experiment comprises of 11 treatments, each replicated (20 cuttings/replication) thrice in completely randomized block design.

Treatment of cuttings: For the treatment, five concentrations of IBA and NAA (1000, 200, 3000, 4000 and 5000ppm) were prepared in solid form by mixing them in talcum powder. Slurry of the auxins was prepared for the even distribution of the hormone.

Observations recorded: Observation of the cuttings was recorded after 60 days of planting. Each cutting was uprooted and then the data was recorded. Root analyzer (WinRhizo STD4800) was used for more accurate results of number of roots and root length.

Statistical analysis: The statistical analysis of recorded data was done using SPSS version 15.0.

RESULTS AND DISCUSSION

There was no significant differences in sprouting percentages (Table 1), IBA treatments consistently outperformed NAA across all concentrations. The highest sprouting percentage was with IBA at 4000 ppm (28.33%), followed by 26.67% at 5000 ppm (In an experiment Anuradha et al.(2024) reported minimum 17.77% to maximum of 40.00% sprouting in Bougainvillea by using different treatment of IBA and NAA). In comparison, NAA showed 20% sprouting at 5000 ppm. Vaishnav and Janghel (2018) reported no growth or differentiation in 25 cm-long Salai cuttings even after 50 days of planting, though a few smaller cuttings sprouted after 65 days. Nale et al. (2024) observed maximum sprouting in *Ficus carica* with IBA at 2500 ppm. Sure et al. (2018) used IBA in *Commiphora wightii* and achieved 85% sprouting and 76.67% rooting at just 500 ppm. IBA 5000 ppm treatment induced significantly higher callusing (21.67%) compared to all other concentrations. In contrast, NAA at 1000 ppm resulted in minimal callusing, merely 1.67%.

IBA at 5000 ppm yielded the most effective rooting (11.67%) in Salai stem cuttings, followed by 10.00% rooting at 4000 ppm and thereafter decreased progressively with lower IBA concentrations. Among the NAA treatments, the highest rooting percentage of 5.00% was at 5000 ppm while 3.33% at 3000ppmn s. Moreover, the sprouting percent had a strong correlation (0.95) with the root number (Table 2). The control cuttings failed to produce any roots. These findings resonate with Patel et al. (2003), reported IBA at 4000 ppm as the most effective concentration for rooting fig cuttings, achieving 65% rooting. Kaur et al. (2022) found that higher concentration IBA 6000 ppm (35.72%) improved the rooting percentage in *Tecomella undulata*.

The highest average number of roots (4.33) occurred in cuttings treated with IBA at 4000 ppm (Table 1). The cuttings treated with NAA at 5000 ppm averaged 1.33 roots, while the lowest number (0.33 roots) was at NAA 1000 ppm. No rooting was observed in control cuttings. Similarly, Patel et al. (2003) reported an average of 8.8 roots per cutting in fig treated with IBA 4000 ppm, and Behera et al. (2018) observed 8.16 roots in *Boswellia serrata* cuttings treated with IBA at 1000 ppm. The callusing percent has a significant impact on the root number (Table 2).

The IBA at 4000 ppm resulted in the greatest mean root

Table 1. Effect of NAA and IBA of rooting behavior of Salai stem cuttings

Treatment	Sprouting (%)	Callusing (%)	Rooting (%)	No. of roots	Total root length (cm)	Root dry weight (mg)
NAA 1000 ppm	13.33	1.67	1.67	0.33	43.59	10.33
NAA 2000 ppm	15.00	5.00	1.67	1.00	39.10	14.00
NAA 3000 ppm	18.33	3.33	3.33	0.67	103.52	36.67
NAA 4000 ppm	16.67	5.00	3.33	1.00	116.13	47.33
NAA 5000 ppm	20.00	6.67	5.00	1.33	151.26	68.67
IBA 1000 ppm	21.67	11.67	3.33	2.33	66.42	25.67
IBA 2000 ppm	20.00	13.33	6.67	2.67	151.70	87.33
IBA 3000 ppm	25.00	15.00	8.33	3.00	143.78	57.33
IBA 4000 ppm	28.33	18.33	10.00	4.33	220.04	115.00
IBA 5000 ppm	26.67	21.67	11.67	3.67	188.55	114.67
Control	11.67	5.00	0.00	0.00	0.00	0.00
CD (p=0.05)	NS	6.47	4.92	2.16	106.14	54.38

Table 2. Correlation studies on various vegetative parameters indicating rooting behaviour of salai stem cuttings

Variables	Sprouting (%)	Callusing (%)	Rooting (%)	Root numbers	Root length	Root dry weight
Sprouting (%)	1.00					
Callusing (%)	0.90	1.00				
Rooting (%)	0.94	0.92	1.00			
Root numbers	0.95	0.96	0.93	1.00		
Root length	0.88	0.75	0.92	0.83	1.00	
Root dry weight	0.86	0.83	0.94	0.86	0.97	1.00

**Correlation is significant at the 0.01 level

length (220.04 cm), significantly outstripping other treatments (Table 1) followed by 188.55 cm in cuttings treated with IBA at 5000 ppm., Behera et al. (2018) recorded root lengths of 21.93 cm in *Commiphora wightii* cuttings, and Bhardwaj et al. (2025) reported an average root length of 25.28 cm in *Punica granatum* treated with IBA at 2500 ppm. IBA 500 ppm, showed highest sprouting percentage (85.00%), rooting percentage (76.67%) and average roots (7.36), root length (13.87 cm) was observed in semi hardwood cuttings of *Commiphora wightii* (Sure et al., 2018). The study demonstrate that cuttings treated with IBA produced the highest mean dry root weights, with the maximum value of 115.00 mg observed at 4000 ppm, followed by 114.67 mg at 5000 ppm. Nale et al. (2024) also found the maximum root dry weight of 4.75 g in *Ficus carica* cuttings treated with IBA at 2500 ppm. All pairs of vegetative parameters exhibit a strong positive correlation, with all values exceeding 0.75 (Table 2).

CONCLUSION

Challenging the long-held belief that only large cuttings of *Boswellia serrata* can regenerate, this study proves that small cuttings are also viable when treated with a high concentration of IBA. This finding offers a promising new approach to bolstering the species' regeneration, which is crucial for a sustainable oleo-resin supply for the pharmaceutical industry. However further research is needed to enhance efficacy.

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Influence of Biofertilizers on Germination and Early Seedling Growth of *Artocarpus heterophyllus* Lam. under Nursery Conditions

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***Abstract*:** The effect of biofertilizer on seed germination and growth of *Artocarpus heterophyllus* Lam. under nursery conditions was evaluated during the 2023-24 at the College of Forestry, Sirsi, University of Agricultural Sciences, Dharwad. The experiment comprises seven treatments (control, *Azotobacter*, PSB, AM fungi, *Azotobacter* + PSB, PSB + AM fungi and *Azotobacter* + PSB + AM fungi) with three replications each. There was statistically significant improvements in all growth parameters with the use of biofertilizers over the control. Among all treatments, the combination of *Azotobacter* + PSB + AM fungi resulted in highest germination percentage (82.22%), maximum seedling height (33.50 cm at 90 days after sowing), highest number of leaves (5.70), maximum stem girth (1.12 cm), root length (17.1 cm), and the most vigorous seedlings as indicated by the seedling vigor index (4160.33). This treatment was significantly superior to the control which recorded the lowest performance across all parameters. Dual inoculation treatments (*Azotobacter* + PSB and PSB + AM fungi) also showed marked improvement compared to single inoculant applications (*Azotobacter*, PSB and AM fungi), highlighting the benefit of synergistic interactions among microbial species. The study concludes that the combined use of *Azotobacter*, PSB, and AM fungi significantly enhances seed germination and early seedling growth in jackfruit.

***Keywords*:** Biofertilizer, *Azotobacter*, Phosphate Solubilizing Bacteria (PSB), Arbuscular Mycorrhizal (AM), *Artocarpus heterophyllus*

Artocarpus heterophyllus Lam. is one of the most important tropical fruit tree species, extensively cultivated across many parts of Asia, particularly in India. Native to the Western Ghats, thrives in warm and humid climates and is highly valued for its large, sweet and nutritious fruits, which serve both as a staple food and a delicacy (Azad et al., 2007). Besides its fruit, jackfruit is also appreciated for its durable timber, contributing to its economic significance (Jambhale et al., 2016). However, cultivation and propagation face several challenges at the nursery stage like, poor seed germination rates and weak seedling vigour. These factors pose significant obstacles to large-scale propagation and field establishment (Singh et al., 2019). In recent years, there has been an increasing emphasis on sustainable and eco-friendly agricultural practices. Among these, the application of biofertilizers has emerged as a promising alternative to chemical fertilizers. Biofertilizers are formulations containing beneficial microorganisms that improve plant growth by facilitating the uptake of essential nutrients through natural processes like nitrogen fixation, phosphorus solubilization and the production of plant growth-promoting substances (Vessey 2003, Bhattacharyya and Jha 2012). Compared to synthetic fertilizers, biofertilizers are more environmentally sustainable, contribute to long-term soil fertility and enhance microbial diversity in the rhizosphere (Mishra and Dash 2014, Maharana Rashmiprava et al., 2018). Applying biofertilizers at the nursery stage has shown considerable benefits by establishing early microbial associations with plant roots, thereby improving seedling growth, root development and resilience against biotic and abiotic stresses (Bhardwaj et al., 2014). For perennial species like jackfruit, which demand robust and vigorous seedlings for successful transplantation and long-term survival, integrating biofertilizers into nursery practices can play a crucial role in ensuring higher productivity and sustainability (Kumar et al., 2017). With this background, the present study was undertaken to evaluate the effects of different biofertilizers like, *Azotobacter*, Phosphate Solubilizing Bacteria (PSB) and Arbuscular Mycorrhizal (AM) fungi on the germination and early growth of jackfruit seedlings under nursery conditions. The study aims to support the development of sustainable nursery management practices by identifying effective microbial combinations that enhance seedling quality and reduce dependency on chemical inputs.

MATERIAL AND METHODS

The study was conducted at the College of Forestry, Sirsi, which is located in the Uttara Kannada district of Karnataka. The experimental site lies at 14.620°N latitude and 74.850°E longitude, within the core region of the Western Ghats. The elevation of the site ranges from 1860 to 2600 feet above mean sea level. The experiment was conducted under polyhouse conditions, which are maintained under warm and humid tropical environment with an average temperature of 25-30 °C and relative humidity around 70 to 80%, ensuring optimum conditions for jack seed germination and seedling

growth. The experiment was laid out in a completely randomized block design comprising seven treatments each replicated three times (Table 1).

Each treatment included 20 seeds and the experimental units were randomly arranged to reduce environmental variability. These treatments were designed to evaluate both individual and combined effects of biofertilizers on seed germination and early seedling growth of jackfruit. For the experiment, healthy, mature, and undamaged jackfruit seeds were collected during August 2023. The seeds were thoroughly washed with clean water to remove adhering mucilage and other debris, followed by shade-drying for 12 to 24 hours. The dried seeds were then stored in polythene bags until sowing. Prior to sowing, a 10 ml solution of jaggery was prepared to serve as a binding agent for the biofertilizer. Each seed was coated with this jaggery slurry and 20 g of the carrier-based biofertilizer, according to the respective treatment, was applied evenly over the seeds to form a uniform microbial layer. The treated seeds were first sown in a standard nursery bed of dimensions 1.2 × 12.2 meters. After 30 days, the germinated seedlings were carefully transplanted into polybags measuring 5 × 7 inches. The potting mixture used in the polybags consisted of red soil, sand and vermicompost mixed in a 2:1:1 ratio. This mixture was thoroughly blended to ensure uniform texture and nutrient content. To facilitate proper drainage, three to four small holes were made at the base of each polybag. Regular nursery maintenance practices were followed throughout the experimental period. Watering was done once daily using a rose can to maintain adequate moisture levels in the rooting media. Observations were recorded at regular intervals of 30 days after sowing (DAS), with data collection continuing up to 90 DAS. The parameters observed included days to germination, plant height, number of leaves, stem girth, root length and seedling vigor index.

Germination was recorded based on the number of days taken for the seeds to sprout, which typically occurred by 15 DAS. Plant height was measured from the base to the tip of the shoot. The number of leaves was manually counted for each seedling. Stem girth was calculated by measuring the collar diameter at 1 cm above the ground level using a digital calliper and then multiplying it by π (3.142) to obtain the girth in centimetres. Root length was recorded at 90 DAS using a measuring scale. The seedling vigor index was computed by multiplying the germination percentage with the average seedling height recorded at 90 DAS.

Statistical analysis: The data was analysed by using opstat app.

RESULTS AND DISCUSSION

Germination percentage: The significant variations among the different treatments was observed (Table 1). The highest germination percentage was observed in T_7 (82.22%), which involved a combined application of *Azotobacter*, phosphate solubilizing bacteria (PSB), and Arbuscular mycorrhizal (AM) fungi. In contrast, the lowest germination percentage (64.45%) was recorded in the control.

Seedling growth: Maximum seedling height at 30 DAS was in T_7 (*Azotobacter*+Phosphate solubilizing bacteria+ Arbuscular mycorrhiza fungi) (18.73 cm) followed by T_5

Table 1. Influence of microbial inoculants on jack fruit seedlings growth and vigor index at different intervals

Treatments	Germination percentage (%)	Plant height (cm)			Number of leaves per seedlings			Stem girth (cm)			Root length (cm)	Seedling vigor index at 90 DAS
		30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS		
$T_{1=}$ Control	64.45	11.00	13.67	20.53	1.60	2.53	4.00	0.34	0.52	0.57	9.80	1954.98
$T_{2=}$ *Azotobacter* (20g)	71.11	13.40	16.40	23.07	2.33	2.83	4.50	0.38	0.64	0.72	10.50	2386.93
$T_{3=}$ Phosphate solubilizing bacteria (20g)	74.56	16.60	19.57	26.37	2.67	3.30	4.53	0.40	0.68	0.77	12.20	2875.53
$T_{4=}$ Arbuscular mycorrhiza fungi (20g)	71.11	14.77	17.33	23.33	2.33	3.07	4.80	0.44	0.70	0.81	14.30	2676.11
$T_{5=}$ *Azotobacter* (10g) + Phosphate solubilizing bacteria (10g)	80.56	17.63	22.27	30.17	2.67	3.60	5.00	0.57	0.78	0.98	14.70	3614.46
$T_{6=}$ Phosphate solubilizing bacteria (10g) + Arbuscular mycorrhiza fungi (10g)	78.44	16.63	20.13	28.17	2.83	3.17	4.80	0.51	0.73	0.88	15.40	3417.37
$T_{7=}$ *Azotobacter* (7g) + Phosphate solubilizing bacteria (7g) + Arbuscular mycorrhiza fungi (6g)	82.22	18.73	24.37	33.50	3.00	4.17	5.70	0.67	0.94	1.12	17.10	4160.33
CD (p=0.05)	4.97	1.50	1.63	2.48	0.76	0.73	0.83	0.06	0.09	0.09	1.35	190.32

DAS=Days after sowing

(Table 1). The lowest plant height was in T_1 (11.0 cm), which had no microbial inoculation. At 60 DAS, the same trend was observed with minimum plant height was in T_1 (13.67 cm). At 90 DAS, the maximum seedling height was also in T_7 (33.50 cm). At 30 DAS, T_7 treatment produced maximum number of leaves (3.0) followed by T_5. The lowest number of leaves were recorded in uninoculated control seedling T_1 (1.60). At 60 DAS, same trend was observed.

The lowest number of leaves (2.53) were recorded in T_1. At 90 DAS, maximum number of leaves were observed in T_7 (5.70) followed by T_5 and the lowest number of leaves were in T_1 (4).At 30 DAS, the maximum stem girth (0.67 cm) was recorded in T_7 (*Azotobacter* + PSB + AM fungi) followed by T_5 (*Azotobacter* + PSB) (Table 1). The minimum stem girth was in T_1 (0.34 cm). At 60 DAS maximum stem girth was in T_7 (0.94 cm) followed by T_5. The minimum stem girth was found in T_1 (0.52 cm) which includes uninoculated treatments. At 90 DAS, the maximum stem girth was recorded in T_7 (1.12 cm) followed by T_5. The minimum stem girth was in T_1 (0.57 cm) which includes control treatment. The root length of *A. heterophyllus* seedlings, was influenced by various biofertilizers applications. At the end of the experiment maximum root length was d in T_7 (17.1 cm) followed by T_6. The lowest root length was recorded in T_1 (9.8 cm). The seedling vigor index (SVI) at 90 days after sowing (DAS) showed significant variation across the different biofertilizer treatments. The highest SVI was recorded in treatment T_7 (4160.33) followed by T_5 and T_6 which is 3614.459 and 3417.37, respectively. Lowest SVI was observed in T_1 (1954.98) which includes control treatment.

The present study demonstrates that microbial inoculation significantly influenced the germination, seedling height, number of leaves per plant, stem girth, root development and vigor of *A. heterophyllus.* The highest germination percentage due to *Azotobacter* + PSB + AM fungi application confirms that a consortium of beneficial microorganisms can synergistically enhance seed germination and early establishment. This enhancement can be credited to greater accessibility of key nutrients, notably nitrogen and phosphorus. The production of growth-promoting phytohormones such as indole-3-acetic acid (IAA) and gibberellins that stimulate seed metabolism and embryo development. Khalid et al. (2017) in similar studies reported that microbial consortia containing beneficial fungi and bacteria improved germination and vigor in fruit crops through nutrient enrichment and hormonal stimulation. Kumar et al. (2022) also observed that biofertilizers improved nutrient mobilization, leading to faster germination and stronger seedling emergence. Parveen and Kumar (2020) found that the use of microbial inoculants (*Azospirillum brasilense* + *Bacillus polyxyma* + VAM) in *Acacia nilotica* enhanced early seedling vigor through better root colonization and nutrient uptake.

Seedling growth parameters like plant height, number of leaves, stem girth and root length were consistently higher in inoculated seedlings, particularly in T_7 (*Azotobacter* + PSB + AM fungi). The improvement in plant height and leaf number can be attributed to the combined functional roles of the inoculants. *Azotobacter* fixes atmospheric nitrogen, PSB solubilizes insoluble phosphates, and AM fungi enhance nutrient and water absorption through their extensive hyphal networks. Kumar et al. (2022) reported a similar trend in multiple horticultural species, where microbial inoculants promoted shoot elongation and leaf expansion due to increased nutrient uptake and phytohormone production. Mohan and Rajendran (2020) observed that combined inoculation of biofertilizers, *Azospirillum* + AM fungi + pseudomonas improved shoot growth and collar diameter in *Feronia elephantum*, attributing it to the complementary actions of nitrogen-fixing and phosphate-solubilizing microbes. After six months of biofertilizer inoculation in *Casuarina equisetifolia*, the treatment combining *Frankia*, *Azospirillum*, and *Phosphobacterium* resulted in significantly greater root length, shoot length, collar diameter, and both root and shoot biomass compared to other treatments (Saravanan et al., 2012). Similarly, the enhancement in seedling biomass production is likely associated with increased nitrogen accumulation facilitated by *Azospirillum* and *Azotobacter* and elevated phosphorus uptake resulting from inoculation with AM fungi and PSB (Ratha Krishnan et al., 2004), while Rajeshkumar et al. (2009) concluded that combined inoculation of biofertilizers improved shoot height and dry matter accumulation in *Melia azedirach*. Ayswarya (2008), *Tectona grandis* seedlings treated with the combined inoculation of AM fungi + *Azospirillum* + *Azotobacter* + PSB showed the highest microbial inoculation effect (MIE), shoot and root growth, biomass accumulation, and overall vigor, indicating that combined application of microbial inoculants effectively improved nutrient uptake and plant development compared to single or dual inoculations.

Enhanced stem girth and root length in inoculated seedlings indicate that microbial inoculants promoted superior nutrient assimilation, carbon allocation, and tissue differentiation. *Azotobacter* and PSB likely enhanced the nitrogen and phosphorus supply, while AM fungi stimulated root branching and root hair formation, improving soil nutrient exploration. Nowak (1998) explained that microbial associations particularly AM fungi have greater importance to improve root colonization and overall root system architecture, leading to better nutrient uptake and water

absorption. Further, the association of AM fungi greatly enhances the root surface area through the development of extensive hyphal networks. This symbiosis improves water uptake and transpiration efficiency, helps regulate leaf temperature, slows down chlorophyll degradation, and ultimately contributes to better overall seedling quality (Ajeesh et al., 2015). Chauhan et al. (2023) found that Neolamarckia cadamba seedlings inoculated with AM fungi exhibited greater stem thickness and root length compared to uninoculated controls. Khalid et al. (2017) also noted that microbial inoculants containing *Azotobacter* and AM fungi improved root structure and function through the production of auxin-like compounds. Madan et al. (1995) observed that AM fungal inoculation significantly increased root dry weight in Anthocephalus excelsa, Pongamia glabra, and Cassia siamea. The seedling vigor index (SVI) was highest in T_7 (*Azotobacter* + PSB + AM fungi), reflecting the cumulative benefits of improved germination, enhanced shoot elongation, and robust root growth. The combined effect of *Azotobacter*, PSB, and AM fungi enhanced overall nutrient uptake, hormonal stimulation, and physiological efficiency. Sreedhar and Mohan (2016) observed that dual inoculation of VAM and Azospirillum significantly increased SVI and biomass in *Neolamarckia cadamba*. Firuzsalari et al. (2012) also identified SVI as a reliable indicator of vigor improvement in inoculated seedlings with *Azospirillum, Azotobacter* and *Pseudomonas*. Vairamani and Rajendran (2021) confirmed that integrated microbial inoculation (*Azospirillum* + *Paenibacillus polymyxa* + AMF) enhanced SVI and stress tolerance in *Casuarina junghuhniana* seedlings. Therefore, the integrated microbial inoculation with *Azotobacter*, PSB, and AM fungi is an effective and sustainable approach to enhance the early growth and establishment of jack seedlings. Khalid et al. (2017) emphasized the role of microbial consortia in stimulating plant growth and nutrient cycling in fruit crops, while Kumar et al. (2022) highlighted the sustainability benefits of biofertilizers as eco-friendly alternatives to chemical fertilizers. Therefore, the integrated biofertilization can play a vital role in improving nursery productivity and field establishment in *Artocarpus heterophyllus* cultivation.

CONCLUSION

Among the seven treatments, the combined application of *Azotobacter*, Phosphate Solubilizing Bacteria and Arbuscular Mycorrhizal fungi consistently outperformed all other treatments across key growth parameters. This treatment recorded the highest germination percentage, plant height, number of leaves, stem girth, root length, and seedling vigor index at all observation stages. In contrast, the control group without any microbial treatment exhibited the lowest performance in all measured traits, reinforcing the importance of microbial inputs for seedling development. These findings indicate that the use of selected biofertilizers can greatly improve the early growth, establishment and overall vigour of jackfruit seedlings. *Azotobacter* + PSB + AM fungi offers a practical, sustainable and cost-effective strategy to produce high-quality planting material.

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Influence of *Salix* Planting Density and Clonal Variation on Aphid Infestation

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***Abstract*:** This study assessed the effects of planting density and clonal variation on growth traits and aphid (*Tuberolachnus salignus*) infestation in four *Salix* clones under short rotation forestry. Clones were planted at three spacings (1×1, 1×2, 2×2 m) in a factorial randomized block design. Growth parameters and aphid incidence were significantly influenced by spacing, clone, and their interaction. UHFS 141 showed the highest volume index (37,803.86 cm^3) at 2×2 m spacing. Aphid infestation was highest under dense planting (1×1 m), with NZ 1140 recording the most colonies (6.2/tree), while UHFS 119 at 2×2 m had the least (0.4 colonies/tree). Imidacloprid 17.8 SL @ 0.3 ml/L effectively reduced aphid populations, followed by Neem oil @ 30 ml/L. Results highlight the importance of integrating optimal spacing, clone selection, and pest management for improved *Salix* productivity.

***Keywords*:** *Salix*, Clones, Spacing, Growth, Volume, Aphid infestation

As the climate crisis intensifies, there is an urgent need to transition toward cleaner and more sustainable energy sources. Biomass from fast-growing perennial woody species, especially those managed under Short Rotation Coppice (SRC) systems, offers a promising route (Luna et al., 2016). These systems provide renewable energy and help reduce atmospheric carbon, with forest−based mitigation potentially cutting global CO_2 emissions by up to 5.5 Gt yr^{-1} by 2040 (IPCC 2002, FAO 2016). In addition, SRC systems-characterized by dense planting and short harvest cycles-deliver ecological benefits such as soil improvement, erosion control, and enhanced biodiversity.

Willow (*Salix* spp.) is particularly suited for SRC systems because of its rapid growth, high biomass yield, and ability to thrive in degraded or nutrient-poor soils, making it valuable both for bioenergy production and ecological restoration (Kuzovkina and Quigley 2005, Jama and Nowak 2012). Globally, the genus comprises about 330–500 species and in India, 31 native and 4 exotic species have been recorded (Sharma et al., 2015). Beyond bioenergy, willows play multiple agroforestry roles, contributing to fodder, fuelwood, and timber production, while also supporting phytoremediation (Bhat 2004, Rawat et al., 2006, Ronald et al., 2007).

In SRC systems, the productivity of *Salix* is influenced primarily by planting density and clonal variation. Closer spacing encourages vertical growth due to competition for light, whereas wider spacing promotes diameter growth and biomass accumulation by reducing root competition (Benomar et al., 2012, Thakur et al., 2023b). Genotypic variation further affects growth vigor, stress tolerance, and adaptability, and the interaction of clone with spacing can alter yield and resilience (Larsson et al., 2001, Karp et al., 2011, Thakur et al., 2023a). High planting densities may exacerbate intraspecific competition, reducing survival and growth (Akers et al., 2013). Thus, assessment of clone performance across spacing regimes is crucial for optimizing survival and biomass yield (Singh et al., 2019).

The growing challenge in *Salix* cultivation is infestation by the willow aphid *Tuberolachnus salignus*, a phloem feeder that colonizes stems and branches. The aphid excretes honeydew, leading to sooty mold formation and attracting ants which interfere with natural aphid predators . While the biology and spread of *T. salignus* are well studied in Europe and other temperate regions (Collins et al., 2001), there is limited information on its behavior, host preference, and management in Indian settings. Understanding how planting density and clonal variation influence aphid infestation is important for integrated pest management and sustainable willow productivity. Denser plantings may facilitate pest spread via close canopy contact, whereas some clones may exhibit inherent resistance or tolerance. In view of the above hypothesis, this study aimed to evaluate the growth performance of selected *Salix* clones under different planting densities, to assess *T. salignus* infestation across clone–density combinations, and to test the efficacy of selected biopesticidal and chemical control measures.

MATERIAL AND METHODS

Location and climate of experiment site: The study was conducted at the research fields of the Department of Forestry and Natural Resources, Punjab Agricultural

University, Ludhiana, India (30°54'26" N, 75°47'38" E; 247 m a.m.s.l.), located in Punjab's central agro-climatic zone. The region has a semi-arid, subtropical to tropical climate with three main seasons: hot and dry summer (April-June), humid monsoon (July-September), and cold winter (December-February). Annual rainfall averages 704 mm, primarily during the monsoon months.

Plant material and experimental design: The Department of Tree Improvement and Genetic Resources, Dr. Y.S. Parmar University of Horticulture and Forestry, Solan (Himachal Pradesh), has introduced over 200 *Salix* clones/hybrids from various countries and developed heterotic hybrids using native species. This diverse germplasm has been maintained and evaluated through nursery and multi-location field trials. From this collection, 28 promising clones were tested under Punjab conditions, and four (NZ 1140, UHFS 141 ,UHFS 85 and UHFS 119)were selected for evaluation under different planting densities. One-year-old plants were established in February 2020 using a factorial randomized block design with three spacing as treatments (1 x 1, 1 x 2, 2 x 2m). Irrigation was applied weekly in summer and fortnightly in winter.

Growth Parameters: Observations on growth parameters *viz*., plant height and basal diameter was recorded initially at the time of transplanting and after two years. Volume index was calculated on the basis of D^2H (square of diameter x height) relationship.

Aphid monitoring: Aphid population was monitored visually at weekly intervals from February to March (2021) by counting the number of aphid colonies present on the stems and branches of five randomly selected trees per plot. The mean aphid population per treatment was calculated and subjected to statistical analysis to determine the influence of clone, spacing, and their interaction.

Aphid management: To evaluate the effectiveness of different control measures against *T. salignus*, a separate experiment was conducted under completely randomized design with four treatments: Imidacloprid 17.8 SL at 0.3 ml/L, Neem oil (Azadirachtin 300 ppm) at 30 ml/L, water spray (as a mechanical removal method), and an untreated control. Each treatment was replicated thrice, and five plants per treatment were selected for observation. The treatments were applied using a tractor operated sprayer during early morning hours to minimize evaporation losses. Aphid colony counts were recorded before treatment and subsequently at 3, 7, and 10 days after spraying by visually counting the colonies on the stems and main branches.

Statistical analysis: The mean data recorded on various growth parameters and aphid monitoring were subjected to statistical analysis) using OPSTAT software developed by CCS Haryana Agricultural University, Hisar (Sheoran et al., 1998).

RESULTS AND DISCUSSION

Effect of spacing and clones on growth characters: The spacing, clone type, and their interaction significantly influenced the growth attributes *i.e*., plant height, basal diameter, and volume index (Table 1, 2, 3). Among the clones, UHFS 119 recorded the highest mean volume index (28,150.92 cm^3), closely followed by UHFS 141. Under spacing treatments, 1 × 2 m achieved the greatest mean plant height (5.96 m), whereas 2 × 2 m produced the highest mean basal diameter (6.77 cm) and volume index (27,267.46 cm^3). The interaction between clone and spacing was significant, with UHFS 141 at 2 × 2 m recording the highest volume index (37,803.86 cm^3). These findings are consistent with earlier research indicating that both genetic makeup (clone) and silvicultural practices (like spacing) can substantially affect tree growth and biomass accumulation (Dvorak et al., 2000). Among the evaluated clones, UHFS

Table 1. Effect of different spacings on plant height (m) of *Salix* clones

Spacings Clones	1x1 m	1x2 m	2x2 m	Mean	1x1 m	1x2 m	2x2 m	Mean
Plant height (m)								
	Initial				2nd year			
NZ 1140	3.80	4.00	3.76	3.85b	4.10	4.33	4.63	4.35d
UHFS 141	4.04	3.63	3.70	3.78b	5.76	5.80	6.52	6.02c
UHFS 85	4.39	3.75	4.20	4.11a	7.20	6.72	6.56	6.83a
UHFS 119	4.57	3.48	4.07	4.04a	6.36	7.02	5.55	6.31b
Mean	4.20a	3.72c	3.93b		5.85b	5.96a	5.81b	
CD (p=0.05)	Clone			0.09	Clone			0.11
	Spacing			0.08	Spacing			0.10
	Clone*Spacing			0.16	Clone*Spacing			0.20

119 recorded the highest overall mean volume index (28150.92 cm³), followed closely by UHFS 141, suggesting that both clones possess superior genetic potential for volume accumulation. The significant variation observed among *Salix* clones in growth parameters such as height and basal diameter aligns with Sharma et al. (2011), who reported considerable genetic diversity in willow clones introduced in Himachal Pradesh, emphasizing the importance of clonal selection for improved growth performance in SRC systems. Similarly, White et al. (2007), emphasized the role of clone selection in maximizing growth and yield under optimal management conditions.

Spacing of 1 × 2 m resulted in the tallest plants (5.96 m). The closer spacing likely enhanced vertical growth due to increased competition for light, which is a known adaptive response in densely planted trees (Pretzsch 2005, Thakur et al., 2023b). On the other hand, 2 × 2 m spacing favoured better basal diameter growth (6.77 cm) and the highest volume index (27267.46 cm³). This wider spacing may have reduced competition for below-ground resources such as water and nutrients, facilitating increased radial growth (Forrester et al., 2006). The findings of this study are consistent with Kumar (2004) in *Populus deltoides* and Patil et al. (2017) and Thakur et al. (2023b) in *Melia dubia*, where wider planting spacing significantly enhances stem diameter. The clone × spacing interaction was significant, demonstrating the importance of matching genetic material to site conditions and silvicultural regimes. The maximum volume index (37,803.86cm³) was observed in UHFS 141 at a spacing of 2 × 2 m. These findings suggest that clone UHFS 141 performs better in wider spacing likely due to its ability to capitalize on resource availability for diameter and height growth. Jayawickrama and Carlson (2000) also emphasized that the optimal performance of clones depends on appropriate spacing, as clones exhibit distinct physiological and morphological responses to planting density.

Effect of planting density and clone on aphid population: The population of *T. salignus* was significantly influenced by

Table 2. Effect of different spacings on basal diameter (cm) of *Salix* clones

Spacings Clones	1x1 m	1x2 m	2x2 m	Mean	1x1 m	1x2 m	2x2 m	Mean
Basal diameter (cm)								
	Initial				2nd year			
NZ 1140	3.02	3.16	3.14	3.10a	5.16	5.87	6.18	5.73c
UHFS 141	3.72	3.08	3.36	3.38a	6.36	6.33	7.61	6.77a
UHFS 85	3.57	3.18	3.11	3.29a	6.24	6.09	6.56	6.29b
UHFS 119	3.66	3.02	3.41	3.36a	6.15	7.06	6.74	6.65a
Mean	3.49a	3.11b	3.25ab		5.97c	6.34b	6.77a	
CD (p=0.05)	Clone		NS		Clone		0.21	
	Spacing		0.26		Spacing		0.18	
	Clone*Spacing		NS		Clone*Spacing		0.36	

Table 3. Effect of different spacings on volume index (cm³) of *Salix* clones

Spacings Clones	1x1 m	1x2 m	2x2 m	Mean	1x1 m	1x2 m	2x2 m	Mean
Volume index (cm³) of								
	Initial				2nd year			
NZ 1140	3499.14	4017.61	3742.36	3753.04b	10933.37	14978.64	17736.76	14549.59b
UHFS 141	5592.02	3475.55	4236.93	4434.90ab	23337.44	23307.79	37803.86	28149.70a
UHFS 85	5697.70	3867.04	4170.29	4578.33ab	28062.46	24966.46	28241.74	27090.22a
UHFS 119	6186.64	3185.10	4759.80	4710.50a	24143.31	35021.95	25287.49	28150.92a
Mean	5243.91a	3636.32b	4227.34b		21619.14c	24568.71b	27267.46a	
CD (p=0.05)	Clone		NS		Clone		1603.13	
	Spacing		719.23		Spacing		1388.35	
	Clone*Spacing		NS		Clone*Spacing		2776.31	

planting density and *Salix* clones, as well as their interaction (Table 4). Among the three spacings, the highest mean aphid population was recorded under 1×1 m spacing (4.6 aphid colonies/tree), followed by 1×2 m spacing (3.5 aphid colonies /tree) and the lowest under 2×2 m spacing (2.2 aphid colonies /tree). The denser spacing likely created a favorable microclimate for aphid multiplication. Among the four willow clones, NZ 1140 recorded the highest overall aphid (4.6 aphid colonies /tree), followed by UHFS 85, UHFS 141 , and the lowest was on UHFS 119 (1.8 aphid colonies /tree). The interaction between spacing and clone was also significant (C.D. = 0.89). The highest aphid incidence was observed in NZ 1140 at 1×1 m spacing (6.2 aphid colonies /tree), while the lowest incidence was found on UHFS 119 at 2×2 m spacing (0.4 aphid colonies /tree). These results suggest that both clone selection and planting geometry play a crucial role in modulating aphid infestation.

Management of aphid: Prior to the spray, aphid populations were statistically at par across all treatments, indicating uniform initial infestation levels (Table 5). At 3 days after spray (DAS), both neem oil (3.8 colonies/plant) and imidacloprid (3.0 colonies/plant) significantly reduced aphid populations compared to the water spray (4.0) and control (4.4). Imidacloprid showed a more pronounced reduction resulted in a significant decline in aphid colonies to 1.4 colonies/plant on 7DAS followed by neem oil, both were statistically superior to water spray and control. Similar trend was observed 10 DAS.

Table 4. Effect of planting density and clones on aphid population during 2021-22

Spacings/Clones	1x1 m	1x2 m	2x2 m	Mean
Spring 2021-22				
NZ 1140	6.20	4.60	3.00	4.60
UHFS 141	3.80	3.80	2.20	3.27
UHFS 85	5.00	4.00	3.20	4.07
UHFS 119	3.40	1.60	0.40	1.80
Mean	4.60	3.50	2.20	
	Clone			0.45
	Spacing			0.515
	Clone*Spacing			0.89

Table 5. Effect of different treatments on aphid management during 2021-22

Treatment	Before spray	3DAS	7 DAS	10 DAS
Neem oil@ 30 ml/L	4.40	3.8	2.40	1.60
Imidacloprid @0.3 ml/L	4.20	3.0	1.40	0.40
Water spray	4.40	4.0	4.20	4.00
Control	4.60	4.4	4.80	5.00
CD (p=0.05)	NS	0.67	0.88	0.68

The present investigation demonstrated that planting density and willow clone significantly influenced the population of *T. salignus*, commonly referred to as the giant willow aphid. High aphid infestation under 1×1 m spacing could be attributed to a more favorable microenvironment for aphid survival and reproduction, including increased humidity, limited sunlight penetration, and reduced air circulation. This is consistent with earlier reports in poplar and apple plantations, where dense plantings were associated with enhanced aphid colonization due to microclimatic effects and host plant accessibility (Wang et al., 2024). Clone-wise variation in aphid incidence suggests that host genotype plays a significant role in pest susceptibility. The highest aphid density on NZ 1140 and the lowest on UHFS 119 across all spacings highlight underlying differences in morphological or biochemical resistance factors. Similar clonal resistance has been reported in poplar against *Chaitophorus* spp. (Ramirez et al., 2004) and in rose cultivars against *Macrosiphum rosae* (Dong et al., 2024). These differences are often linked to variation in trichome density, leaf toughness, or secondary metabolites. Imidacloprid 17.8 SL @ 0.3 ml/L provided the most consistent and significant reduction in *T. salignus* population over time and is consistent with the findings of Khursheed (2015) and Tak et al. (2017) in apple and mustard, respectively

CONCLUSION

The study demonstrated that both planting density and clonal variation significantly affected the growth and aphid infestation in *Salix* clones. Clones UHFS 119 and 141 showed superior growth, while NZ 1140 had the highest aphid infestation and UHFS 119 the least. Denser spacing (1×1 m) promoted aphid build-up, whereas wider spacing (2×2 m) improved biomass. Among control measures, Imidacloprid was most effective, followed by Neem oil. The results highlight the importance of selecting suitable clones, optimizing spacing, and integrating eco-friendly pest management for sustainable *Salix* cultivation.

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AUTHOR'S CONTRIBUTIONS

All authors have made substantial contributions: the conception and design of the study (ST), acquisition of data

or analysis (MK, AK) and interpretation of data (MK, ST, AK), drafting the article (MK, AK), revising the final manuscript (ST, AK) and approved.

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Influence of Different Irrigation Regimes on Physiological Growth and Yield Parameters of *Stevia rebaudiana* Bertoni under Subtropical Agro-climatic Conditions

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***Abstract*:** The present investigation was conducted at Division of Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, to determine the effect of different irrigation depths and IW:CPE ratios on the growth and leaf yield of *Stevia rebaudiana*. The experiment included ten treatments comprising various combinations of irrigation water depths (40 mm, 50 mm, 60 mm) and IW:CPE ratios (0.8, 1.0, 1.2), along with a rainfed control. The irrigation had significant influence on all measured growth and yield parameters. Among the treatments, irrigation at 60 mm depth with an IW: CPE ratio of 1.0 (T9) resulted in the highest plant height, number of branches and leaves per plant, as well as fresh and dry leaf yield. Although IW60mm: CPE=1.2 was statistically at par with T9, showed slightly reduced growth and yield, possibly due to waterlogging and nutrient leaching. In contrast, rainfed conditions recorded the lowest values for all parameters. The findings suggest that optimal irrigation not only enhances physiological growth but also contributes to higher biomass accumulation in *S. rebaudiana*. Therefore, irrigation with 60 mm water depth at an IW: CPE ratio of 1.0 is recommended for maximizing leaf yield under subtropical conditions. Additionally, applying three irrigations per month during the critical summer months (May–June) at 8–10-day intervals is suggested to maintain optimum soil moisture and ensure superior crop performance.

***Keywords*:** Irrigation, IW: CPE ratios*, Stevia rebaudiana,* Steviol glycosides, Sweetener

Stevia rebaudiana Bertoni is a perennial shrub (Jahan et al., 2014) belonging to the family Asteraceae In native habitat, *Stevia rebaudiana* thrives in the semi-humid subtropical regions of Paraguay at elevations ranging from 200 to 400 meters above mean sea level, receiving annual rainfall between 1500–1800 mm, and typically growing on poor, sandy, acidic soils (Peteliuk et al., 2021). Beyond native environment, the crop has been successfully cultivated across a broad range of climatic zones in countries such as China, Japan, Canada, Vietnam, Taiwan, South Korea, USA, India, Thailand, Russia, Spain, Italy, Germany, and Sweden (Razak et al., 2014, Miladinova-Georgieva et al., 2022). In India, *Stevia* is well-suited to the southern climate and is commercially cultivated, with recent expansion into the northern plains and mid-hill regions. The crop shows good adaptability to the subtropical and sub-temperate conditions of the Jammu region under irrigated conditions. Morphologically, the plant attains a height of 65 to 75 cm and bears sessile, oppositely arranged lanceolate to oblanceolate leaves that are serrated above the middle. The flowers are small, white, and arranged in an irregular cyme. With growing consumer awareness of the health risks associated with high sugar intake, there is a rising preference for food products containing natural sweeteners. *Stevia*, as a zero-calorie, low-glycemic sweetener, has emerged as a promising natural substitute for sugar and synthetic sweeteners like saccharin, aspartame, and acesulfame-K, especially given the global diabetic population exceeding 346 million. The leaves of *Stevia* are rich in two primary steviol glycosides (Peteliuk et al., 2021). One of the most significant developments in *Stevia* research is understanding the role of irrigation management not just on yield but also the composition of steviol glycosides (Shivanna et al., 2013). The irrigation criteria based on soil water tension affects both leaf yield and the specific composition of steviol glycosides (Parris et al., 2017). This finding is crucial for commercial production, as different glycosides have varying sweetness intensities and market values. The relationship between water availability and glycoside production appears to be complex, with moderate water stress potentially enhancing the concentration of certain compounds while excessive stress reduces overall productivity (Tadhani et al., 2007). This balance is critical for optimizing both the economic return and the functional quality of stevia leaves. To promote its commercial cultivation, it is crucial to standardize agronomic practices across different agro-climatic regions. Among these, irrigation management, popularly advocated as precision silviculture in forestry tree and medicinal plants species is a critical factor influencing biomass and yield. (Luna et al., 2011, Jagani et al., 2020, Shrivastava et al., 2025). *Stevia* requires careful irrigation management and is sensitive to water quality (Reis et al., 2015). The

development of region-specific irrigation schedules is essential for optimizing its production.

MATERIAL AND METHODS

The investigation was conducted at Division of Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Chatha, Jammu. The site is situated within the university campus at an elevation of 332 meters above mean sea level, located at 32°40′ N latitude and 74°58′ E longitude. The experimental area falls under the sub-tropical zone of Jammu division in Jammu and Kashmir State, characterized by hot dry summers, hot humid rainy seasons, and cold winters. The region receives an average annual rainfall of approximately 1000–1200 mm, with about 75–80% occurring between July and September and the remaining 20–25% during the winter months from December to February. The temperature in this region can rise above 40°C during May to August, while it may drop as low as 3°C in the winter season (Fig. 1).

The experiment was laid out in a randomized block design comprising ten treatments with three replications. Raised beds measuring 1.5 × 1.0 m² were prepared, and seedlings were planted at a spacing of 25 cm × 50 cm. Three irrigation water depths 40 mm, 50 mm, and 60 mm were used to achieve IW:CPE ratios of 0.8, 1.0, and 1.2 for each depth level. Daily pan evaporation and rainfall data were recorded throughout the study. To achieve the desired IW:CPE ratios, irrigation was applied when cumulative pan evaporation reached specific thresholds. For the 40 mm depth, irrigation was applied after 50 mm, 40 mm, and 33.33 mm of cumulative pan evaporation to maintain IW:CPE ratios of 0.8, 1.0, and 1.2, respectively. Similarly, for the 50 mm depth, irrigation was scheduled after 62.5 mm, 50 mm, and 41.6 mm of pan evaporation, and for the 60 mm depth, after 75 mm, 60 mm, and 50 mm of cumulative evaporation. Observations were recorded on various growths and yield attributes, including plant height (cm), number of branches per plant, stem diameter (mm), number of leaves per plant, fresh and dry leaf yield per plant (g), and estimated fresh and dry leaf yield per hectare (q). Data were collected from 15 randomly selected plants per treatment to assess treatment effects.

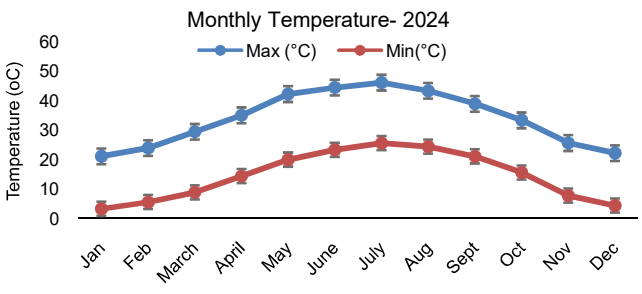

Fig. 1. Monthly temperature of Jammu region

RESULTS AND DISCUSSION

Mean performance of growth and yield attributes as affected by irrigation: The irrigation had significant and positive impact on the growth and leaf yield of *S. rebaudiana* (Table 2). Among the various irrigation treatments, T_9 (IW60mm: CPE60mm = 1.0) showed enhancement in growth parameters, but was statistically at par with T_{10} (IW60mm: CPE50mm = 1.2). Both treatments received five irrigations during the six-month growth period, two irrigations in May and three in June. The irrigation schedule T_9 not only improved vegetative growth but also substantially enhanced leaf yield. In 40 mm and 50 mm irrigation depths, while there was a gradual increase in growth and yield attributes with increasing IW:CPE ratios, the differences between the 0.8 and 1.0 ratios were not statistically significant. The highest plant height, number of branches per plant, and number of leaves per plant were recorded under T_9, and although slightly lower. Similar trend was observed in T_{10}, indicating statistical parity between the two. The fresh and dry leaf yield were significantly influenced by irrigation schedules, with T_9 producing the highest dry leaf yield per hectare (5.58 q), which was also statistically similar to T_{10}.

There was strong positive linear relationship between irrigation schedule and plant height, where plant height increases with higher irrigation levels, directly influencing growth and yield parameters (Fig. 2). The very strong relation between plant height and number of branches, ($y=0.7806x-26.531y$) show that each 1 cm increase in height adds about 0.78 branches($R^2=0.9649$) which explains 96.5% of the variation. The strong positive correlation between plant height and dry leaf yield was observed ($R^2=0.9681$), where yield rises by about 0.14 units per cm increase in height (Fig. 2 b). There was weak correlation between plant height and stem diameter ($R^2=0.529$), only 53% of the variation is explained (Fig. 2c). The plant height is strongly correlated with number of leaves ($R^2=0.962$), adding about 7.4 leaves per cm growth (Fig. 2d). Similarly, there was strong positive correlation between plant height and fresh leaf yield ($R^2=0.9622$), with about 0.47 units of fresh yield gained per cm increase in height (Fig. 2e).

Aladakatti et al. (2012b) also reported that irrigation at IW60mm: CPE60mm = 1.0 is optimal for maximizing dry leaf yield and water use efficiency in *S. rebaudiana*. However, the dry leaf yield reported was considerably higher (10.54 t ha^{-1}) compared to the current study. This discrepancy may be attributed to differences in the growing period at the respective locations-Jammu and Belavatagi (Karnataka).

Additionally, the current study involved only a single

harvest after six months, whereas Aladakatti et al. (2012b) recorded five harvests annually, which likely contributed to increased branching, foliage, and overall yield. Mahajan and Pal (2022) reported that the dry leaf and total steviol glycosides (SGs) yield of stevia was maximum with the irrigation at 50 kPa. At harvest, the plants irrigated at 50 kPa produced 26.9-32.5% higher dry matter over limited application of water (75 kPa). Recent research has significantly advanced our understanding of irrigation management in *S. rebaudiana* cultivation, particularly in the context of precision irrigation technologies and climate adaptation strategies (Abdelsattar et al., 2024). Studies conducted in cooler climates, such as Poland, demonstrated

Table 1. Treatments with different levels of irrigation

Treatment no.	Irrigation schedule
T_1	Control (Rainfed)
T_2	IW_{40mm}: CPE_{50mm}=0.8
T_3	IW_{40mm}: CPE_{40mm}=1.0
T_4	IW_{40mm}: $CPE_{33.33mm}$=1.2
T_5	IW_{50mm}: $CPE_{62.5mm}$=0.8
T_6	IW_{50mm}: CPE_{50mm}=1.0
T_7	IW_{50mm}: $CPE_{41.6mm}$=1.2
T_8	IW_{60mm}: CPE_{75mm}=0.8
T_9	IW_{60mm}: CPE_{60mm}=1.0
T_{10}	IW_{60mm}: CPE_{50mm}=1.2

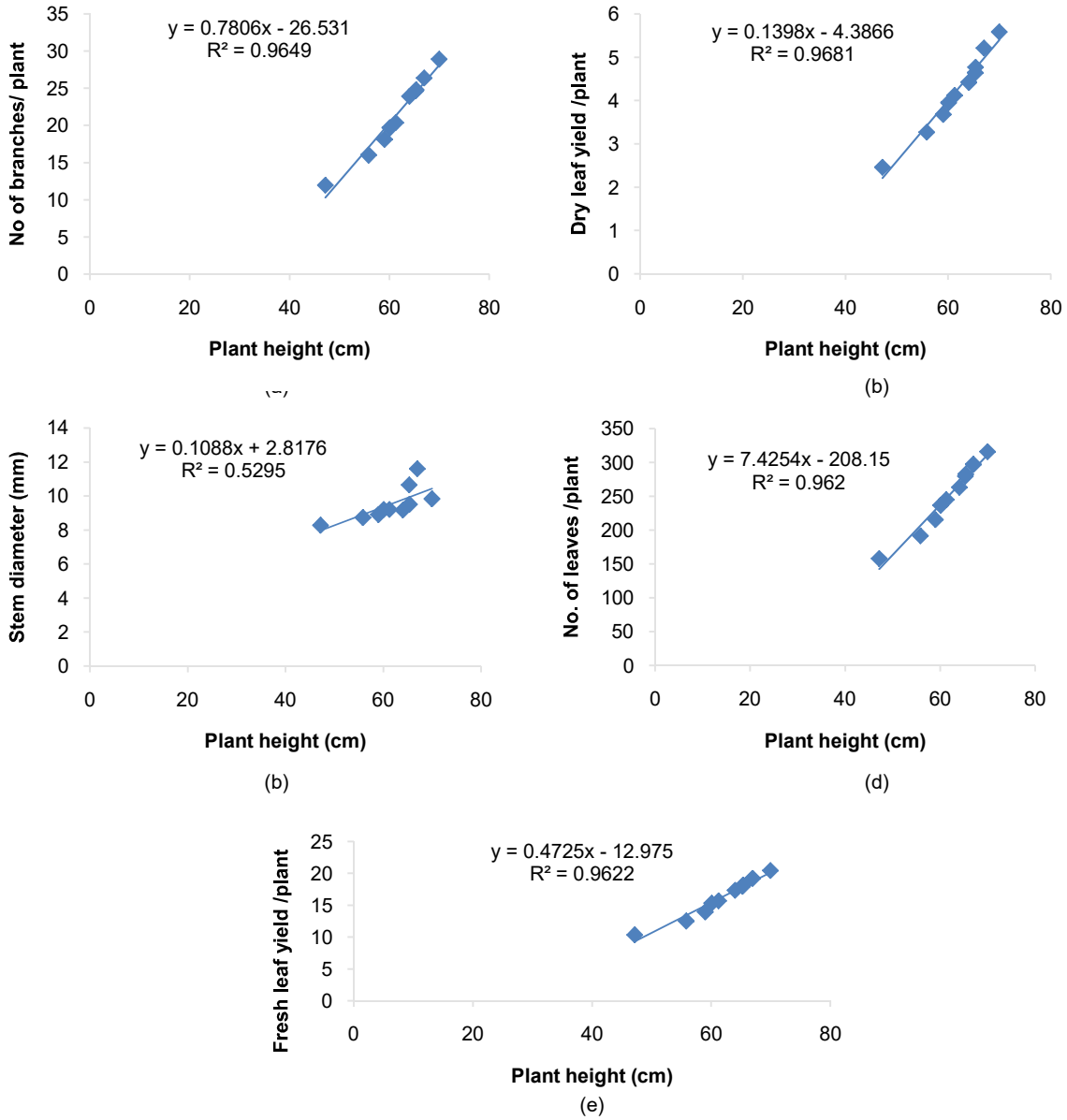

Fig. 2. Relationship between irrigation schedule, plant height and other parameters of plant growth and yield

that different irrigation practices can significantly influence both yield and composition of stevia leaves when grown outside their native warm climate regions (Ceunen and Geuns 2013). This finding is particularly relevant for expanding stevia cultivation to temperate regions where water management becomes even more critical. The superiority of the 60 mm irrigation depth over the 50 mm and 40 mm treatments can be attributed to the consistent moisture availability during critical growth stages, facilitating better root development and enhanced nutrient uptake, which ultimately led to improved growth and productivity. This observation aligns with the findings of Acevedo and Kalra et al. (2024), which emphasized the role of water in root development and cell elongation. Conversely, limited water availability in 40 and 50 mm treatments likely caused moisture stress, reducing growth and yield. Singh (2009) also reported that water stress inhibits plant growth by limiting cell enlargement.

Table 2. Effect of irrigation on growth and yield parameters

Treatments/ Irrigation levels	Plant height (cm)	No. of branches plant^{-1}	Stem diamete (mm)	No. of leaves plant^{-1}	Leaf yield plant^{-1} (gm)		Leaf yield (q ha^{-1})	
					Fresh	Dry	Fresh	Dry
T_1 (Rainfed)	47.18	11.96	8.28	158.07	12.94	3.08	10.35	2.46
T_2 (IW_{40mm}/CPE=0.8)	55.83	16.02	8.73	191.53	15.64	4.09	12.51	3.27
T_3 (IW_{40mm}/CPE=1.0)	59.01	18.12	8.91	215.29	17.43	4.60	13.95	3.68
T_4 (IW_{40mm}/CPE=1.2)	60.09	19.68	9.20	236.72	19.13	4.94	15.30	3.95
T_5 (IW_{50mm}/CPE=0.8)	61.26	20.39	9.21	244.88	19.60	5.16	15.68	4.12
T_6 (IW_{50mm}/CPE=1.0)	64.02	23.91	9.17	263.33	21.67	5.52	17.33	4.42
T_7 (IW_{50mm}/CPE=1.2)	65.29	24.63	10.65	279.52	22.42	5.80	17.93	4.64
T_8 (IW_{60mm}/CPE=0.8)	65.35	24.78	9.51	282.54	22.65	5.97	18.12	4.77
T_9 (IW_{60mm}/CPE=1.0)	69.97	28.89	9.83	315.95	25.54	6.98	20.43	5.58
T_{10} (IW_{60mm}/CPE=1.2)	66.96	26.36	11.60	297.06	23.98	6.51	19.21	5.21
CD (p=0.05)	8.60	3.63	NS	33.34	2.73	0.57	2.19	0.46

Table 3. Effect of irrigation on growth and yield parameters of stevia

Source / Study	Irrigation treatments	Observed growth/yield	Key insights
Irrigation on growth and yield parameters in Subtropical Agro-climatic Conditions of India	Rainfed to IW_{40mm}/CPE=0.8, 1,1.2, IW_{50mm}/CPE = 0.8, 1,1.2 IW_{60mm}/CPE=0.8, 1,1.2	IW_{60mm}/CPE=1.0resulted in the highest plant height, number of branches and leaves per plant, as well as fresh and dry leaf yield.	Providing three irrigations per month during the critical summer period (May–June) at intervals of 8–10 days is recommended (Current study)
Irrigation regimes in Southern Italy	T33 (~33% irrigation), T66 (~66%), T100 (full irrigation)	Dry leaf yield increased by ~40% at full irrigation (T100) compared to minimal (T33). Harvest index & water-use efficiency (WUE) decreased as irrigation increased. Leaf glycoside content remained unchanged across treatments.	Full irrigation boosts yield, but can lower efficiency; quality stable (Lavini et al., 2008).
Irrigation frequency in Poland (cool climate)	No irrigation, irrigation once per week, irrigation twice per week, irrigation only during drought	Highest yields (2.42–2.58 kg/m²) were achieved with irrigation once per week or during drought. Un-irrigated plants were shortest and narrowest; had higher dry mass and more phenolics. Irrigated plants had lower chlorophyll & carotenoid levels at harvest.	Regular irrigation enhances biomass but influences leaf chemistry (Śniegowska et al., 2024)
Soil Water Tension (SWT) criteria in US cultivars	Drip irrigation thresholds (10, 20, 40, 60, 80 kPa)	Wetter criteria (lower tension) generally led to increased dry leaf yield and steviol glycoside traits; but results were not always statistically clear—although linear trends were significant.	Greater soil moisture tends to enhance yield and quality glycosides (Parris et al., 2017).
Supplementary irrigation during flowering and seeding	Addition of two supplementary irrigations in greenhouse/farm settings	Supplementary irrigation at critical stages (flowering and seeding) significantly improved sugar (presumably stevioside) yield.	Targeted irrigation at critical stages enhances yield efficiency (Ghamarnia et al., 2022).

Contemporary research has revealed that *S. rebaudiana* exhibits complex physiological responses to water stress that directly impact both biomass accumulation and steviol glycoside production (Shahverdi et al., 2019). Studies from Morocco have shown that water stress significantly affects growth, yield, quality, and physiological responses of different stevia varieties. The plant's response to water deficit involves alterations in leaf morphology, stomatal behaviour, and metabolic processes that ultimately influence the concentration of sweet compounds in the leaves (Zeng et al., 2013). Interestingly, despite receiving fewer irrigations, T_9 outperformed T_6 (IW50mm/CPE50mm = 1.0) and T3 (IW40mm/CPE40mm = 1.0), likely due to the higher irrigation water depth in T_9, which maintained soil moisture for longer periods and effectively compensated for evapotranspiration losses. The increase in branches, leaf count, and leaf yield in T_9 was nearly double that of the rainfed control, underscoring the significant role of irrigation. Although T_{10} had the highest irrigation frequency under 60 mm depth, T_9 produced better growth and yield, possibly because excessive irrigation in T_{10} may have led to nutrient leaching and waterlogging, which could negatively impact root respiration and nutrient uptake, ultimately reducing photosynthesis.

CONCLUSION

The study demonstrates that irrigation levels have a significant impact on the vegetative growth and leaf yield of the crop. The irrigation with a depth of 60 mm at an IW:CPE ratio of 1.0 proved to be the most effective in enhancing plant growth characteristics such as height, branching, number of leaves, and overall leaf biomass. This treatment consistently outperformed others in terms of fresh and dry leaf yield per plant and estimated yield per hectare, indicating its superiority under the given agro-climatic conditions. In contrast, rainfed conditions led to the lowest performance across all growth and yield parameters, emphasizing the importance of timely and adequate irrigation. The irrigation at 60 mm depth with an IW:CPE ratio of 1.0 is optimal for maximizing leaf yield**.** Additionally, providing three irrigations per month during the critical summer period (May-June) at intervals of 8-10 days is recommended for achieving better productivity under similar soil and climatic conditions.

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Early Growth Performance of *Melia* species in Different Agro-Climatic Zones of Shivalik Region of Lower Himalayas

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***Abstract*:** Short rotation fast growing tree species have gained attention among farming community and wood-based industries. Among them, *Melia* species (family- Meliaceae) are considered promising due to their fast growth, straight stem, clear bole, small leaves, and resistance to pests and insect attacks, making them highly suitable for farmers' plantations. In this experiment, saplings of three *Melia* species, *viz: Melia azedarach*, *M. composita* and *M. dubia* were planted in two agro-climatic zones during 2020. The first site was the experimental farm of Silviculture and Agroforestry, SKUAST-Jammu, located in the sub-tropical zone, while the second was a farmer's field at Dingi Simbli, Billawar, in Kathua district, representing the intermediate zone. After two years of growth (2021–22), *Melia composita* recorded the maximum plant height (3.03 m and 5.64 m), collar diameter (45.6 mm and 90.9 mm), leaf area index (1.20 and 1.78), and crown diameter (0.87 m and 1.85 m) under the sub-tropical zone, which were statistically higher than observed in the intermediate zone. The overall performance of the three *Melia* species with respect to growth parameters in the sub-tropical zone followed the order: *M. composita*>*M. dubia*> *M. azedarach* during both years of the study.

Keywords: *Melia azedarach, Melia composita, Melia dubia*, Crown diameter, Collar diameter, Leaf area index

Melia azedarach, belonging to Meliaceae family and known by its common name 'chinaberry' or 'Perisan lilac' is a moderate deciduous tree with a short bole and spreading crown, bi-pinnate and tri-pinnate leaves and a dark grey bark with shallow longitudinal furrows (Tiwari and Prajapati 2024). *M. azedarach* thrives in variety of soils, and the species is cold hardy and drought resistant. *M. azedarach* is now naturalized in most sub-tropical and tropical regions of the world (World Agroforestry Centre 2006) because of its fast-growing nature, stem straightness, fewer number of branches, less shade effect and being less susceptible to pest and insect attack (Srivastva et al., 2025, Parmar et al., 2019a,b). The multi-various uses like pulpwood, timber, fuel wood and ply wood can fit as a suitable species for farm forestry plantation programme and agroforestry.

For quick augmentation of domestic wood production and to fetch early income to the farmers, *M. dubia* and *M. composita* has been identified as one of the potential native species for plantation and agroforestry to supply industrial wood (Thakur et al., 2019, 2023, Jinger et al., 2024). Globally *M. dubia* is found in Sri Lanka, Malaysia, Indonesia, the Philippines and Australia. Fast growth, straight and round bole, self-pruning, good coppicing abilities, light demanding and adaptability to wide range of climatic and soil types have made a *Melia dubia* one of the most preferred tree species among planters (Sharma et al., 2017 and 2019; Prajapati et al., 2020, Thakur et al., 2021, Jinger et al., 2025). Despite its increasing importance, the interaction between fast-growing *Melia* species and environmental conditions remains poorly understood, particularly in the lower Himalayas, which represent a transitional region with distinct agro-climatic variability. Understanding these growth–environment interactions is critical for optimizing plantation success and enhancing agroforestry practices. It is hypothesized that the growth performance of different *Melia* species varies significantly across agro-climatic zones of the Shivalik region, with superior growth expected under the sub-tropical zone compared to the intermediate zone. In line with this hypothesis, the present study aimed to evaluate the comparative growth performance of *M. azedarach*, *M. composita*, and *M. dubia* under two contrasting agro-climatic conditions. The specific focus was to assess variations in plant height, collar diameter, crown diameter, and leaf area index, and to identify the most promising species that can be recommended for plantation and agroforestry interventions in the lower Himalayas.

MATERIAL AND METHODS

Study site characteristics: The study was conducted at Division of Silviculture and Agroforestry, Sher- e- Kashmir University of Agricultural Science and Technology Jammu (Zone 1) and at farmer field of Billawar, District Kathua (Zone 2). Jammu is located at an altitude of 332 m above MSL with 32º40ˈ N latitude and 74 º58ˈ E longitude which falls under sub-tropical agro-climatic zone. This agro-climatic zone (sub-tropical zone of Jammu) experiences hot dry summer,

humid rainy season and cold dry winter months. The summer usually starts from April and last up to June. The maximum temperature rises up to 45ºC during May to June and minimum falls to 1ºC during winter months (December-January). The average annual rainfall ranges from 1000-1200 mm out of which 75-80 per cent is received during July to September and rest 20-25 per cent is received during winter months of December to February (Fig. 1). Soil samples were collected and analysis for the chemical properties at the beginning of the experiment. The soil texture in sub-tropical zone was sandy loam having pH of 7.78 and organic carbon of (0.56 %). The available N, P and K of the experimental site of sub-tropical zone were low to medium in range. The intermediate zone of Billawar region, district Kathua is a transition between sub-tropical-temperate zone of the mid and high altitude areas of lower Himalayas (Shivalik range). The Billawar region have an altitude of 844 m above mean sea level with 32º36˙598 N latitude and 75º30˙950 E longitudes. The zone is characterized by monsoon, concentration of precipitation, relatively wetter, cold winters and higher mean annual rainfall than sub-tropical zone. The soil texture of intermediate zone of Billawar region was observed to be clay loam and having a pH of 5.80 and organic carbon (0.36%). Soil available N, P and K of experimental site of intermediate zone was found to be low.

Experimental design: Uniform sized (approx 45 cm) sapling of *M. azedarach*, *M. composita* and *M. dubia* were transplanted (as main plot) for plantation in two agro-climatic zones (as sub-plot) *i.e.* sub-tropical and intermediate zone with a spacing of 3 m × 3 m. The experiment was laid out in factorial randomized block design and replicated three times at both the agro-climatic zones. The transplantation of saplings was done in the month of September, 2020 and the data was collected for consecutively two years for different growth parameters.

Field Preparation: The field was ploughed with one deep disc harrower by three round of rotavator to remove the unwanted debris of weed. Pits of 45 cm × 45 cm × 45 cm were dug up. Each pit was filled with 3-4 kg of FYM and supplement irrigation were given after the planting

Growth Parameters: Plant height was measured in meters from the ground level to the tip of the main shoot with the help of calibrated measuring rod. Collar diameter was measured using digital caliper from 2-5 cm above the ground level.

Lear area index and crown diameter: Ten leaves from selected trees were taken from each replication and their actual area was determined with the help of graphic method. Maximum length was measured from juncture to tip and maximum width was taken from center of the leaves. After calculating the leaf area, leaf area index was measured by using formula LAI= Leaf area (cm²)/Ground area (cm²). Cross sectional crown diameter was measured using meter tape and two poles holding straight touching to the outermost tip of the crown leaf in opposite side of the tree. The distance between these two poles were recorded. Similarly, it was repeated at perpendicular to measure the other direction and average crown diameter was computed out of the saplings.

Statistical analysis: Statistical analysis was conducted with the software package of OPSTAT, (Sheoran et al., 1998).

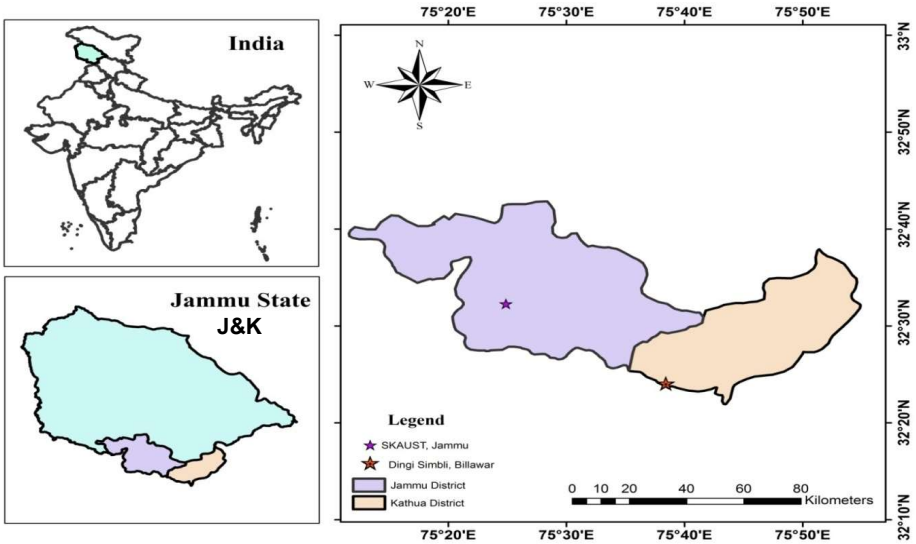

Fig. 1. Location map of two agro-climatic zone Jammu District (Sub-tropical zone) and Billawar (intermediate zone)

RESULTS AND DISCUSSION

Plant height: The agro-climatic zones had significant effect on plant height during both the year of study irrespective of species (Table 1). The average plant height was significantly higher (2.53 and 2.05 fold) in sub-tropical zone as compare to intermediate zone during both the years of study. The order of plant height under sub-tropical zone among *Melia* species was *M. composita* > *M. dubia* > *M. azedarach* during both the years. In intermediate zone, the performance of species with respect to plant height was different. In first year, *M. composita* attained significantly higher (1.20 m) in intermediate zone while in the second year *M. dubia* recorded the maximum height (3.12 m) as compared to *M. composita* and *M. azedarach*. Among species, the performance of *M. composita* observed to be significantly higher as compared to *M. azedarach* and *M. dubia* regardless of agro-climatic zones. The average maximum plant height of 2.31 m and 4.58 m was during August 2021 and 2022, respectively in *M. composita*. However, during second year, plant height of *M. composita* was statistically at par with *M. dubia* in intermediate zone. The interaction of agro-climatic zone and species was significant. The interaction effect of (sub-tropical zone × *M. composita*) resulted in maximum plant height of 3.43 m and 6.39 m which was statistically superior from the remaining interactions during both the study years. Tree height may have served as an important trait in determine the growth of the species under given site qualities and climate. The significantly higher plant height in sub-tropical zone during both the year as compared to that in intermediate zone indicates better environmental and site quality conditions for plant growth. This could be ascribed to available soil moisture during dry season which favour the nutrient absorption in plants which resulted in higher plant height in *M. dubia* (Niveditha and Shirhatti 2017). Trees height growth are often largely controlled by climate and specifically by water availability, while factors such as soil fertility are secondary (Wagner et al., 2014, Guan et al., 2015).

Higher precipitation and shorter and less intense dry period are associated with significantly higher plant growth rates (Toledo et al., 2011, Meason and Meason 2014). The soil texture of sub-tropical zone was found to be sandy loam. Sandy soils with high drainage, accompanied by well-developed root system prevent saturation of soil during the growing season. This emphasizes the importance of ground water for plants which can reach at least the capillary fringe during dry periods (Tuzinsky 2006). The response of intermediate zone with respect to plant height reflected a significant variation among climatic and site qualities characteristics. The intermediate zone had mid-altitudinal zone which had a profound effect on temperature. Growth may decline with altitude because of reduce air soil

Table 1. Plant height (m) and collar diameter (mm) of *Melia* spp. under different agro-climatic zones after 12 months (August 2021) and 24 months (August 2022)

Species/Location	August 2021				August 2022			
	M. azedarach	*M. composita*	*M. dubia*	Mean	*M. azedarach*	*M. composita*	*M. dubia*	Mean
Plant height (m)								
Sub-tropical zone	2.70	3.43	2.94	3.03	5.04	6.39	5.50	5.64
Intermediate zone	1.12	1.20	1.16	1.16	2.36	2.78	3.12	2.75
Mean	1.91	2.31	2.05		3.70	4.58	4.31	
CD (p=0.05)								
AZ	0.20				0.35			
Species	0.24				0.42			
AZ x Species	0.34				0.60			
Collar diameter (mm)								
Sub-tropical zone	40.9	51.4	44.5	45.6	83.8	99.3	89.5	90.9
Intermediate zone	17.5	20.7	24.7	21.0	31.5	40.0	45.8	39.1
Mean	29.2	36.1	34.6		57.7	69.6	67.6	
CD (p=0.05)								
AZ	3.05				5.60			
Species	3.74				6.86			
AZ x Species	5.29		`		NS			

AZ=Agro-climatic zone

temperature, shorter growing season and reduced supply of nutrients (Coomes and Allen 2007). Decrease in plant height with increase in altitude was also reported by Ndema and Missanjo (2015) in *Pinus oocarpa*. Colder regions may lead to reduced photosynthetic activity and chilling injury of tropical trees (Feng and Cao 2005). *Melia*, being a species of tropical to sub-tropical zone strive hard to acclimatize in adverse climatic and soil conditions during first year of plantation.

Collar diameter: There was significant variation in root collar diameter among the different *Melia* species grown in sub-tropical zone The maximum collar diameter was of *M. composita* (51.4 mm) followed by *M. dubia* and *M. azedarach* after 12 months of study (Table 1). Collar diameter growth was *M. composita>M. dubia>M. azedarach*. Response function of the *Melia* species showed significant relation with collar diameter under sub-tropical zone might be due to appropriate availability of moisture, light and nutrients and also morphology of the species (Song et al., 2020). Furthermore, favorable climatic conditions such as increase in temperature after bud burst in February promote cell production and precipitation during the monsoon period which enhanced the growth in *M. composita*. Climatic factors mainly light intensity and rainfall may have a strong effect on collar diameter (Toledo 2011 and Janson 2013). Temperature rise in general, may increase stem diameter as well as plant height (Way and Oren 2010). Soil texture of the site which was sandy loam might have improved the soil moisture content by permitting water to infiltrate into the horizons which directly increased the water level in the soil (Nanda et al., 2021). Role of soil nutrients and moisture in improving collar diameter in *M. composita* under sub-tropical conditions are well reported by Sharma et al., (2017 and 2019).

In intermediate zone, significant effect on collar diameter among the different *Melia* species was observed. However, as compared to sub-tropical zone it was comparatively on lower during both the years of study. The order of increase in collar diameter was as *M. dubia>M. composita>M. azedarach*. Growth of *Melia* species reduced significantly with different soil moisture conditions prevailed under different agro-climatic zones. This indicated that growth is specifically driven by moisture availability in case of fast growing species (Zobel et al., 1987). Despite of soil moisture conditions, altitudinal changes might be another reason for lower growth in intermediate zone. The changes in altitude attributed to difference in supply of soil nutrients which may contribute to slow growth at higher altitude (Ndema and Missanjo 2015). The soil texture in intermediate zone was clay loam which due to high run off resulted in less recharge of the soil profile, having higher micro-porosity, bind water molecule more tightly and hence lesser availability to plants. Flooded soil due to heavy precipitation during monsoon period (ending June onward) reduced growth potential rates as well, due to their anaerobic conditions and to the phytotoxins which are by product of the reductive processes (Pezeshki and De 2012). Despite, the climatic variability and poor soil fertility, the performance of *M. dubia* was observed better in intermediate zone during course of study. This is because of the trait that enables *M. dubia* to perform well under moisture limited conditions (Tolia et al., 2019, Parthibhan et al., 2009, Warrier 2011).

Leaf area index : The overall better performance was observed in sub-tropical zone among the different *Melia* species during two-year (Table 2). Increasing order in leaf area index was *M. composita>M. dubia>M. azedarach* after 24 months of study. Leaves exhibit a remarkable ability to acclimatize in variable environment conditions by acquiring plasticity in morphological, anatomical and physiological traits (Valladares et al., 2007). The leaf attributes in the present study were significantly influenced by season, site and their interactions. Craven et al. (2011) stated that species vary in their photosynthetic rate seasonally and demonstrated adaptive capacity to regulate leaf photosynthesis between wet and dry season. This is in agreement with findings where *Melia* species showed greater variation in leaf area. Abundant light availability could enhance the growth rate of leaf area and also improve the site qualities by shedding leaves during winter period by adding more nutrients to the soil (Nanda et al., 2021). *M. composita* being a highly light demanding species suppressed under shade (Laxmi et al., 2021) and tendency to gain more height is depicted under plant height parameter. The significant variation was observed in leaf area index in intermediate zone among different *Melia* species . The leaf area index decelerates significantly in intermediate zone as compared to sub-tropical zone during both the years of study. The order of increase in leaf area index among the different *Melia* species was *M. dubia>M. composita>M. azedarach* after 12 and 24 months of plantation.

The varied results with respect to agro-climatic zone can easily be distinguished. The possible reason for minimum leaf area index as compared to sub-tropical may be due to altitudinal variation (Coomes and Allen 2007), temperature effect (Castro et al., 2017), light variation (Park et al., 2022) and soil properties (Meijer et al., 2011). Among these species, *M. dubia* was better in terms of leaf area index in intermediate zone due to the adaptabilities and tolerance under intermittent moisture variant conditions. These results under limited moisture stress condition in *Melia* species are coinciding with Loushambam (2017), Loushambam (2021) and Dias et al. (2014).

Table 2. Leaf area index and crown diameter (m) of *Melia spp* under different agro-climatic zone after 12 months (August 2021) and 24 months (August 2022)

Species/Location	August 2021				August 2022			
	M. azedarach	*M. composita*	*M. dubia*	Mean	*M. azedarach*	*M. composita*	*M. dubia*	Mean
Plant height (m)								
Sub-tropical zone	1.10	1.34	1.16	1.20	1.65	1.98	1.72	1.78
Intermediate zone	0.83	0.91	0.94	0.89	1.25	1.38	1.45	1.36
Mean	0.96	1.13	1.05		1.45	1.68	1.59	
CD (p=0.05)								
AZ	0.06				0.06			
Species	0.07				0.08			
AZ x Species	0.10				0.11			
Collar diameter (mm)								
Sub-tropical zone	0.84	1.00	0.77	0.87	1.71	2.02	1.81	1.85
Intermediate zone	0.58	0.61	0.64	0.60	1.14	1.30	1.47	1.31
Mean	0.70	0.80	0.71		1.43	1.66	1.64	
CD (p=0.05)								
AZ	0.04				0.09			
Species	0.04				0.11			
AZ x Species	0.06		`		0.16			

AZ=Agro-climatic zone

Crown diameter: The crown diameter presented wide variation in maximum crown diameter with respect to sub-tropical zone was observed after 12 and 24 months of study period (Table 2). The maximum of 2.02 m was in *M. composita* followed by *M. dubia* and *M. azedarach* during second year. The better performance of *M. composita* in sub-tropical zone attributed to well distributed light which is a determining factor in seasonal tropical forest, as spatial and temporal dynamics of light and moisture availability inflict major constraints on leaf phenology and canopy occupancy of the plants between wet and dry season (Jinger et al., 2024). For growth to take place, the formation of substrate in the form of sugar is the basic requirement. Therefore, carbon assimilation by the leaves through the efficient interception of light is the driving force of the growth (Niinemetes 2007). The orientation of branches and leaves usually shape the geometry of the crown, and is related to its adaptive strategy for light interception. Increase of day length after the bud burst in February and higher precipitation during monsoon period resulted in increased growth rate of crown diameter. Higher temperature is also associated with N uptake and the production of leaves, increasing the total leaf area per plant (Castro et al., 2017).

However, the crown diameter among the different *Melia* species under intermediate zone reflected a reducing trend as compared to sub-tropical zone. The order of increase in crown diameter was *M. dubia*>*M. composita*>*M. azedarach* after 24 month of study. The intermediate zone having higher elevation, temperature and light variation resulted in stunted growth in all the three *Melia* species. The available soil moisture required for growth in fast growing species was comparatively low in intermediate zone. Plant genotype responds to variability of environmental condition (light, soil moisture and soil nutrient availability) by producing differences in phenotype.

CONCLUSIONS

The present study demonstrated that agro-climatic zones (sub-tropical and intermediate) exerted a significant influence on the growth performance of *Melia* species. These species exhibited better growth under the sub-tropical zone, with *M. composita* emerging as the most promising species due to its superior growth characteristics. The future prospects of *M. dubia* in the *Shivalik* region of lower Himalayas appear highly promising owing to its fast growth, adaptability to diverse conditions, and suitability for multiple end-uses such as timber, pulpwood, veneer and fuelwood. However, successful large-scale adoption will depend on careful site selection to avoid frost-prone areas, provision of adequate soil moisture through conservation or irrigation, and the availability of quality planting material. Integration into agroforestry systems, combined with market linkages to plywood, pulp and emerging carbon markets, can offer farmers attractive income opportunities while contributing to

ecological restoration. Thus, with scientific management, farmer awareness and institutional support, *M. dubia* can emerge as a viable short-rotation forestry species for livelihood enhancement and environmental sustainability in this region. These findings suggest that while *M. composita* is highly recommended for large-scale plantations in sub-tropical regions, *M. dubia* holds potential for introduction and expansion in the intermediate zone of the Jammu division, making it a valuable species for agroforestry interventions.

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Root Plasticity as Influenced by Planting Material and Planting Density in Teak Using Logarithmic Spiral Trenching in Kerala, India

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***Abstract*:** Teak (*Tectona grandis* L.f.), a premier tropical timber species, is widely adopted in agroforestry systems, though its shallow, spreading root system raises concerns over competition with intercrops. Traditionally established through stump planting teak typically develops horizontally oriented, fibrous roots with limited vertical development. Alternatively, root trainer seedlings are hypothesized to promote deeper, more compact root systems, potentially mitigating belowground competition. This study investigates the root distribution of five-year-old teak plantations established through stump and root trainer methods at 3 × 3 m spacing in Karakkad, Kalady Range, Malayattoor Forest Division, Kerala, using the logarithmic spiral trenching method. Additionally, it evaluates the effect of tree spacing (2 × 2 m vs. 3 × 3 m) on the root distribution of root trainer-raised teak. Root intensity (roots m^{-2}) was quantified at various lateral distances from the teak plants and soil depths up to 50 cm. Root trainer-grown trees consistently showed higher root intensities (3205 roots m^{-2}) than stump-grown trees (2750 roots m^{-2}) at 0.35 m lateral distance, while the corresponding root intensities were 1355 and 900 roots m^{-2} at 2.35 m lateral distance from the tree base, for root trainer and stump-grown trees, respectively. Root trainer seedlings also exhibited higher root presence at deeper soil layers. Tree spacing significantly influenced the rooting behavior with the closely spaced (2 x 2 m) stand showing root intensity confining to the proximal distance to the tree while the widely spaced (3 x 3 m) stand showed better root spread with respect to vertical and lateral distribution. The findings demonstrate the superior vertical rooting of root trainer-raised teak, reducing crop competition and improving resource uptake making it well-suited for agroforestry. The spacing-induced root plasticity highlights the importance of tree density in shaping root distribution patterns and optimizing belowground resource utilization in a plantation as well as agroforestry systems.

Keywords: Agroforestry, Root distribution, Root trainer seedlings, Spiral trenching, Stump planting

Teak (*Tectona grandis* L. f.) is one of the highly valued tropical hardwood species globally, known for its superior timber quality, durability, and high market demand. India accounts for approximately 35% of the world's planted teak area, with an estimated 1.7 million hectares under cultivation (IUFRO–TEAKNET 2022). Kerala holds a significant place in teak history, being home to the world's earliest managed teak plantations established in the 1840s at Nilambur (Chandrasekharan 1973). The major portion of teak timber supply originates from homegardens, which contribute nearly 80 per cent of the state's total timber output (Krishnankutty and Chundamannil 2012). However, despite its ecological and economic importance, the root system characteristics of teak particularly its shallow, spreading roots pose challenges in agroforestry contexts. When propagated through conventional root-shoot cuttings (stumps), teak tends to produce numerous fibrous roots concentrated in surface soil, leading to heavy competition for water and nutrients with adjacent crops (Khedkar and Subramanian 1997, Rao et al., 2001). This shallow rooting habit may also restrict anchorage and limit deeper resource uptake. In contrast, container-raised seedlings using root trainers are gaining prominence for producing more compact and deeper root systems that promote better vertical soil exploration and reduce belowground competition. Field studies in humid Kerala have shown that teak raised in root trainers outperforms stump-grown plants in early growth, including height, diameter, and survival rate, likely due to improved root system (George et al., 2019). Rooting depth, lateral spread, and root diameter classes have been recognized as critical determinants of root spread and resource acquisition patterns for optimizing tree–crop interactions, water and nutrient acquisition, and long-term plantation stability (Huang et al., 2024).

Although differences in nursery-level performance between stump-planted and root trainer-raised teak are well documented, limited research has examined their root distribution pattern under field conditions. Understanding how planting material influences root distribution is crucial for enhancing the design of agroforestry systems and improving resource-use efficiency. Similarly, the influence of spacing on root distribution remains poorly understood, particularly in the context of root trainer-grown teak plantations. In this regard, the present study investigates the comparative root distribution patterns of five-year-old teak plantations established using stump and root trainer planting materials under uniform spacing (3 × 3 m), employing the logarithmic spiral trenching method in the Malayattoor Forest Division,

Kerala. Additionally, the study evaluates the effect of spacing on the root distribution of root trainer-grown teak. This study aims to assess both lateral and vertical rooting behavior across soil depths and distances from the tree base, providing insights into the suitability of each planting material and spacing regime for effective resource utilization.

MATERIAL AND METHODS

The study was carried out in five-year-old teak (*Tectona grandis* L. f.) plantations located at Karakkad Station (10°12′10.88″ N, 76°28′36.31″ E), within the Kalady Range of the Malayattoor Forest Division in Kerala, India. The area is characterized by a tropical monsoon climate, receiving an average annual rainfall of approximately 3000 mm, with mean annual maximum and minimum temperatures of 31.3 and 24.2 °C, respectively. The plantations were established using two types of planting materials: conventional stump plants (root-shoot cuttings) and root trainer-raised container seedlings with a 3 × 3 m spacing. For the experiment, three trees were randomly selected from each treatment combination (planting material × spacing × age class), ensuring uniformity in tree size and microsite conditions to reduce variability caused by site heterogeneity.

Spiral trenching method: To study root distribution, the logarithmic spiral trenching method was employed, with modifications suited to field conditions in tropical humid soils. This technique enables quantitative assessment of both lateral and vertical root spread with minimal disturbance to tree stability. The trench trajectory was laid out using a mathematical model based on the following equations:

$$x = 1.5\,(d)$$

$$y = [\ln (r/d)]/\pi$$

$$z = x\, e^{y\theta}$$

Where:

d = diameter at breast height (in meters)

r = average crown radius measured at four cardinal directions (in meters)

x = initial radial distance from the base of the tree (m)

θ = angle of measurement along the spiral arc (°), taken at 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, and 180°

z = distance to the spiral point from the tree base at each angle (m)

Plastic ropes were used to mark the spiral layout, and trenching was done to a depth of 60 cm and width of 60 cm. Proper care was taken to prevent soil collapse and maintain trench wall integrity (Fig. 1).

Root sampling and classification: Root sampling was conducted along both the inner and outer walls of the trench using a 50 × 50 cm quadrat placed at four fixed lateral distances from the tree base: 0.35 m, 0.75 m, 1.55 m, and 2.35 m. Each quadrat was vertically divided into five successive soil depth intervals: 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm. Within each depth layer, all severed, live roots intersecting the quadrat surface were recorded. The roots were then classified into four diameter-based categories such as fine roots (<2 mm), small roots (2–5 mm), medium roots (>5 mm), and coarse roots (>1.0 cm). This systematic approach enabled the spatial and vertical distribution of root size classes to be assessed in relation to the tree base. The recorded root counts were converted into rooting intensity, expressed as the number of roots per square meter (roots/m²), following the protocol outlined by (Böhm 1979) . Statistical analysis was performed to evaluate differences in rooting intensity across various factors, including planting material types (stump vs. root trainer), soil depth classes, and lateral distances from the tree base. The independent t-test was employed to determine statistically significant differences between mean values.

RESULTS AND DISCUSSION

Influence of planting material on the root distribution: Root distribution was significantly influenced by the types of planting material used. In five-year-old plantations, root trainer-raised seedlings consistently exhibited higher total root intensity across all lateral distances compared to stump-grown trees (Table 1). At 0.35 m from the tree base, root trainer trees recorded 3205 roots m^{-2}, while stumps showed 2750 roots m^{-2}. This trend continued up to 2.35 m, with root trainer trees maintaining greater root presence

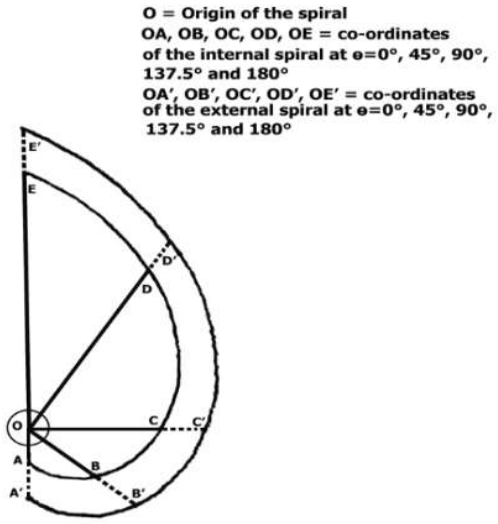

Fig. 1. Schematic diagram showing co-ordinates of logarithmic spiral trench

(1355 roots m^{-2}) than stumps (900 roots m^{-2}). Although root intensity declined with increasing lateral distance in both planting types, the decline was more gradual and sustained in root trainer trees, indicating a more expansive rooting pattern.

The changes in root intensity and distribution pattern for stump and root trainer grown teak stands showed interesting trends. In general, both the stands showed decrease in root intensity with increasing lateral distance from the tree base and increasing soil depth. However, the changing trends

Table 1. Total root intensity as affected by planting techniques and distance from the tree in five-year-old teak plantations

Planting techniques	Total root intensity (number per m^2) at different distance from the base of the tree (m)			
	0.35	0.75	1.55	2.35
Stump	2750	1510	1065	900
Root trainer	3205	1970	1965	1355
P value	0.064^{ns}	0.05*	0.006*	0.088^{ns}

Table 2. Variation in root intensity across the lateral distance and soil depth influenced by stump and root trainer grown at 3x3 m spacing of five-year-old teak plantation

Soil depth (cm)	Stump	Root trainer	Stump	Root trainer	Stump	Root trainer	Stump	Root trainer
	0.35		0.75		1.55		2.35	
Root intensity (number per m^2) at different distance from the base of the tree (m)								
<2 mm								
0-10	855	700	510	455	415	475	390	400
10-20	610	555	435	410	365	380	345	340
20-30	410	485	315	275	185	365	55	280
30-40	380	470	95	360	30	295	-	130
40-50	155	195	-	170	-	160	-	110
Total	2410	2405	1355	1670	995	1675	790	1260
2 mm-5 mm								
0-10	80	110	50	55	30	25	55	5
10-20	75	105	30	30	10	25	10	15
20-30	30	115	15	25	10	35	20	10
30-40	65	130	10	30	5	35	-	10
40-50	5	55	-	35	-	35	-	5
Total	255	515	105	175	55	155	85	45
>5 mm								
0-10	30	50	20	25	5	15	15	15
10-20	15	65	15	30	5	15	-	5
20-30	15	95	10	30	5	35	10	10
30-40	25	50	5	25	-	25	-	10
40-50	0	25	-	15	-	45	-	10
Total	85	285	50	125	15	135	25	30
>1 cm								
0-10	20	-	-	5	-	-	-	
10-20	15	25	-	-	5	-	-	5
20-30	5	35	5	20	-	-	-	
30-40	-	10	-	5	-	5	-	
40-50	-	-	-	-	-	15	-	
Total	40	70	5	30	5	20	-	5

were different. For instance, the stump based teak stand showed better intensity of small roots in the top soil (0-20 cm) which was 61% of the total root intensity (2410 number per m^2) at proximal end (0.35m) at 50 cm soil depth for 5 year old stand (Table 2). The corresponding root intensity for root trainer based stands was only 52% of the total root intensity at the proximal lateral distance and 50 cm soil depth (2405 number per m^2). However, the trends showed gradual reversal at deeper soil depths with an increase in root intensity of root trainer based teak stands. For example the corresponding root intensities for stump and root trainer stands at deeper depth (30-50 cm) were 22 and 28%, respectively of the total root count at the same proximal lateral distance (0.35 m). These trends clearly illustrate the differences in the root growth habit of the two stands. The increase in root intensity at deeper soil for root trainer trees clearly indicates its better vertical spread contributed by multiple taproots. However, stump grown trees lack a well-defined tap root system leading to lower vertical root. It is also noteworthy that in the absence of prominent tap root, the stump grown teak produced larger number of small roots at shallow depth at proximal end. Further, this increase could not be maintained neither with increase in lateral distance nor with increase in soil depth.

Analysis of root size class and soil depth revealed clear differences between the two planting materials (Table 2). In both stump- and root trainer-grown teak, fine roots (<2 mm) dominated the root system, particularly in surface layers. However, root trainer trees consistently exhibited greater root intensity across all diameter classes, especially at deeper soil depths and greater lateral distances from the stem base. At shallow depths (0–10 cm) and close proximity (0.35 m), stump-grown trees recorded slightly more fine roots than root trainer trees (855 vs. 700 roots m^{-2}), indicating a tendency for surface-level concentration. Yet, as depth and lateral distance increased, root counts in stumps declined sharply, whereas root trainer trees maintained substantial root presence even at 40–50 cm depth and 2.35 m lateral distance.

For medium roots (2–5 mm), root trainer trees had significantly higher counts at depth—for instance, at 50 cm and 0.35 m distance, they recorded 515 roots m^{-2} versus 255 roots m^{-2} in stump-planted trees. Large roots (>5 mm and >1 cm) were nearly absent beyond 1.55 m in stumps but remained present in root trainer trees, reflecting superior soil penetration and anchorage capacity. These contrasts in root composition between planting types are further visualized in Fig. 3c, which shows that root trainer seedlings developed a more balanced proportion of fine, medium, and coarse roots compared to the fine root dominance observed in stumps. These differences in root spread are visually illustrated in Fig. 2a and 2b, where root trainer seedlings show significantly higher root counts at each radial interval compared to stump-raised plants, confirming the numerical values observed in Tables 1 and 2.

The relatively higher count of larger roots (> 1 cm) for root trainer grown trees indicated the prominent nature of multiple tap rooting habit of root trainer grown plants. Kalsi et al. (2025) reported that variation in the container type also showed significant variation in the root shoot ratio reported that tree spacing and thinning significantly affect root distribution, with thinning contributing to increased DBH and enhanced root reinforcement. Root trainer grown plantations showed more lateral root spread along with more DBH reported positive relation of rooting depth and total tree height. The current investigation also showed similar findings, with better rooting depth for root trainer origin trees along with higher height growth. The depth-wise decline in fine root intensity is also evident in Figure 3d, where root trainer trees maintained a relatively consistent number of fine roots across all five soil layers, while stump-grown trees showed a marked reduction beyond the top 20 cm. This supports the conclusion that root trainer planting stock promotes deeper and more functionally diverse root systems in teak.

These patterns are visually reinforced by Figure 2a and 2b, which show heat maps and schematic root profiles of stump- and root trainer-grown teak, respectively, both at 3 × 3 m spacing. While Fig. 2a reveals a sharp drop in root intensity with increasing depth and distance in stump-grown trees, Figure 2b illustrates the more balanced and deeper rooting behaviour of root trainer trees, with relatively uniform root intensity across both soil depth and lateral spread.

Influence of spacing on root intensity on root trainer plantations: Root intensity was also impacted by tree spacing. In five-year-old root trainer plantations (Table 3), closely spaced trees (2×2 m) had higher root density near the base (4010 roots m^{-2} at 0.35 m), while wider spacing (3×3 m) favoured greater lateral root spread, with significantly higher intensity at 2.35 m (1355 vs. 460 roots m^{-2}). This suggests that closer spacing increases belowground competition, concentrating roots near the tree, whereas wider spacing facilitates more balanced and extensive root system development. These spacing-induced patterns in root distribution are depicted in Fig. 3b, where the line graph illustrates the contrasting trajectories of root intensity across distances in 2×2 m and 3×3 m spacing regimes. The graph confirms that while narrow spacing favours early resource uptake near the stem, wider spacing promotes a more efficient root spread into deeper and farther zones.

This trend in the root distribution could be primarily attributed by the competitive nature of trees in the closer spaced stand. The trees concentrate more roots at proximal region to base of tree and reduce spread as compared to wider spaced stand. Similar result was observed in young *Acacia mangium* plantation while analyzing the effect of stand density and pruning on root activity by using ^{32}P soil injection method. The result revealed that high stand density of *Acacia mangium* induces greater root uptake capacity close to the stem and from the subsoil and low-density plantations showed higher root activity at far lateral distance from tree base. Spacing trials demonstrated that narrow spacing (2 × 2 m) resulted in a higher concentration of fine and small roots near the tree base, whereas wider spacing (3 × 3 m) facilitated the extension of roots into deeper and more lateral soil zones (Table 4). At 2.35 m lateral distance,

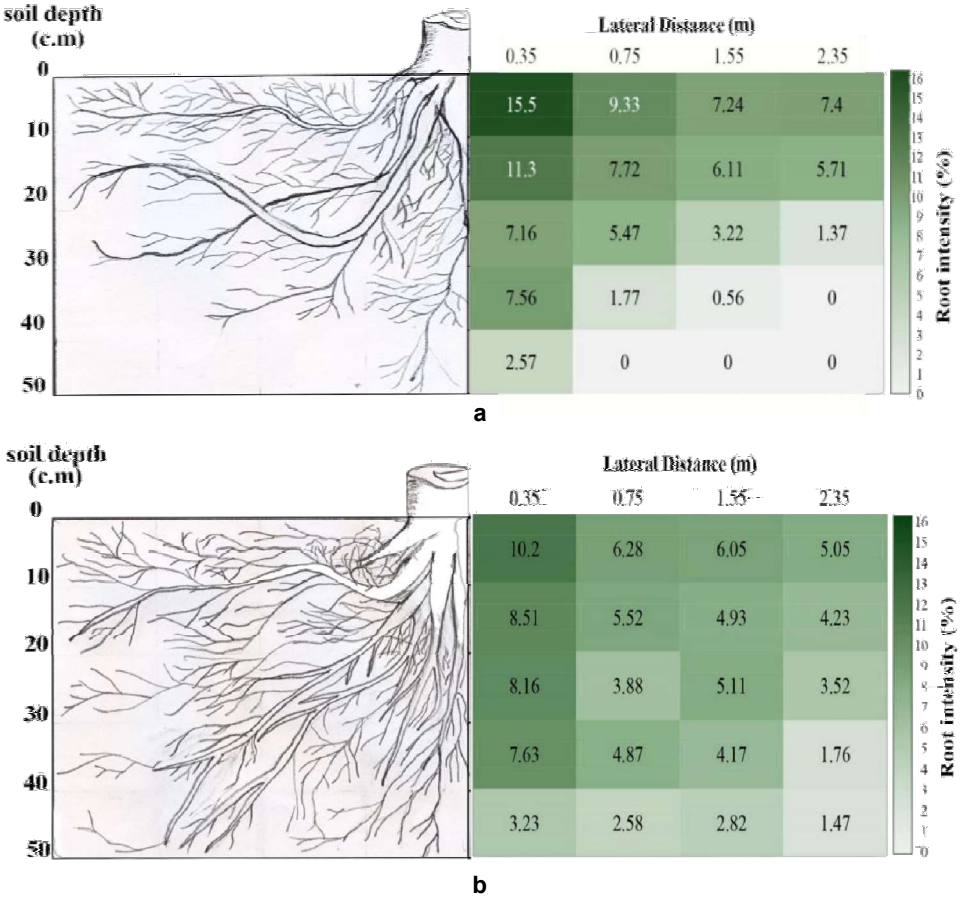

Fig. 2. a) Schematic representation and heat map showing root intensity (%) of stump-grown teak at 3×3 m spacing as influenced by soil depth and lateral distance from the tree base in a five-year-old plantation at Karakkad, Kalady Range, Malayattoor Forest Division, Kerala, and b) Schematic representation and heat map showing root intensity (%) of root trainer-grown teak at 3×3 m spacing in a five-year-old plantation at Karakkad, Kalady Range, Malayattoor Forest Division, Kerala

Table 3. Total root intensity as influenced by planting spacing and distance from the tree base in five-year-old teak plantations (up to 50 cm soil depth)

Planting techniques	Total root intensity (number per m^2) at different distance from the base of the tree (m)			
	0.35	0.75	1.55	2.35
3x3 m	3205	1970	1965	1355
2x2 m	4010	2155	1065	460
P value	0.001*	0.260^{ns}	0.026*	0.004*

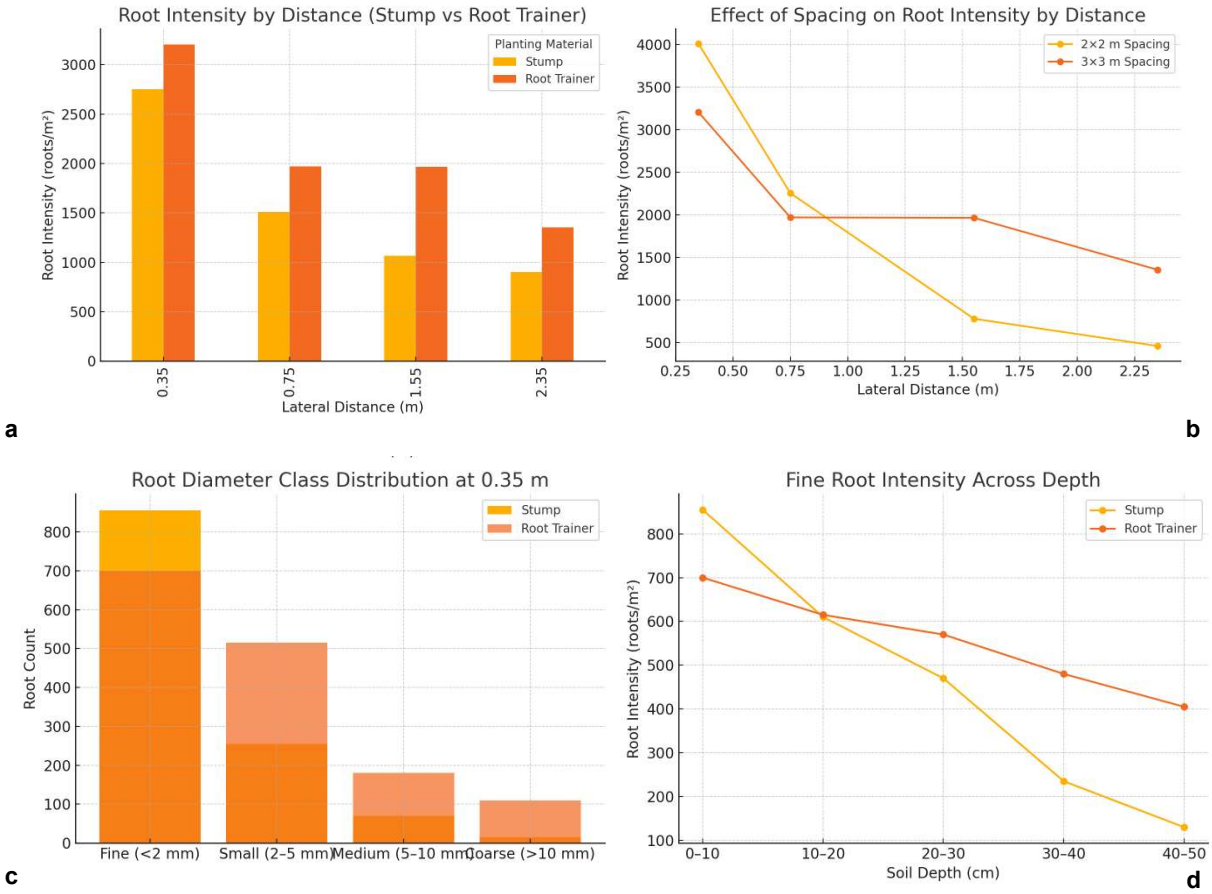

Fig. 3. Visual comparison of root intensity and distribution in five-year-old teak plantations under different planting materials and spacings- (a) Clustered bar chart comparing root intensity at increasing lateral distances for stump- and root trainer-raised trees, (b) Line graph showing the effect of spacing (2×2 m vs 3×3 m) on root intensity at various distances from the tree base, (c) Stacked bar chart of root diameter class distribution at 0.35 m distance for stump and root trainer stock, (d) Line graph of fine root intensity across soil depth layers (0–50 cm) between planting types

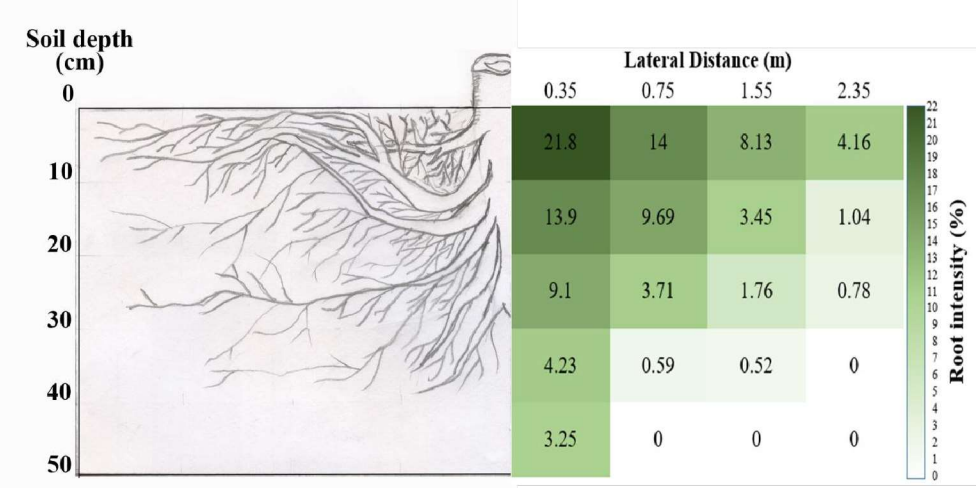

Fig. 4. Schematic representation and heat map showing root intensity (%) of root trainer grown teak tree at 2x2 m spacing at five-years of age plantation

root trainer-grown trees under 3 × 3 m spacing recorded higher root counts across all root diameter classes compared to those under 2 × 2 m spacing, indicating better soil resource exploration.

The 2 × 2 m spacing showed a greater number of fine roots at shallow depths and closer proximity to the stem (e.g., 1180 roots m^{-2} at 0.35 m), this trend reversed at deeper layers. At depths of 30–50 cm and distances beyond 1.55 m, root counts and the presence of medium and large diameter roots were significantly greater under wider spacing. This shift supports the advantage of wider spacing in promoting both vertical penetration and lateral spread of the root system. These trends are clearly illustrated in Figure 2b and Figure 4, which shows that while root trainer-raised trees at 2 × 2 m spacing developed dense rooting near the base compared to the 3 × 3 m spacing, their root expansion was comparatively limited beyond 1.55 m lateral distance—highlighting the spatial constraint imposed by close spacing (Figure 4).

Comparative reduction of root intensity for higher root size class also reported for spacing trial. The distribution of higher sized roots also followed the trend of smaller roots. The distribution of higher sized roots also restricted to the proximal lateral distance and shallow depths for closer spaced trees. This reduction in numbers of roots at deeper soil depths and farthest distance for narrow spaced trees again reiterates the differences in belowground competition on account of the spatial limitations.

Table 4. Root density of five-year-old teak plantations established by root trainer grown teak in variable spacing

Soil depth (cm)	3x3 m	2x2 m	3x3 m	2x2 m	3x3 m	2x2 m	3x3 m	2x2 m
	0.35		0.75		1.55		2.35	
Root intensity (number per m^2) at different distance from the base of the tree (m)								
<2 mm								
0-10	700	1180	455	840	475	540	400	245
10-20	555	820	410	655	380	230	340	70
20-30	485	560	275	235	365	135	280	55
30-40	470	260	360	40	295	40	130	-
40-50	195	205	170	-	160	-	110	-
Total	2405	3025	1670	1770	1675	945	1260	370
2 mm-5 mm								
0-10	110	315	55	155	25	65	5	45
10-20	105	155	30	55	25	25	15	10
20-30	115	95	25	40	35	-	10	5
30-40	130	35	30	5	35	-	10	-
40-50	55	35	35	-	35	-	5	-
Total	515	635	175	255	155	90	45	60
>5 mm								
0-10	50	135	25	85	15	20	15	30
10-20	65	85	30	35	15	10	5	-
20-30	95	45	30	10	35	-	10	-
30-40	50	25	25	-	25	-	10	-
40-50	25	10	15	-	45	-	10	-
Total	285	300	125	130	135	30	50	30
>1 cm								
0-10	-	-	5	20	-	-	-	-
10-20	25	30	-	5	-	-	5	-
20-30	35	10	20	-	-	-	-	-
30-40	10	10	5	-	5	-	-	-
40-50	-	-	-	-	15	-	-	-
Total	70	50	30	25	20	-	5	-

Interpretation and ecological relevance: The study clearly shows that root trainer-raised teak develops a deeper, more distributed root system, while stump-planted teak tends to form dense, shallow roots near the base. This has important implications for agroforestry, where reduced belowground competition with crops is essential. Greater rooting depth in root trainer trees suggests better anchorage, improved nutrient and water uptake, and higher system resilience, also emphasized the significance of root distribution for productivity and interspecies competition.

CONCLUSION

The present study demonstrated that the type of planting material significantly influences the root distribution pattern in teak. Root trainer-raised seedlings exhibited higher total root intensity compared to stump-planted trees, particularly at greater soil depths and farther lateral distances from the tree base. The logarithmic spiral trenching method effectively captured both lateral and vertical root spread, revealing that root trainer plants developed a more balanced and deeper rooting, while stump-raised plants showed a predominantly superficial and peripheral root distribution. Spacing also played a crucial role in shaping belowground development. Trees established at wider spacing (3 × 3 m) had more extensive lateral and vertical root systems than those planted at closer spacing (2 × 2 m), suggesting reduced intra-specific competition and greater soil exploration potential. Root intensity decreased with increasing soil depth in all cases, but the decline was more pronounced in stump-grown trees. These findings underline the advantages of using root trainer-raised planting stock for teak establishment, especially in agroforestry systems where belowground competition with crops must be minimized. Adoption of improved planting material and optimized spacing can contribute to better resource-use efficiency, improved tree stability, and enhanced long-term productivity. The study also highlights the need for further research on long-term root dynamics and their functional implications in diverse agroecological settings.

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AUTHOR'S CONTRIBUTION

George conceptualized the study, conducted the fieldwork, collected primary data, Kunhamu formulated the research objectives, and supervised the overall work, and also provided all scientific guidance for the work as major advisor, Bharath associated in fieldwork and prepared the scientific illustrations for the manuscript and contributed to writing the results and discussion sections, Ravuther performed data analysis and interpretation. Prepared tables, figures, and statistical outputs. Contributed to writing the results and discussion sections, Sarath supported literature review, contributed to methodology refinement, and assisted in manuscript drafting and editing, Niyas provided technical guidance, validated analytical results, and reviewed the manuscript for intellectual content, and Sooraj Kumar assisted in drafting the initial sections of the manuscript, managed references and formatting, and contributed to proofreading the final manuscript.

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Effect of Branch Circumference Girdling on Fruit Yield in Neem (*Azadirachta indica*)

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Abstract: This study was conducted at Bhubaneswar, Odisha to evaluate the effect of girdling on *Azadirachta indica* (Neem) fruit yield and quality. A five-year-old neem tree was subjected to 25, 50, 75 and 100%, girdlingof branch circumference, with ungirdled branches as a control. Observations included fruit morphology and the time taken to reach maturity fruit drop percentage. Among the treatments, 50% girdling yielded the best results, with maximum fruit diameter (11.66 mm), length(16.37 mm), weight (1.34g/fruit), and seed dry weight(0.35 g/fruit). It also reduced fruit drop and shortened the maturity period. In contrast, complete girdling causes excessive fruit drop and reduced seed weight. Wound healing was slower in thicker branches, requiring more than 60 days. The study concluded that 50% girdling in neem trees would be useful for increasing the fruit parameters and yield.

Keywords: *Azadirachta indica*, Fruit parameter, Girdling, Neem

Azadirachta indica A. Juss. is commonly known as Neem belonging to family Meliaceae. Neem is known for benefits of its fruits, seeds, oils, leaves, roots and bark in Ayurveda and Unani system of medicine. Neem based preparations are efficacious against skin diseases and used for cosmetics, soaps, lubricants and biofertizer. The tree is usually evergreen, making it an excellent shade tree in summer. The panicles of greenish white flowers appear in the first week of April in North India, central India, and Tamil Nadu, and in the first week of May in the sub-Himalayan region (Mitra 1963). The fruits ripen from June to August. Neem is a strong light demander and can withstand droughts. The neem is a sturdy tree that can adapt to a wide range of climatic, edaphic, and topographical conditions. It thrives well in areas with temperature from 40 to 42.5C, annual rainfall of 450-1200 mm, and well drained acidic soil. Water logging and poorly drained soils are unsuitable for neem. The rate of growth of neem in plantations varies considerably depending mainly on the quality of the soil. The data taken from three, 15 years old neem trees at Pune showed that each neem tree produced approximately 400 kg of wood (Kalla et al., 1978).

Often, the trees do not bear fruits, although are in good health and may not show any apparent disease symptoms. Two chemical elements in organic matter are extremely important, especially in proportion to each other: carbon and nitrogen. The growth and fruitfulness of plants are greatly influenced by the relative proportions of carbohydrates and nitrogen (Miller 2000, Kunte and Yawalkar 2005).Girdling is a horticultural practice that involves the removal of a complete ring of bark from a tree trunk or branch, thereby blocking the downward translocation of photosynthates and metabolites through the phloem. This increases foliar carbohydrates (sugars and starch) and plant hormones in the upper parts of the girdle, which enhances floweringand fruit-bud formation. Other important materials, such as hormones, amino acids and minerals move in the bark in the same direction (Ticho 1970). As a result of girdling the leaf N content, the C/N ratio and carbohydrate content improved. Therefore, flowering and fruit sets increase (Shao et al., 1998). It was observed that 1/4th (25%) girdling of trunk girth by removing 2mm bark in the last week of March exhibited best performance in terms of improvement in flower and yield parameters namely- no. of flowers/shoot, per cent fruit set, no. of fruits per shoot and total yieldin *Actinidia delicoisa* (Azizi et al., 2022). Praveen et al. (2025) reported wide variety of fruit species are girdled to induce flowering, improve fruit set, increase in yield, enlarge fruit size, advance maturity and improve quality. Keeping in view the importance of fruit and seed of neem plant, the present study was designed to study the intensity of girdling of branches in increasing the fruit morphology and yieldin Neem.

MATERIAL AND METHODS

The experiment was conducted during 2025 in the field of AICRP (Agroforestry), OUAT, Bhubaneswar, which is located at 20^{0}27'99" N latitude and 85^{0}78'30" E longitude. The trees were planted at 8x3m^2 alleys. Neem trees (5 years old) with tertiary branches bearing 8–10 inflorescences were selected. Experiment was laid out in a completely randomized design with five treatments namely T1 – Control (no girdling); T2, T3, T4, T5 25, 50, 75 and 100% girdling of branch circumference and were replicated fourtimes.

Girdling treatments were done in the 2nd week of April, 2025 just at the start of flowering stalks. Girdling was

performed using a 4 mm wide girdling knife. In the partial treatments, the respective percentage of bark circumference (4mm wide) was removed without damaging the xylem, whereas in T5, a complete circular ring was removed. Immediately after girdling, the following parameters were recorded for each selected branch: branch diameter, number of inflorescences, fruit setting time, total number of fruits per branch, fruit length, fruit diameter, fresh weight of fruit and dry weight of seeds. From each replication, 20 fruits were measured and the average value per fruit and seed with respect to fruit and seed morphometric parameters were worked out. The fruit parameters were measured by electronic calliper and fruit weight was measured.

RESULTS AND DISCUSSION

Fruit and seed morphometric characters: The treatment T2 (25% girdling) recorded maximum days (40) taken for maturity of fruits from fruit set, whereas in T3 (50% girdling of branch circumference) took minimum days (31). The maximum fruit diameter (11.6 mm) was in 50% girdling of branch circumference, and minimum (9.12 mm) was due to 100% girdling (Table 1). Maximum fruit length (16.37 mm) was observed in response to 50% girdling and (13.91 mm) was due to no girdling (Table 1). The fruit length in T4 (15.25 mm) was not found significantly different from T3. The maximum fruit weight (1.34 g) was observed in treatment exposed to 50% girdling of branch circumference and 0.79 g in control (no girdling). T_4 and T_3 *i.e.,* 75% and 50% branch girdling differed non-significantly from each other (Table 1). The maximum seed weight was 0.35 g in treatment response to 50% girdling and minimum (0.29 g) in treatment response to 100% girdling of branch circumference. Length-to-diameter ratio was maximum (1.62) in 100% girdling of branch circumference and was least (1.38) in 50% girdling. The 100% girdling of branch circumference was significantly different from all other treatments (Table 1). The pulp weight was maximum (0.99g) in treatment response to 50% girdling, and minimum (0.48) in control (Table 1).

Initial and final number of fruits, fruit drop, fruit retention, days taken to fruit set and days taken to mature from fruit set was recorded among different branch gridling treatments. All these parameters showed significant variation among the treatments (Table 2). Initial number of fruits was more (23.25) due to 25% girdling of branch circumference (T2), and minimum (15.25) in control (Table 2). Final number of fruits at maturity ranged between 6.75 (control) to 15.75 (50% girdling of branch).

Considering fruit retention and drop in Neem, T3

Table 1. Fruit morphometric characteristics as influenced by branch girdling treatments in Neem

Treatments	Fruit diameter (mm)	Fruit length (mm)	Fruit weight (g)	Seed dry weight (g)	Pulp dry weight (gm)	L/D
T1	9.72	13.91	0.79	0.31	0.48	1.43
T2	10.13	14.57	0.95	0.31	0.64	1.53
T3	11.66	16.37	1.34	0.35	0.99	1.38
T4	10.15	15.25	1.10	0.30	0.80	1.50
T5	9.12	14.55	0.90	0.29	0.61	1.62
CD (p=0.05)	0.92	2.24	0.23	0.26	0.18	0.19
CV (5%)	6.02	1.41	13.31	18.66	11.81	7.77

Note: T1 – Control (no girdling); T2 – 25% girdling of branch circumference; T3 – 50% girdling of branch circumference; T4 – 75% girdling of branch circumference; T5 – 100% girdling of branch circumference; L/D-Length-to-Diameter ratio

Table 2. Fruit setting, fruit maturity, fruit retention in different treatments in Neem

Treatments	Initial no. of fruits	Final no. of fruits	Fruit drop (%)	Fruit retention (%)	Days taken to fruit set	Days taken to mature from fruit set
T1	15.25	6.75	55.34	44.65	6.00	36.25
T2	23.25	13.00	42.98	57.02	9.00	40.00
T3	21.25	15.75	29.46	70.54	10.75	31.25
T4	18.25	8.50	52.99	47.01	7.00	38.75
T5	22.00	10.50	55.37	44.63	7.00	39.75
CD (5%)	15.56	12.77	27.09	27.84	5.94	6.76
CV (5%)	7.31	11.00	27.06	4.95	7.02	8.53

See Table 1 for details of treatments

treatment (50% girdling) recorded maximum fruit retention (70.54%) and was minimum (44.63%) in T5 (100% girdling). Maximum fruit drop (55.37%) was in T5 (100% girdling of branch circumference), which was significantly different from all other treatments. However, T3 (50% girdling) resulted in 29.46 per cent fruit drop (Table 2). The period of fruit set ranged from 6 (control) to 10.75 days (50% girdling of branch circumference), while fruit maturation also varied among branch girdling methods. The maximum fruit harvesting period was 40 days in T2 with 25% branch girdling and the minimum fruit harvest period (31.25 days) was observed in trees subjected to 50% girdling of branch circumference (Table 2).

Branch girdled wound healing time: The branches of diameter less than 10 mm healed first (within 30 days) than branch diameter between 10 mm to 15 mm. However, the branches with diameters greater than 15 mm took more than 60 days' time for healing. The 50% girdling of branch circumference (T3) yielded the best results among all the treatments. It produced the largest fruit diameter, fruit length, highest fruit weight, pulp weight and maximum seed weight (19.96, 17.69, 69.62, 106 and 12.90%, respectively) more in comparison to control. In T3, final number of fruits at maturity, and per cent fruit retention were maximum. The 50% girdling of branch circumference recorded the lowest with respect time for fruit maturity (31.25 days) and fruit drop (29.46%) compared to 36.25 days and 55.34%, respectively as in control. Partial girdling allowed regulated stress by restricting phloem transport without completely blocking water and nutrient movement, thereby concentrating the assimilates in the fruit. In contrast, 100% girdling (T5) caused excessive stress, leading to smaller fruits and higher fruit drops. These results are consistent with earlier findings (Khandaker et al., 2011, Gawankar et al., 2019), where better fruit growth and oil content with partial girdling as compared to full girdling. Girdling treatments advanced the fruit maturity over control in 18-year-old “Patharnakh” Pear as reported by Singh et al. (2014). The healing of girdled wounds varied with branch thickness; branches <10 mm healed within 30 days, whereas those >15 mm required more than 60 days, suggesting that thicker branches are more suitable for girdling. The wound healing duration of girdled portion increases with increasing the size of girdling notch in *Litchi chinensis* (Kumar et al. 2017) which is consistent with the findings of the present study.

CONCLUSION

The 50% girdling of branch circumference was the most effective treatment that produced bigger fruits with higher fruit weight, faster maturity, and dropped less fruits. Branches with a diameter greater than 15 mm were more suitable for girdling, which also showed better healing capacity. Therefore, 50% girdling in tertiary branches with more than 15 mm diameter just at the start of flowering in the 1st week of May is recommended for better fruit size quality and yield.

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AUTHORS CONTRIBUTION

T.L. Mohanty is the project supervisor who designed the experiment. Utpalika Hota is the research scholar who conducted the research trial. M.C. Behera has organised and managed the data. S.G. Nair has analysed and interpreted the data. H. Nayak has helped in facilitating the field for the study.

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Recent Advances in Forest Inventory and Mapping: A Review

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***Abstract*:** Forest inventory and mapping are foundational for effective forest management, enabling systematic assessment of forest structure, composition, biomass, and ecological changes over time. Traditional methods, while historically valuable, are constrained by limited spatial coverage, high labour costs, and slow data processing. Recent technological advances have revolutionized forest inventory practices through the integration of remote sensing platforms, unmanned aerial vehicles (UAVs), robotics, artificial intelligence (AI), and mobile-based data collection tools. Satellite based optical imagery from platforms such as Landsat, Sentinel-2, and Planet Scope facilitates high resolution and long-term monitoring of forest cover and health. Light Detection and Ranging (LiDAR) and Terrestrial Laser Scanning (TLS) enable precise 3D characterization of forest structure and aboveground biomass. Digital Aerial Photogrammetry (DAP), which employs drones to generate point clouds through structure-from-motion algorithms, provides cost-effective alternatives for even-aged forest inventory. Robotic systems such as the FGI ROAMER and Komatsu 931.1 now automate ground-level forest measurements using real-time LiDAR processing, even in GPS-denied environments. Furthermore, AI and machine learning algorithms are increasingly deployed for species classification, biomass estimation, and change detection from satellite and LiDAR data. Mobile-based tools such as Open Foris, Van Darshan, and Forest Watcher enable real-time, geo-tagged forest data collection, improving participatory monitoring and forest governance. Collectively, role and opportunities of these technologies have been over viewed, which offers scalable, accurate, and timely inventory systems essential for sustainable forestry, biodiversity conservation, and climate change mitigation.

***Keywords*:** Forest inventory, Forest mapping, LiDAR, Remote sensing, UAVs, Artificial intelligence

Forest inventory is a systematic process of collecting, analysing, and interpreting data related to forest resources within a defined area. It involves measuring various forest attributes such as tree species, diameter at breast height (DBH), tree height, age, basal area, volume, biomass, and overall forest health. Ferretti et al. (2024) emphasized a well-designed forest inventory creates a comprehensive and scientifically sound database that serves as a baseline for monitoring temporal changes in forest structure and composition. Forest maps may depict forest types, tree cover, canopy density, biomass distribution, and land use changes (Kanga 2017). The various reasons highlighting the importance of conducting forest inventory and mapping are summarized in Table 1. According to Gimrnez-Garcia et al. (2023), forest mapping plays a crucial role in spatial analysis, enabling researchers, planners, and decision-makers to visualize and interpret the spatial heterogeneity of forests more effectively. The inventory provides the raw quantitative data, mapping helps in translating this data into spatial patterns across the landscape (Ferretti et al., 2024). However, conventional forest inventory and mapping methods are often labour-intensive, time-consuming, spatially limited, and prone to human error. In large or inaccessible forest areas, only a small fraction can be surveyed, leading to biased estimates and delayed information (Corona 2010). One of the most significant advancements in recent years is the application of LiDAR (Light Detection and Ranging) technology in forest assessment. LiDAR systems use laser pulses to measure distances to the Earth's surface, enabling the creation of three-dimensional representations of forest structure (Dassot 2011). Modern airborne LiDAR surveys can detect individual trees with a diameter greater than 10 cm with up to 95% accuracy, and can generate canopy height models (CHMs) at resolutions as fine as 1 meter (Zhengnan et al., 2023).

RESULTS AND DISCUSSION

Important conventional techniques of forest inventory and mapping

Strip and plot sampling: Sample plots or linear strips of known dimensions are established systematically or randomly throughout a forest area. Within these plots, tree and vegetation attributes such as Diameter at Breast Height (DBH), tree height, species identity, and regeneration status are recorded. This is one of the most common methods employed by forest departments and research institutions (Kangas and Maltamo 2006, FSI 2021).

Point sampling: This method, also known as angle count sampling or Bitterlich sampling, utilizes tools like angle gauges or prisms to identify trees for measurement based on their apparent width when viewed from a fixed point (Avery and Burkhart 2002, Bitterlich 1984, Gregoire and Valentine 2008).

Timber marking and stock mapping: Trees selected for harvesting are marked with paint or tags, and their positions are noted on paper maps. These maps help document felling series, the distribution of species, and stocking densities. However, these traditional stock maps lack spatial resolution and accuracy compared to modern GPS-based systems (MoEF&CC 2014, Spurr 1952, Chaturvedi and Khanna 2011).

Ocular estimation: Experienced foresters estimate forest parameters such as canopy cover, dominant species, and regeneration status through visual observation. It is often used in preliminary surveys or rapid forest assessments (Somanathan et al., 2009, Husch et al., 2003, Loetsch and Haller 1973).

Quadrat sampling: Fixed-area quadrats (e.g., 1m², 10 m²) are laid out within the forest to systematically record plant species, frequency, density, and coverage. Quadrats can be randomly or systematically placed depending on study objectives (Muller et al., 2018, Misra 1968, Mueller-Dombois and Ellenberg 1974).

Aerial photography: These photos helped identify forest types, canopy gaps, terrain features, and land use patterns. Interpretation was done manually using stereoscopes to view the images in 3D. Though now largely replaced by satellite imagery, aerial photography was foundational in historical forest inventory and mapping (Lillesand and Keifer 2000, Avery 1977, Colwell 1997).

Topographic sheet overlaying: Forest boundaries and compartments were historically traced and mapped over topographic maps issued by the Survey of India. These topographic sheets provided base maps showing elevation, terrain features, and hydrology. Forest boundaries were drawn manually using these sheets, serving as the foundation for early forest maps (FSI 2005, Davis et al., 2001, Burrough and McDonnell 1998).

Compass and chain surveying: A traditional method for boundary demarcation and plot layout, this technique uses a Brunton compass and measuring chains or tapes. It is still used in areas where GPS or digital tools are unavailable (Manandhar et al., 2019, Reddy 1983, Chaturvedi and Khanna 2011).

Plane table and theodolite surveying: Used for terrain mapping, contour creation, and compartment layout, this method provides higher angular precision than compass-based surveys. A plane table is used to record field observations directly onto a map, while the theodolite measures horizontal and vertical angles accurately. It is suitable for detailed surveys of small areas and for producing base maps for forest management (Sharma and Chaudhary 2007, Kiser and Dilger 2008, Husch et al., 2003).

The key limitations and challenges associated with traditional forest inventory and mapping methods are summarized in Table 2**.** To address these challenges, forestry research and practice have increasingly shifted towards modern, technology-driven approaches that are faster, more precise, and scalable. This paradigm shift has given rise to a

Table 1. Need for conducting forest inventories and mapping

Reason	Information	Methodology/Technique used	References
Detection of changes in forest cover	Globally, 420 million hectares of forest area has been lost from 1990 to 2020	Satellite-based remote sensing (multi-temporal Landsat data analysis)	Global Forest Resources Assessment Report, 2020
	Forest and tree cover of India increased by 1445.81 km^2	Remote sensing & GIS mapping (high-resolution satellite imagery by FSI)	Indian State of Forest Report, 2023
Climate change mitigation and carbon stock estimation	289 Giga tons of carbon is being stored by forests worldwide, this information helpful in climate change mitigation efforts like REDD+, NDC's etc.	Global forest inventory & biomass modelling using remote sensing + ground-based plots	Global Forest Resources Assessment Report, 2020
Biodiversity and habitat conservation	Across the globe, forests are home to 80 % of terrestrial biodiversity of which 25 % of them are globally threatened.	Global biodiversity outlook synthesized from ecological monitoring, species inventory databases, and remote sensing	Convention on Biological Diversity, 2020
Forest fire assessment	Around 4 % of forest area is globally affected by wild fires annually	Satellite-based fire detection (MODIS, VIIRS) and GIS-based fire mapping	UNEP Global Wildfire Assessment report, 2022
	Worldwide, 41.82 % of tropical and subtropical forests are highly vulnerable to fires	Remote sensing-based fire risk modelling and spatial vulnerability mapping	
Ecosystem services valuation	Forests contribute 125 trillion dollars per year in ecosystem services like water purification, erosion control *etc*.	Economic valuation models (TEEB framework) integrated with GIS-based ecosystem service mapping	TEEB Report (The Economics of Ecosystems and Biodiversity), 2018
Timber resource assessment for industrial demand	The global timber consumption is projected to reach 5.8 billion cubic meters by 2050, up from 2.2 billion cubic meters in 2018	Statistical modelling and market forecasting using global timber trade datasets	Gresham House Global Timber Outlook Report, 2020

suite of advanced methodologies—ranging from satellite remote sensing and LiDAR to UAVs, robotics, and artificial intelligence—that have transformed the way forests are inventoried and mapped (Wallace et al., 2012, Thaker 2024).

Advancements in forest inventory and mapping: Recent advancements in technologies such as remote sensing, drones, robotics, and AI-based tools are at the forefront of this digital revolution in forestry, reshaping traditional practices and offering new possibilities for forest inventory, health assessment, and restoration (Thaker 2024).

Remote sensing technologies for enhancing forest inventories and mapping: Among the various methods, satellite-based optical imagery, digital aerial photogrammetry, air borne and terrestrial laser scanning plays a pivotal role in detecting forest cover, assessing biomass, monitoring biodiversity, and tracking changes over time (Saukkola et al., 2019, White et al., 2016).

Satellite based optical imagery: Satellite-based optical imagery use sensors aboard satellites to detect and record reflected sunlight across various spectral bands, such as visible, near-infrared, and shortwave infrared (Bayr et al., 2016). Among the most commonly used platforms are medium-resolution satellites like Landsat, which offers a spatial resolution of 30 meters, and Sentinel-2, which provides data at resolutions ranging from 10 to 20 meters (Puliti et al., 2021). Technology has enabled more robust data collection, but operational use of remote sensing (via satellites such as MODIS, Landsat, and Sentinel) for forest phenology monitoring in India is still limited. Remote sensing offers the ability to track large-scale, long-term patterns that are difficult to capture with traditional field methods (Sedha et al., 2024)

For more detailed analysis, high-resolution commercial satellites such as WorldView-3 (0.31 m resolution), Quick Bird, and Geo Eye have proven extremely useful (Alonso et al., 2022, Tokar et al., 2017 and Astola et al., 2010). In real-world applications, the integration of Planet Scope imagery (3 m resolution) with deep learning models has enabled researchers to detect selective logging activities in the Brazilian Amazon, which are often difficult to identify with coarser-resolution datasets (Silva Junior et al., 2021). Such approaches enhance monitoring efforts, especially in areas facing illegal or small-scale deforestation pressures. This has improved the ability to differentiate species at the understory level, which is typically challenging due to dense canopy cover and spectral similarities among vegetation types (Das et al., 2022). Overall, satellite-based optical imagery remains an essential and evolving tool for enhancing forest inventories, offering a cost-effective and scalable solution for long-term forest monitoring and management.

Air borne laser scanning: Airborne Laser Scanning (ALS), commonly known as LiDAR (Light Detection and Ranging), is a cutting-edge active remote sensing technology that enables the capture of the three-dimensional structure of forests with high precision. Unlike passive systems that rely on sunlight, LiDAR operates by emitting laser pulses from an airborne platform (typically an aircraft or drone) and measuring the time it takes for the pulses to return after striking the ground or vegetation. LiDAR is particularly useful in forestry for a range of critical applications (Tonolli et al., 2011). One notable real-world application of this technology is NASA's Global Ecosystem Dynamics Investigation (GEDI), launched in 2019. GEDI uses full waveform LiDAR to measure forest structure and biomass across the globe, providing essential data for global carbon monitoring, climate modelling, and REDD+ (Reducing Emissions from

Table 2. Key factors responsible for the need of advancement

Limitation	Impact	Example	References
Time consuming fieldwork	Slow data collection in large/remote forests	Himalayan ranges require 5–6 weeks per range for inventory	FSI (2021)
Labour intensive	Needs large trained teams & coordination	1000 ha forest may need 8–12 people for 20–25 days	Tripathi et al. (2020)
Limited spatial coverage	Plots cover small % of forest, risking bias	Only 0.1–0.5% area sampled in large forests	Chazdon et al. (2016)
Manual mapping errors	Compass deviations & misplotting common	Hilly terrains show 10–20 m boundary shifts	FSI (2019)
Subjective visual estimations	Observer bias affects canopy cover data	Error margin up to ± 30% between individuals	Nagendra (2001)
No real time monitoring	Fires, encroachments often go unnoticed	Detection can lag weeks/months	Global Forest Watch (2023)
No spatial integration	Hard to overlay with slope, soil, climate layers	Lacks geotagging for GIS compatibility	FAO (2016)
Difficult terrain access	Rugged zones under-surveyed or skipped	Only 30% of steep areas mapped in Nanda Devi Biosphere Reserve	MoEF&CC (2017)

Table 3. Tabular representation of application of drones in forest inventory and mapping

Location	Sensor	Key contribution	Reference
Interior Douglas fir forest	UAV-DAP (ALS)	Detected 246 trees, measured growth between 2013–2015. UAV-DAP estimated avg. tree height growth as 0.68 m and volume growth of 0.05 m³/tree	Goodbody et al. (2017)
Australia	UAV-LiDAR (ALS)	Measured tree heights with precision comparable to ground-based measurements	Wallace et al. (2014)
Tropical forests of Costa Rica	UAV-DAP (RGB)	Tracked tropical forest recovery, assessed canopy closure and vegetation structure over time	Zahawi et al. (2015)
Coniferous forests of Finland	UAV-Hyperspectral	Detected bark beetle infestation at individual-tree level using spectral traits	Näsi et al. (2015)

Deforestation and Forest Degradation) reporting (Dubayah et al., 2020). In the Indian context, LiDAR has been applied in regions like Karnataka and the Western Ghats to estimate aboveground biomass and model the complex topography of tropical moist deciduous forests. These applications have demonstrated the effectiveness of LiDAR in enhancing forest inventory practices and supporting sustainable forest management strategies (Reddy et al., 2021).

Terrestrial laser scanning: Terrestrial Laser Scanning (TLS) is a ground-based LiDAR technology that uses fixed or mobile scanners to produce high-density 3D point clouds of forest components at tree and plot levels. It is particularly effective for measuring diameter at breast height (DBH), stem taper, branch architecture, and leaf area index (LAI) with high precision. A real-world application of TLS is the TreeQSM algorithm, which reconstructs 3D tree models and accurately estimates aboveground biomass using TLS data (Calders et al., 2015).

Digital aerial photogrammetry: Digital Aerial Photogrammetry (DAP) uses overlapping aerial images captured by drones or aircraft, which are processed through Structure-from-Motion (SfM) algorithms to generate 3D point clouds. In India, drone-based DAP has been employed in the Aravalli Hills and community forests of Maharashtra to assess forest degradation and support joint forest management planning (IIFM Report 2022).

Unmanned aerial systems for precision forest inventory and mapping: Unmanned Aerial Vehicles (UAVs) have emerged as a powerful tool for forest inventory and mapping due to their ability to capture ultra-high-resolution imagery at low altitudes. UAV-based photogrammetry, often referred to as Digital Aerial Photogrammetry (DAP), involves collecting overlapping RGB or multispectral images and converting them into dense 3D point clouds using Structure-from-Motion (SfM) algorithms. Despite certain limitations—such as short flight times due to battery constraints, limited payload capacity for heavier sensors (like LiDAR), and regulatory requirements such as visual line-of-sight rules—UAV-DAP offers a cost-effective, repeatable, and highly adaptable method for forest monitoring. The growing affordability and accessibility of drones, along with advances in image processing software, have further enhanced their utility in generating Enhanced Forest Inventories (EFIs) across diverse forest types (White et al., 2016, Puliti et al., 2020).

AI and mobile based tools: Artificial Intelligence (AI), especially Machine Learning (ML) and Deep Learning (DL) techniques, is playing a transformative role in modern forest monitoring and management. The successful example is use of CNNs with Planet Scope (3 m resolution) and LiDAR data in the Amazon Rainforest, which enabled the detection of selective logging activities with over 90% accuracy (Silva Junior et al., 2021), showcasing the precision and potential of AI-powered monitoring systems. In India, the Forest Survey of India's (FSI) mobile application Van Darshan facilitates photographic inventories of degraded forest patches under the CAMPA scheme. Likewise, the Forest Watcher app from Global Forest Watch (GFW) empowers patrol teams in Congo and Peru by providing offline access to satellite-based deforestation alerts and allowing in-field verification of illegal logging activities. These innovations bridge the gap between remote sensing outputs and field validation, making forest governance more data-driven, participatory, and responsive.

CONCLUSION

Recent advancements in forest inventory and mapping technologies represent a significant paradigm shift from traditional, labour-intensive methods to more efficient, data-driven, and scalable approaches. Today, the integration of advanced tools such as satellite imagery, LiDAR (Light Detection and Ranging), UAV (Unmanned Aerial Vehicle)-based photogrammetry, robotics, artificial intelligence (AI), and mobile data collection platforms has revolutionized the way forest resources are monitored and managed. Collectively, these advancements are not only strengthening local forest governance and sustainable resource management but are also contributing to national and global initiatives aimed at promoting ecological resilience, climate adaptation, and environmental sustainability.

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Circular Economy and Vedic Ecological Wisdom: Pathways for Sustainable Forest Futures in India

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Abstract: Deforestation, biodiversity loss, and unsustainable resource exploitation are critical challenges facing India's forests. The circular economy (CE) offers solutions for resource optimization and waste reduction, though often lacking cultural relevance. This paper explores integrating CE principles with India's Vedic ecological wisdom and traditional ecological knowledge (TEK) to develop sustainable, culturally relevant forest management strategies. Through a conceptual review of CE, indigenous knowledge, and Vedic texts, supported by case studies of sacred groves, community forest management in Odisha, and agroforestry systems, this study highlights how CE's focus on resource efficiency aligns with Vedic values of restraint and stewardship. The paper concludes that integrating CE into India's ecological and cultural context can conserve biodiversity, reduce resource conflicts, and inform stronger environmental policies.

Keywords: Circular economy, Vedic philosophy, Traditional Ecological knowledge, Forest management, Sustainability

Forests in India are vital for sustaining biodiversity, climate stability, and livelihoods. However, deforestation, unsustainable resource exploitation, and socioeconomic pressures threaten their survival. Traditional conservation models have made progress, yet frameworks like the circular economy (CE) offer new opportunities for waste reduction, resource optimization, and closed ecological cycles. A gap exists in current CE applications, as these models often lack cultural relevance and ethical grounding, limiting their effectiveness in India's unique socio-ecological context. Vedic ecological knowledge and traditional ecological knowledge (TEK) offer time-tested practices of environmental stewardship. Key principles, such as Rta (cosmic order) and Bhumi Sukta (Mother Earth), advocate for sustainability, restraint, and reciprocity. TEK, though distinct, is rooted in community-based practices like sacred groves, community forestry, and agroecological systems, which enhance sustainable resource management and resilience.

Integrating CE with indigenous knowledge systems can provide ethically grounded, culturally relevant sustainability models. Such integration ensures practices resonate with local traditions, making them more effective and socially accepted. Research suggests that aligning CE with Vedic wisdom and TEK could significantly enhance forest sustainability and resilience in India (Negi 2023, Kumar and Singh 2023, Xess 2024).

The circular economy (CE) has emerged as a global alternative to the traditional linear model of "take-make-dispose." Instead of viewing waste as the endpoint of a product's lifecycle, CE advocates for reuse, repair, recycling, and regenerative design. When applied to forestry and natural resources, CE emphasizes biomass recycling, bio-based products, eco-designed forest products, and integrated agroforestry systems. However, CE's implementation in India has faced challenges. Rajayya (2025) argues that CE frameworks remain ineffective due to uncoordinated policies, poor stakeholder engagement, and infrastructure issues. CE must be adapted to India's regional and cultural contexts rather than imported from Western models. Mandpe (2023) supports this view, highlighting that CE practices thrive when co-created with local communities, rather than being imposed. Reis (2023) notes that global technological advancements in CE may fail without cultural adaptation. Gaur (2024) extends CE's relevance to e-waste management, connecting it to the Sustainable Development Goals (SDGs). Hadfield (2025) calls for a shift in CE transitions to focus on social justice and equity, particularly in the Global South. These perspectives underscore the need for dialogue between CE and indigenous practices. Bridging the gap between CE and traditional ecological knowledge (TEK) could create sustainable, culturally resonant solutions for local communities.

Indian environmental thought is deeply rooted in vedic traditions, where interconnectedness, restraint, and cyclical balance precede modern sustainability concepts. The Bhumi Sukta of the Atharvaveda portrays the Earth as a mother, emphasizing reciprocity and stewardship. The principles of Rta (cosmic order) and Dharma (duty) guide ecological practices, promoting balance and non-exploitation of nature. These principles manifest in practices such as sacred groves, ritual protection, and sustainable agriculture, aligning with modern ecological thinking. Vedic ecological wisdom mirrors CE principles like zero waste and cyclical resource flows, predating these ideas. Studies demonstrate that

agroforestry systems in India are rooted in Vedic texts. Growing interest in Vedic ecological philosophy (Singh 2023) suggests its practical application in modern sustainability efforts. Integrating Vedic ethics into CE frameworks can help India develop culturally relevant and scientifically robust sustainability models.

Alongside Vedic practices, TEK developed by indigenous communities offers dynamic, context-specific approaches to environmental stewardship. Unlike static models, TEK evolves with community needs, making it a valuable resource for resilience. For example, Gangadhar (2020) describes how tribal communities in Adilabad, Telangana, interpret ecological signals, such as bird behavior, as indicators of climate hazards. This adaptive governance system offers practical, local solutions that outperform rigid scientific models. Xess (2024) further emphasizes TEK's role in adaptation strategies in rapidly changing environments. TEK also plays a crucial role in biodiversity conservation and social cohesion, which strengthens community resilience (Negi 2023). By integrating TEK with modern systems, we can address challenges like climate change and resource depletion, linking local knowledge with global sustainability goals. Tehrani (2025) highlights a successful case from Canada where TEK was integrated into CE transitions, showing that hybrid models work effectively in practice. In India, various forms of TEK, such as community forestry in Odisha, sacred groves in Maharashtra, and pastoral commons in Rajasthan, exemplify CE principles like biomass recycling, resource conservation, and energy regeneration. These practices protect biodiversity while respecting cultural traditions. Sacred groves, for instance, function as informal conservation areas that preserve biodiversity without formal legal status (Gokhale et al., 2023, Ministry of Environment 2024). This paper examines how combining these frameworks with scientific forest management can shape future forest policies that are both scientifically valid and culturally grounded.

MATERIAL AND METHODS

This study employs a conceptual review methodology to examine the intersections of Circular Economy (CE), Vedic ecological wisdom, and Traditional Ecological Knowledge (TEK) in the context of sustainable forest management in India. The methodology combines elements of systematic literature review, comparative analysis, and thematic synthesis, creating an interdisciplinary framework to explore potential sustainable futures for Indian forests.

Literature selection and sources: To ensure comprehensive coverage of relevant studies, a systematic search plan was developed. The selection criteria focused on peer-reviewed studies, policy documents, and cultural-philosophical texts directly related to CE, TEK, and Vedic ecological ethics. A transparent, replicable selection process was employed, outlined below:

Peer-reviewed databases: A systematic search was conducted across several prominent databases, including Scopus, Web of Science, Springer, Elsevier, Emerald, MDPI, and Nature Sustainability. Keywords such as *"circular economy"*, *"sustainable forest management"*, *"waste management"*, and *"ecological economics"* were used to identify relevant articles (Rajayya 2025, Mandpe 2023, Reis 2023, Hadfield 2025).

Indian Academic Sources: Given the cultural context of the study, priority was given to Indian academic sources, for case studies and cultural research on TEK and Vedic ecological knowledge (Gangadhar 2020, Xess 2024).

Policy documents: Key Indian forest and environmental policy frameworks, such as the Forest Rights Act (FRA, 2006), Joint Forest Management (JFM) guidelines, Plastic Waste Management Rules (2016), and relevant SDG implementation reports, were reviewed. These provided insights into the policy landscape surrounding CE and forest management in India.

Cultural-philosophical texts: To integrate indigenous philosophical dimensions, Vedic scriptures like the Bhumi Sukta, along with secondary scholarship on Vedic environmental ethics, were included. These texts provided the historical context for the ecological principles discussed. This multi-source approach ensured scientific rigor and cultural contextualization, allowing for a holistic view of forest sustainability.

Thematic coding and synthesis: The collected literature was analyzed using thematic coding to identify the intersections between CE principles, TEK practices, and Vedic ecological ethics. The thematic analysis was structured around three key clusters:

Circularity and resource cycles: This theme compared CE principles (reduce, reuse, recycle, regenerate) with cyclical models found in Vedic and indigenous practices.

Community stewardship and governance: This focused on the alignment between CE's emphasis on stakeholder collaboration and community-driven initiatives, such as community forest management and sacred grove traditions.

Ethics and sustainability: This explored how Vedic moral codes (Dharma, Rta, Aparigraha) support ecological limits, often overlooked in technocratic CE models. The thematic synthesis allowed for the identification of both convergences and contradictions between these systems, highlighting areas where they complement each other and areas requiring further integration.

Case study anchoring: To contextualize the theoretical synthesis, case studies were used to illustrate how the concepts of CE, Vedic wisdom, and TEK converge in practice. These case studies served as illustrative anchors rather than empirical data sources, showcasing real-world applications:

Sacred groves (Meghalaya, Maharashtra): These are examples of culturally enforced conservation, aligned with CE's regeneration principle.

Community forest management (Odisha): This demonstrated TEK-based governance, which ensures resource circularity and community resilience.

Agroforestry practices: These practices demonstrate how Vedic-rooted land-use systems align with CE models of sustainability.

Waste-to-resource innovations: This compares modern CE applications with traditional methods like composting and biochar production, showing their potential integration.

Analytical framework: The final analysis employed a comparative-conceptual framework that mapped CE principles against indigenous ecological ethics. This framework evaluated the following:

Conceptual convergence: Shared principles of circularity, balance, and stewardship between CE, Vedic wisdom, and TEK.

Operational strategies: How each system addresses practices in waste management, forest conservation, and agro-ecosystem governance.

Policy potential: The integration of these frameworks within existing Indian policies like the FRA, JFM, and SDG frameworks. By combining review-based evidence with cultural-ethical analysis, this methodology goes beyond descriptive synthesis, aiming to generate practical, policy-relevant insights.

Limitations: As a conceptual review, this study did not involve the collection of primary field data. While this allows for broad interdisciplinary insights, caution is required when generalizing findings. However, by grounding the framework in peer-reviewed studies, policy documents, and culturally rooted practices, this study provides a solid foundation for future empirical research.

RESULTS AND DISCUSSION

The analysis reveals clear complementarities between circular economy (CE), Vedic ecological wisdom, and traditional ecological knowledge (TEK). CE emphasizes efficiency, recycling, and waste minimization; Vedic traditions highlight ethics, restraint, and cosmic balance (Rta); while TEK provides practical, community-based stewardship grounded in lived experiences. Together, these frameworks offer a comprehensive approach to rethinking the sustainability of forests in India. The synergy between circular economy, Vedic ecological wisdom, and traditional ecological knowledge in promoting forest sustainability practices is illustrated in Table 1. It highlights how each framework contributes to various aspects of environmental conservation and resource management. CE emphasizes efficiency, recycling, and waste minimization, aligning with sustainable forest practices such as sacred groves, where biodiversity is conserved through religious and cultural beliefs, without the need for formal regulations. Vedic Ecological Wisdom, rooted in principles like Rta (cosmic order) and Bhumi Sukta (Mother Earth), advocates for a balanced relationship with nature, influencing practices like agroforestry, which integrates agriculture with tree planting for improved biodiversity and soil fertility. Meanwhile, TEK supports community-based resource management, as seen

Table 1. Synergy between circular economy, Vedic ecological wisdom, and traditional ecological knowledge in forest sustainability practices

Land use systems/ interventions	Circular economy alignment	Vedic ecological wisdom	Traditional ecological knowledge
Sacred groves	Conservation of biodiversity aligns with CE's principle of resource regeneration.	Reverence for nature (Bhumi Sukta) and cosmic order (Rta) promote protection of sacred sites.	Community-managed areas preserving biodiversity without formal legal status.
Community forest management (Odisha)	Community-led governance ensures sustainable resource use and waste minimization.	Collective responsibility and stewardship resonate with Vedic values of dharma and restraint.	Local communities manage forest resources, ensuring ecological balance and resilience.
Agroforestry ecosystems	Integration of trees with crops promotes biodiversity and efficient resource use.	Harmony between nature and human needs reflects Vedic principles of balance and sustainability.	Indigenous practices of integrating trees with agriculture enhance soil fertility and biodiversity.
Waste-to-resource innovations	Conversion of agricultural waste into compost and biochar exemplifies CE's waste minimization.	Ethical reuse (Aparigraha) aligns with Vedic teachings of non-possessiveness and minimal consumption.	Traditional composting and biochar production methods enhance soil health and reduce waste.

in community forest management in Odisha, where local governance ensures resource sustainability and resilience. The table emphasizes the integration of modern efficiency models with indigenous practices, showing how they complement each other in fostering long-term ecological balance and community resilience.

Concrete examples of synergy: Case studies demonstrate the synergy between these systems. For instance, sacred groves—protected through religious and cultural taboos—play a vital role in biodiversity conservation and ecological stability, functioning effectively without the need for formal regulatory structures (Negi 2023). In Odisha, community forest management (CFM) highlights the effectiveness of local institutions in resource governance and adaptive resilience, showcasing how community-driven efforts align with CE principles (Kumar and Singh 2023). Agroforestry systems, deeply rooted in rural Indian practices, combine agricultural productivity with conservation, reflecting the cyclicity central to CE and integrating both Vedic values of harmony with nature and TEK's community-based resource management (Sharma and Patel 2024). Furthermore, studies on waste-to-resource initiatives show that CE strategies, when combined with traditional practices like composting and biochar production, are enhanced by cultural and ethical foundations (Mandpe 2023).

These examples underscore the potential for integrating CE with indigenous knowledge systems, reinforcing the findings of previous research that advocate for the inclusion of cultural frameworks in modern sustainability models (Xess 2024, Reis 2023). In particular, Vedic ecological philosophy adds a crucial ethical dimension that is often absent in technical CE models. It emphasizes responsibility toward future generations, reverence for nature, and restraint in consumption—values that complement the efficiency-driven approach of CE. This integration strengthens CE by embedding it in cultural contexts, addressing critiques that CE may otherwise overemphasize efficiency while neglecting issues of equity and justice (Hadfield 2025).

Tensions and contradictions: While the synergies between CE, Vedic ecological wisdom, and TEK are clear, inherent tensions and contradictions must be addressed for a more nuanced understanding of their integration. For example, CE's emphasis on efficiency and technological innovation can conflict with Vedic values of restraint and non-possession (aparigraha). Vedic philosophy advocates for minimal consumption, which may at times clash with CE's drive for continuous growth and technological advancement. Similarly, TEK's community-based governance systems often rely on traditional ecological practices that may not always align with modern CE frameworks, which prioritize large-scale, systemic solutions over localized approaches.

Additionally, reconciling CE's focus on resource efficiency with Vedic ecological values that emphasize a spiritual relationship with nature presents challenges. The pursuit of efficiency in CE models could unintentionally overlook the moral and ethical considerations highlighted by Vedic traditions, such as the sacredness of natural resources and the duty to protect them for future generations. These tensions underscore the complexity of integrating CE with indigenous knowledge systems. While there are clear areas of alignment, addressing these contradictions is essential to creating a holistic and culturally resonant sustainability model. To synthesize these findings, a comparative framework was developed to map the alignment of the circular economy, Vedic ecological wisdom, and TEK across selected case examples (Table 2). By aligning CE with India's ecological traditions, this framework contributes to advancing SDG 12 (responsible consumption and production) and SDG 15 (life on land) while empowering local communities as custodians of sustainability. It also reinforces India's policy directions, where the integration of modern innovations with traditional ecological knowledge is increasingly recognized as essential for achieving climate resilience and ecological security (Xess 2024). To visualize these associations, we developed a conceptual framework that could integrate circular economy, Vedic ecological philosophies, and TEK in a synthesized sustainability model (Fig. 1).

Table 2. Comparative framework of circular economy (CE), Vedic ecological wisdom, and traditional ecological knowledge (TEK)

Case example	Circular economy principles	Vedic ecological wisdom	Traditional ecological knowledge
Sacred groves (India)	Resource conservation, protection of biodiversity hotspots	Reverence for nature, sacredness of land (*Bhumi Sukta*)	Community norms, taboos preserving biodiversity
Community forest management (Odisha)	Decentralized governance, efficient resource management	Balance (*Rta*), duty toward collective good	Collective stewardship, adaptive local practices
Agroforestry systems	Closed-loop nutrient cycling, sustainable productivity	Harmony between human needs and nature (*Dharma*)	Traditional soil and water management knowledge
Waste-to-resource models	Recycling, recovery, and optimization of resources	Restraint in consumption, ethical reuse (*Aparigraha*)	Local innovations in recycling, indigenous craft reuse

Actionable policy recommendations: Policy Integration: Indian policy frameworks must recognize and incorporate traditional ecological institutions as legitimate partners in CE initiatives. Policymakers should actively involve local communities in the design and implementation of CE strategies, ensuring these practices align with indigenous values and needs. Cultural Stewardship: Promote the cultural ethic of ecological stewardship, emphasizing the importance of sacred groves, agroforestry, and community-led conservation efforts as core components of forest management strategies. Policies should support waste-to-resource models that are tailored to local customs and practices.

Localized CE models: Ensure that CE models are not one-size-fits-all but are adapted to India's diverse ecological and cultural contexts. Policymakers should collaborate with local communities to develop frameworks that respect both modern ecological goals and traditional knowledge systems.

Interdisciplinary collaboration: Foster collaboration between environmental scientists, cultural experts, and policymakers to create hybrid governance models that balance the technical efficiencies of CE with the cultural richness of Vedic and TEK systems.

Future research directions: To further validate the proposed framework, future research should focus on the following areas:

Empirical studies on CE integration: Conduct empirical studies to evaluate how CE principles can be effectively integrated with Vedic and TEK practices in specific Indian regions. This could include case studies on the success of community forest management in Odisha or sacred grove conservation in Maharashtra.

Cultural impact assessments: Investigate the cultural impact of implementing CE models in India, focusing on how these models are received by local communities and how they affect cultural traditions and practices related to resource management.

Longitudinal studies on community resilience: Carry out long-term studies to assess the effectiveness of TEK-based governance systems in building community resilience to climate change and resource depletion, particularly in rural and indigenous communities.

Gaps and opportunities for integration: Despite shared principles between CE, Vedic ecological wisdom, and TEK, integrating them into policy and practice has proven challenging. Much of the CE research in India is policy-oriented, focusing on technological implementation, while Vedic and TEK solutions are often considered theoretical or

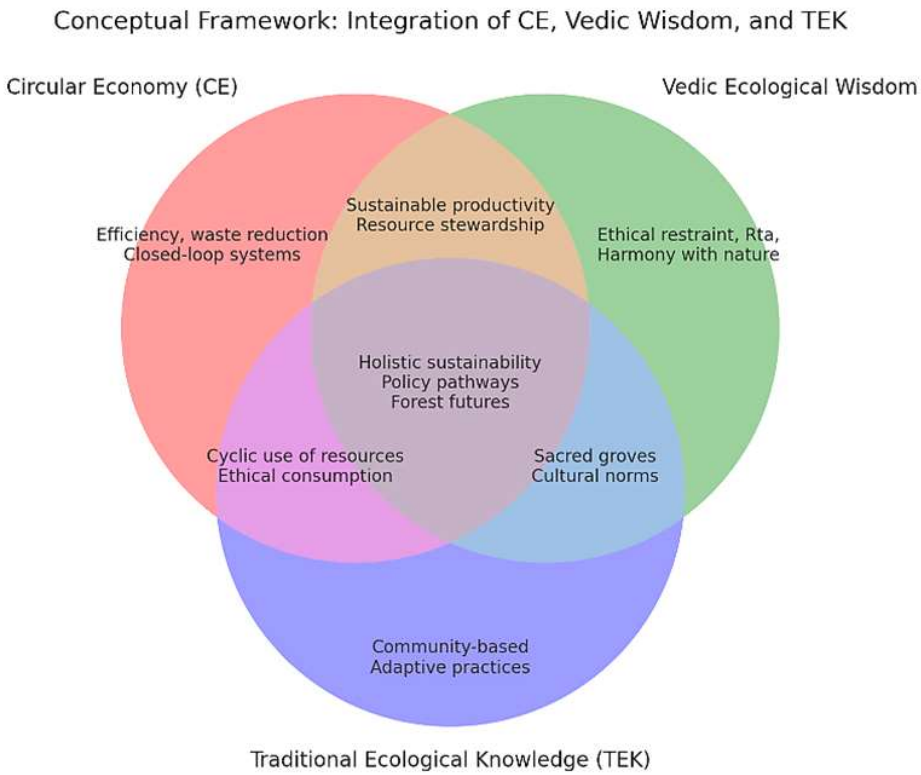

Fig. 1. Conceptual framework of how Circular Economy (CE), Vedic Ecological Wisdom & Traditional Ecological Knowledge (TEK) can be linked to sustainable forest futures in India

cultural, with limited practical application. This divide hinders the development of integrative models that balance ecological function with cultural integrity. To bridge these gaps, the integration of Vedic ecological ethics, TEK, and CE can offer Vedic ecological ethics can provide moral and cultural legitimacy to CE frameworks

Policy framework evaluation: Explore the policy implications of integrating TEK and Vedic wisdom into national forest management strategies. Research should focus on identifying barriers to policy adoption and recommending strategies to overcome these challenges. By bridging the gap between innovative technologies and ancient wisdom, India can position itself as a leader in creating sustainability models that resonate both globally and within its own cultural and ecological contexts. This interdisciplinary approach—blending science, policy, and philosophy—redefines sustainability as a multifaceted issue that is both technical and ethical. India is making progress toward its climate and biodiversity goals. To accelerate this progress, hybrid governance models that combine the efficiencies of CE with the cultural and ethical complexities of indigenous practices will be key to shaping a forest future that is ecologically sustainable, socially equitable, and philosophically rooted in India's traditions. Hybrid models can redesign forest governance to ensure both ecological effectiveness and social justice. By synthesizing CE with Vedic wisdom and TEK, India could pioneer a culturally grounded circular forestry model, offering valuable lessons for the Global South.

CONCLUSION

Achieving sustainable forest futures in India requires more than technical solutions—it necessitates a deep cultural connection. The integration of Circular Economy (CE) principles with Vedic ecological wisdom and Traditional Ecological Knowledge (TEK) offers a balanced approach that blends modern efficiency with traditional ecological practices. CE focuses on resource optimization and waste minimization, while Vedic traditions provide an ethical framework based on restraint, balance, and reverence for nature. TEK offers locally adapted strategies for community-based stewardship, such as sacred groves, community forest management, and agroforestry systems. Together, these elements form a culturally embedded, ethically mature sustainability model. However, the emphasis on technical CE transitions can overlook crucial cultural and ethical considerations. By embedding CE within India's ecological and cultural traditions, we not only enhance ecological outcomes but also promote community engagement, social justice, and long-term resilience. These integrative solutions can significantly contribute to achieving SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land), while supporting national policies on climate change and biodiversity conservation.

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Precision Forestry-Technological Advancements in Forest Science

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***Abstract*:** Precision forestry integrates advanced technologies to revolutionize forest management, enhancing productivity, sustainability, and environmental stewardship. This review explores recent developments across multiple domains, including forest inventory, tree improvement, timber harvesting, and wood processing. Technological tools such as Terrestrial Laser Scanning (TLS), Synthetic Aperture Radar (SAR), Unmanned Aerial Vehicles (UAVs), and satellite remote sensing have significantly improved forest inventory accuracy, species identification, and real-time pest outbreak monitoring. In tree improvement, Free-Air CO_2 Enrichment (FACE) experiments and mini-plug techniques demonstrate how genetic and environmental responses to elevated CO_2 levels and nursery innovations can optimize seedling quality and forest growth. Mechanized harvesting technologies, such as software-assisted multi-tree handling, improve operational efficiency, while advancements in organosolv and Kraft pulping enhance pulp quality and sustainability. Additionally, deep learning models and X-ray computed tomography are facilitating automated wood quality assessment, offering non-destructive insights into density, moisture, and defect detection. Despite the promise of precision forestry, challenges persist, including high implementation costs, technological integration hurdles, and the need for skilled personnel. Addressing these barriers is crucial for the widespread adoption of precision forestry in sustainable forest management.

***Keywords*:** Free-Air CO_2 Enrichment, Precision forestry, Synthetic Aperture Radar, Terrestrial Laser Scanning and X-ray computed tomography

The growing need for wood production, combined with increasing economic and environmental expectations from forests, necessitates innovative solutions and advanced technologies. Taylor (2002) defines precision forestry as the planning and execution of site-specific forest management activities aimed at improving wood product quality and utilization, reducing waste, increasing profits, and maintaining environmental quality. Ziesak (2006), observed that precision forestry employs advanced sensing and analytical tools to facilitate site-specific, economic, environmental, and sustainable decision-making throughout the forestry value chain—from bare land management to the final consumer purchasing paper or board (Kovacsova and Antalova 2010). The concept of precision farming emerged in the 1990s, recognizing the need to address spatial and temporal variability in crop production through site or soil-specific management practices (Tran and Nguyen 2006). This precision approach was later applied to the forestry sector in the early 2000s in the United States (Becker 2001), where the First International Symposium on Precision Forestry aimed to present advancements in information technologies and analytical tools for supporting site-specific, economic, environmental, and sustainable decision-making (Dyck 2003). Precision forestry integrates information technology and analytical tools to enhance economic, environmental, and sustainable forestry practices (Gallo et al., 2013, Fardusi et al., 2017).

Technological innovation spans multiple disciplines (Lindroos et al., 2017) and, when integrated with sustainable practices, can significantly enhance forestry management (Shah 2020). Smart sensors equipped with predictive analytics can leverage soil and weather data to support conservation and sustainable forest management (Shah 2020). In plant breeding, modern approaches incorporate advanced molecular marker technologies such as gene pyramiding, QTL identification, marker-assisted selection, and transgenic crop development alongside traditional morphology-based selection methods (Panda et al., 2020). Advanced technologies like Remote sensing are important for understanding environmental dynamics and ensuring sustainable management of resources (Wani et al., 2025). Additionally, recent scientific and technological advancements offer new possibilities for improving the efficiency and effectiveness of wildfire management (Zimmerman 2011, Ravivarma et al., 2024). This paper explores the latest developments in precision forestry technologies, with a focus on geospatial information tools that aid in forest management, tree improvement, wood processing, and quality assessment.

Application of Advanced Technologies in Forest Management

Forest inventory: Local forest inventories, traditionally conducted through intensive ground-based sampling, have played a crucial role in strategic planning by offering

managers a detailed understanding of timber composition to support tactical decision-making. Enhanced Forest Inventories (EFIs) aim to improve confidence in forest management decisions while maximizing returns on investment throughout the commodity supply chain (White et al., 2013). By integrating traditional inventory data with advanced Laser Scanning technology, EFIs enhance spatial and temporal accuracy. The resulting three-dimensional (3D) representation of the operating area, from tree canopy to ground level, provides managers with precise, customizable, and highly informative insights into forest operations (Bechtold and Patterson 2005, Goodbody et al., 2017).

Terrestrial laser scanning: Terrestrial Laser Scanning (TLS) has been widely applied in various forestry studies, including tree mapping (Pueschel et al., 2013), callipering (Srinivasan et al., 2015), tree height estimation (Olofsson et al., 2014, Srinivasan et al., 2015), and forest biomass calculation (Greaves et al., 2015). Additionally, TLS has been extensively investigated for estimating canopy structural parameters (Cifuentes et al., 2014, Fardusi et al., 2017). Singhal et al. (2021) compared TLS-based tree-level carbon stock estimation with traditional allometric equations in tropical forests of India. Their study found that TLS-based estimates, with a relative RMSE of 26.01%, were more accurate than those derived from local (42.58%-101.88% RMSE) and global allometric equations (38.8%-50.69% RMSE), highlighting TLS as a reliable and non-destructive method for tree biomass estimation, especially for large trees, while allometric equations remain useful when field-measured parameters are available.

Synthetic aperture radar: Synthetic aperture radar (SAR) is an active remote sensing technology known for its ability to estimate biomass and operate in all-weather conditions (Tsui et al., 2013). Wulder et al. (2012) mentioned that SAR provides complementary datasets for forest biomass estimation (Fardusi et al., 2017). Biomass assessment involves volumetric vegetation analysis, leveraging SAR's unique capability to penetrate tree canopies, an advantage not present in optical remote sensing. The accuracy of SAR-based estimation is influenced by wave polarization and frequency, as longer wavelengths exhibit greater penetration capacity, and cross-polarized waves show higher sensitivity to biomass. These characteristics enable SAR to provide more reliable biomass estimates with reduced uncertainties, as microwaves exhibit less saturation at high biomass levels compared to optical electromagnetic waves (Sinha et al., 2015). Gama et al. (2010) utilized interferometric and polarimetric SAR data to estimate biomass and volume in Eucalyptus plantations. By applying X- and P-band SAR images along with multivariate regression analysis, their study identified strong correlations between interferometric height and tree volume, as well as the canopy scattering index (CSI) for biomass estimation. The models developed demonstrated high accuracy, with prediction errors around 10%, underscoring SAR technology's potential for large-scale forest inventory.

Identification of tree species: The use of UAV-based remote sensing for species identification is increasingly gaining attention within the research community (Sothe et al., 2019). Convolutional Neural Networks (CNNs) have been employed for tree species identification using terrestrial datasets, including RGB images of bark (Carpentier et al., 2018), cross-section surfaces of trees (Hafemann et al., 2014), and terrestrial LiDAR data (Mizoguchi et al., 2017). Research has also explored CNN applications for species classification using airborne sensors such as LiDAR and hyperspectral imaging (Trier et al., 2018). Fricker et al., (2019) applied CNN models to airborne hyperspectral imagery labelled with high-precision field training data to identify individual tree species. Their study also compared classification accuracies between the CNN model applied to full hyperspectral imagery and an RGB pseudo true-color subset. CNNs have demonstrated effectiveness in UAV-based tree segmentation and species mapping, whether for individual species, broad vegetation types, or plant cover analysis. Kattenborn et al., (2019) conducted fine-grained mapping of two vegetation species using a CNN-based segmentation approach, with training data derived from UAV-based high-resolution RGB imagery. Similarly, Lobo Torres et al. (2020) evaluated five deep, fully convolutional networks for semantic segmentation of a single tree species using UAV-captured RGB images. Natesan et al. (2020) investigated the application of Dense Convolutional Networks (DenseNet) for identifying individual tree species from high-resolution UAV-based RGB images. Their model achieved high classification accuracy (over 84%) in distinguishing five predominant coniferous species in eastern Canada, despite variations in seasonal, temporal, and illumination conditions. These findings underscore the potential of UAV-integrated deep learning models in automating forest inventory and management, offering a cost-effective alternative to traditional methods.

Real-time monitoring of insect outbreaks: The introduced insects and pathogens pose a significant threat to the health of forested ecosystems, leading to considerable ecological and economic consequences (Lovett et al., 2016). However, identifying changes in forest conditions linked to insect pests over large areas remains a persistent challenge (Senf et al., 2017). The Landsat satellite family is widely used in forest insect disturbance studies due to its moderate spatial

resolution and extensive archive of imagery (Senf et al., 2017). The modern Landsat series captures spectral data in visible, near-infrared, and shortwave infrared bands at a 30 m × 30 m pixel resolution, with image acquisitions occurring at least every 16 days. However, because defoliation events are often short-lived, cloud cover remains a significant challenge in leveraging Landsat imagery for operational forest health monitoring (Rullan-Silva et al., 2013, Townsend et al., 2012, Pasquarella et al., 2017). Falanga et al. (2024) introduced a novel method for detecting insect outbreaks in urban trees using high-resolution Planet Scope satellite imagery. By combining remote sensing with field surveys, the study effectively identifies infestations of *Toumeyella parvicornis* in *Pinus pinea* trees across Rome. The research highlights the Renormalized Difference Vegetation Index (RDVI) as a highly accurate indicator of pest damage, achieving an accuracy rate exceeding 99%, underscoring the potential of satellite-based monitoring for proactive pest management and urban forest conservation.

Application of Advanced Technologies in Tree Improvement

Free-Air CO_2 Enrichment (FACE) experiments: The atmospheric CO_2 concentration remained stable at approximately 270 µmol mol^{-1} for at least 1,000 years before the onset of the Industrial Revolution. Since then, CO_2 levels have been rising at an accelerating rate. As a result, both natural and managed ecosystems are now exposed to elevated CO_2 concentrations that terrestrial vegetation has not encountered since the early Miocene (Pearson and Palmer 2000), leading to uncertain future consequences. With advancements in scientific understanding and the identification of underlying mechanisms, the necessity of testing hypotheses under realistic open-air conditions became evident. This led to the development of Free Air Carbon dioxide Enrichment (FACE) technology (Hendrey and Miglietta 2006).

A similar experiment at Aspen FACE, involving North American plantation species such as aspen (*Populus tremuloides*) and birch (*Betula papyrifera*), also demonstrated a lack of photosynthetic acclimation in the initial years. Instead, maximal stimulation was observed (Karnosky et al., 2003, Leakey et al., 2009). Downregulation of photosynthetic capacity in trees in response to Free-Air CO2 Enrichment (FACE) exhibits considerable variability. A significant portion of the data for trees included in this meta-analysis originates from the Duke FACE experiment, which investigated both loblolly pine and understory hardwood species (Rogers and Ellsworth 2002). Findings from the Rhinelander experiment indicate that while elevated CO2 levels enhance leaf area index (LAI) in *Populus tremuloides*, ozone stress diminishes LAI. Consequently, when both CO2 and O3 levels are elevated, there is no net change in LAI (Karnosky et al., 2003, Ainsworth and Long 2005).

Mini-plug technique: The use of low-quality planting stock is often a key factor in reforestation failure (Radoglou and Raftoyannis 2001). Seedling quality, defined by its morphological and physiological characteristics, is the only aspect that can be directly controlled to enhance survival rates after out planting (Kostopoulou et al., 2011). Nursery practices play a crucial role in root development during the nursery phase, which can have lasting effects on seedling establishment (Costa et al., 2004). Among these practices, container type significantly influences both seedling production costs and overall seedling quality (Chirino et al., 2008). A promising innovation in nursery stock production is the use of mini-plugs, where seedlings undergo a short pre-cultivation period under near-optimal environmental conditions (Radoglou et al., 2011). Mini-plug containers, typically smaller than 33 cm^3, enable a shorter production cycle compared to standard container-grown seedlings. This approach allows for the development of high-quality seedlings with well-formed fibrous root systems within a single growing season (Kostopoulou et al., 2011).

Kostopoulou et al. (2011) examined the growth of *Picea abies*, *Robinia pseudoacacia*, *Pinus brutia*, and *Pinus nigra* in mini-plug containers of two different depths (37 mm and 60 mm) over a five-week period. Their findings indicated that *P. nigra* and *R. pseudoacacia* benefited from deeper containers, whereas *P. abies* exhibited better growth in shallower ones. Similarly, Kostopoulou et al., (2010) reported that mini-plug transplants outperformed traditional nursery stock, producing seedlings with superior root development, higher quality, and improved field survival. Factors such as seed origin, mini-plug density, and substrate type were found to significantly influence seedling growth. Additionally, pre-cultivation in mini-plugs for five weeks under controlled conditions enhanced seedling survival and transplant success.

Application of advanced technologies in wood processing pulping: Despite advancements in information and communication technology, paper production remains a key indicator of industrialization and educational development worldwide. Pulp and paper production capacity continues to grow (Sridach 2010). Consequently, research and development efforts have focused on minimizing the environmental impact of pulp and paper production through various strategies. These include adopting alternative raw materials, optimizing pulping chemicals, and adjusting pulping conditions such as time, temperature, and pressure, as well as reducing energy consumption.

The organosolv pulping process has gained attention due to its ability to produce high-yield pulp with low residual lignin content, high brightness, and good strength (Yawalata and Pasnez 2004). The advancements in organosolv pulping have led to the development of methods capable of producing pulp with properties comparable to kraft pulp (Sridach 2010). Non-wood fibers are widely used for various paper types, including writing, printing, and packaging papers. Additionally, advances in micro and nanotechnology offer significant benefits to pulp and paper manufacturers, helping the industry achieve its future goals.

Cellulose and lignocellulose have great potential as nanomaterials due to their abundant renewability, non-fibrillar structure, and ability to self-assemble into well-defined architectures while being multifunctional (Mohieldin et al., 2011, Ogunwusi and Ibrahim 2014). Pulping involves chemical, mechanical, and biological methods to break the bonds in woody materials and separate cellulose fibers from lignin (Wang et al., 2014). Improvements in pulping processes have been achieved through lignin genetic modifications, diversification of pulp-based products, the development of extended impregnation and pre-hydrolysis techniques to enhance the Kraft pulping process, and modifications in chemical pulps for nanocellulose production. These modifications improve fibre characteristics, including fiber size, crystallinity, chemical composition, and fibre surface functionality (Jiménez et al., 2008, Rojo et al., 2015, Mboowa 2024). Dissolving pulp production involves pre-hydrolysing wood chips before subjecting them to the standard Kraft and sulphite pulping processes (WangQ et al., 2014, Mboowan 2024). Wei et al. (2020) studied the liquid hot water (LHW) pre-hydrolysis method, using the Combined Severity Factor (CSF) to quantify treatment severity.

Wood quality assessment: Wood defects, including knots, cracks, and discolorations, present a significant challenge for industries that rely on high-quality wood products. The lack of an efficient, automated detection system leads to increased production costs, potential quality issues, and delays. To address these challenges, this study proposes the development of a deep learning model capable of accurately identifying various defect patterns in images of wood surfaces. Recent advancements in deep learning

Table 1. Technological innovations in forest science

Technology	Purpose	Methodology	Conclusion	Reference
Terrestrial Laser Scanning	Carbon stock estimation	12 trees were scanned from at least 4 positions and at most 8 positions	26.01% more accurate than local equations	Singhal et al. (2021)
Synthetic Aperture Radar (SAR)	Biomass and volume estimation	Variables such as interferometric height (Hint), Canopy Scattering Index (CSI), and radar backscatter polarizations (e.g., VV and HH) were analyzed	Models showed a prediction error of around 10% to estimate the biomass and volume.	Gama et al. (2010)
Dense Convolutional Network (DenseNet)	Tree species identification	CNN and DenseNet	84% accuracy	Natesan et al. (2020)
Renormalized Difference Vegetation Index (RDVI)	Real-Time monitoring of Insect Outbreaks	satellite images (PlanetScope) and RDVI Index	99% accuracy	Falanga et al. (2024)
Free-Air CO2 Enrichment (FACE) experiments	To assess effects of elevated CO_2 concentrations	elevated CO_2 treatment (e− CO_2 -550 ppm) and ambient CO_2 (a− CO_2;- 395 ppm)	Elevated CO_2 significantly increased C/N litter biomass flux of N, SS, SP and lipid in to the soil, cellulose, hemicellulose and lignin inputs to soils	Rai et al. 2020).
Mini-plug technique	To improve quality of planting stock	mini-plug containers of two different depths (37 mm and 60 mm) over a five-week period.	*P. nigra* and *R. pseudoacacia* benefited from deeper containers	Kostopoulou et al. (2011)
Multi−tree cut−to−length harvesting	Harvesting	software-based, multi-tree handling (MTH) is used for harvesting	10% higher productivity in comparison with a traditional one	Magagnotti et al. (2020)
Pre hydrolysis Kraft Pulping	Pulping	Reactor was filled with 250 g wood chips and 1.5 L deionized water. The reactions were conducted at a temperature between 100 °C to 200 °C (at 20 °C increments) for 60 min using a stirring speed of 150 rpm and Air-dried hydrolysis wood chips (100 g) were cooked at 165 °C for 90 min	α-cellulose of 92.3%, degree of polymerization (DP) of 1081, brightness of 85.1% ISO, and Kappa number of 0.61.	Wei et al. 2020
X-ray computed tomography (CT)	Wood quality assessment	X-Ray Computed Tomography Technique to determine the Density and Moisture content	R2 , of the models were all higher than 0.97	Wang et al. 2024

frameworks, such as DenseNet (Densely Connected Convolutional Networks), offer a promising solution for automating wood defect detection. DenseNet, a Convolutional Neural Network (CNN) architecture, is particularly effective due to its dense connectivity pattern, which enhances feature reuse and propagation across network layers (Dhanamathi et al., 2024).

Computed tomography (CT) techniques provide a non-destructive and non-invasive means of measuring internal properties of wood specimens (Wang et al., 2020). Wang et al. (2020) specifically utilized X-ray Computed Tomography to determine the density and moisture content of poplar (*Populus xiangchengensis*) and bamboo (*Phyllostachys edulis*). Their findings revealed statistically significant differences in CT-measured values for D and MC between these species. The study established independent D-CT and MC-CT linear models for both species:

Poplar: D = 0.00098 × H + 1.02603, MC = 0.00309 × H + 1.89982

Bamboo: D = 0.00118 × H + 0.98684, MC = 0.00131 × H + 0.31488

where H represents the CT number. The determination coefficients (R^2) for all models exceeded 0.97, demonstrating the feasibility of using X-ray CT technology for accurately determining the density and moisture content of wood and bamboo. Ji et al., (2021) further explored how CT scanning can assess wood quality and predict tree value by analysing knot characteristics in amabilis fir and western hemlock. Their study linked knot features to stand density and sawmilling efficiency, revealing that tree diameter significantly influences knot properties and lumber yield. Additionally, stand density was found to have a greater impact on western hemlock than on amabilis fir. The predictive models developed in this research contribute to preharvest stand valuation and enhanced forest management strategies.

CONCLUSION

The evolution of precision forestry signifies a transformative shift in forest science, integrating cutting-edge technologies to enhance the efficiency, accuracy, and sustainability of forest management. From terrestrial laser scanning and synthetic aperture radar to UAV-based deep learning and X-ray computed tomography, the array of tools now available has revolutionized traditional approaches to inventory, monitoring, tree improvement, harvesting, and wood processing. Advanced techniques like Free-Air CO_2 Enrichment (FACE) and mini-plug cultivation support sustainable silviculture, while sustainable harvesting systems and nanotechnology-driven pulping processes align with modern industrial demands. Despite promising results across diverse applications, the full-scale adoption of precision forestry is hindered by high costs, technical complexities, and a shortage of skilled personnel. Overcoming these challenges will require strategic investment in education, training, and institutional capacity building.

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Volatile Phytochemicals of *Sterculia foetida* Leaf Detected through GC-MS and their Associated Biological Properties Divulged through Meta-analysis

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Abstract: *Sterculia foetida* is commonly called as wild Indian almond belonging to the family Malvaceae. In present study analysed leaf samples from 8 different sources from south Gujarat region to detect the volatile phytochemicals through in nontargeted gas-chromatography mass-spectrometry (GC-MS). In total, 38 volatile phytochemical compounds were detected in *S. foetida* leaves. Based on the relative area percentage, Lupeol, Squalene, dl-α-Tocopherol, ß-Amyrin and D-Friedoolean-14-en-3-ol were top 5 having respective area percentage of 17.16, 11.39, 11.35, 10.12 and 8.11. These were followed by another important ones namely Phytol, Sitosterol, Neophytadiene, 24-Noroleana-3,12-diene and Stigmasterol. Furthermore, compounds like ß-Tocopherol, Campesterol, γ-Tocopherol, and d-Tocopherol with important biological activities were also detected. The meta-analysis for corroboration of biological activities revealed that most represented biological properties were antioxidant, antibacterial, anti-inflammatory, and anti-microbial by 14, 9, 8 and 6 compounds. Furthermore, although represented by a smaller number of compounds, were anti-diabetic, antifungal (4 compounds each), analgesic, antidepressant (3 compounds), anti-allergic, anti-pyretic, anti-ulcer (2 compounds), anti-cancer, anti-tumour, antispasmodic, anti-aging, anti-HIV-1 and other various biological properties (1 compound each). Thus, *S. foetida* leaf is a store house of array of important chemical compounds and their derivatives with important biological activities.

Keywords: *Sterculia foetida*, GC-MS, Volatile phytochemical, Biological activity

Plants have been used as source of food and medicine since ancient time. Plants are rich source of bioactive compound. Plant bioactive substances are currently the focus of a lot of research. Numerous phytochemicals, usually referred to as secondary metabolites, are found in plants. Due to their individual, additive, or synergistic effects on health, phytochemicals are helpful in the treatment of some illnesses (Jana et al., 2023). *Sterculia foetida* L is a large, straight, deciduous tree (Orwa et al., 2009) and found from Eastern tropical Africa to North Australia, through Malaysia, Burma, Bangladesh, India, Sri Lanka and Malaccas. It has been reported from West Bengal, Bihar, Orrisa, Andhra Pradesh, Maharashtra, Tamil Nadu and Kerala in India (Sharma and Sanjappa 1993, Mujumdar et al., 2000). The fruits, seeds and leaves of *S. foetida* have been conventionally known for its many therapeutic purpose (Jafri et al., 2019). Its seeds are roasted and eaten like chestnuts. Gray coloured wood is used in making rough packing cases. Gum is used in the medicine. The bark yields fibre. The leaves of this plant are used as herbal medicine as aperient and diuretic (Chopra et al., 1992, Mujumdar et al., 2000). A gum that resembles 'gum tragacanth' is obtained from the trunk and branches and is used for bookbinding and similar purposes. *S. foetida* leaves contain up to 2.66% calcium and are also a good source of protein and phosphorus, meeting nutritional requirements of ruminants (Orwa et al., 2009). Seeds and bark of *S. foetida* possess a vast array of biologically active compounds which are chemically diverse and structurally complex (Amuthavalli and Ramesh 2021, Alam et al., 2021, Jana et al., 2023). The medicinal plants are widely used in traditional medicine to prevent and treat various diseases. The phytoconstituents present in the various part of the plant can be exhibit anti-cancer, anti-tumour, anti-diabetic, antispasmodic, anti-inflammatory, anti-oxidant and antibacterial activities (Nanadagopalan et al., 2015). The study was conducted to unveil the various phytochemicals of *S. foetida* from south Gujarat region.

MATERIAL AND METHODS

The leaf samples of *S. foetida* were collected from distantly located eight different locations in winter and summer from south Gujarat. The samples of winter and summer were pooled and 2 samples were drawn from each season and phytochemicals were detected through GC-MS partly following Murugesan et al. (2013) and Sukhadiya et al. (2021) as under:

One gm of the powdered sample was extracted using Hexene: Acetone (1:1) solvent in centrifuge tube and after 72 hrs of incubation the homogenate centrifuged for 20 min. at 3500 rpm and supernatant was collected. Pinch of activated charcoal was added to treat chlorophyll content. 2 ml of supernatant was collected in pre cleaned glass test tube and

evaporated using cold nitrogen air drier. After drying 2 ml ACN solution was added to test tube, vortex for 2-3 min and sonicate for 2 min. The content was then filtered using injection and disk filter in to 2 ml glass sampling vile. Reading was taken in GC-MS (Thermo make trace GC ultra – ITQ 900). The GC-MS analysis was carried out on Thermo make Trace GC-ULTRA-ITQ 900 with fused silica capillary column (Rx-1-5MS) of 30 m length, 0.25 internal diameter and 0.25 µm film thickness. The injection volume was 1µl and the total run time of the sample was 33.00 minutes.

RESULTS AND DISCUSSION

Non-targeted gas-chromatography mass-spectrometry (GC-MS) analysis of *S. foetida* leaves from different locations of south Gujarat region revealed array of total 38 volatile phytochemical compounds (Fig. 1). Amongst 38 compounds, lupeol, squalene, dl-α-Tocopherol, ß-Amyrin and D-Friedoolean-14-en-3-ol were top 5 with respective area percentage of 17.16, 11.39, 11.35, 10.12 and 8.11. These were followed by another important ones namely phytol, sitosterol, neophytadiene, 24-Noroleana-3, 12-diene and stigmasterol. Furthermore, compounds like ß-Tocopherol, Campesterol, γ-Tocopherol, and d-Tocopherol were also detected in *S. foetida* leaf in this study. Jana et al. (2023) reported 34 phytoconstituents through GC-MS from methanol extract of *Sterculia foetida* (bark). Amuthavalli and Ramesh (2021) reported 13 bioactive compounds were identified through GC-MS analysis of seed powder of *S. foetida.* Alam et al. (2021) identified 29 compounds through GC-MS analysis from methanolic extract of *S. foetida* seeds. Siswadi and Saragih (2021) identified fifteen compounds from stem bark, twenty-one compounds from leaves and fourteen compounds from seeds of *Sterculia quadrifida.* The *S. foetida* volatile phytochemicals identified in the study have been corroborated with available literature. It is found that many of the compounds detected in *S. foetida*, in present study are reported in other plant species and have one or the other beneficial biological properties/activities (Table 1). The diversity of these phytochemicals underscores their potential for therapeutic, nutraceutical and agro-industrial applications, as corroborated by their reported biological activities in other plant species. Further meta-analysis done from the corroboration of biological properties (Fig. 2a & b) revealed that as highest number of phytochemical

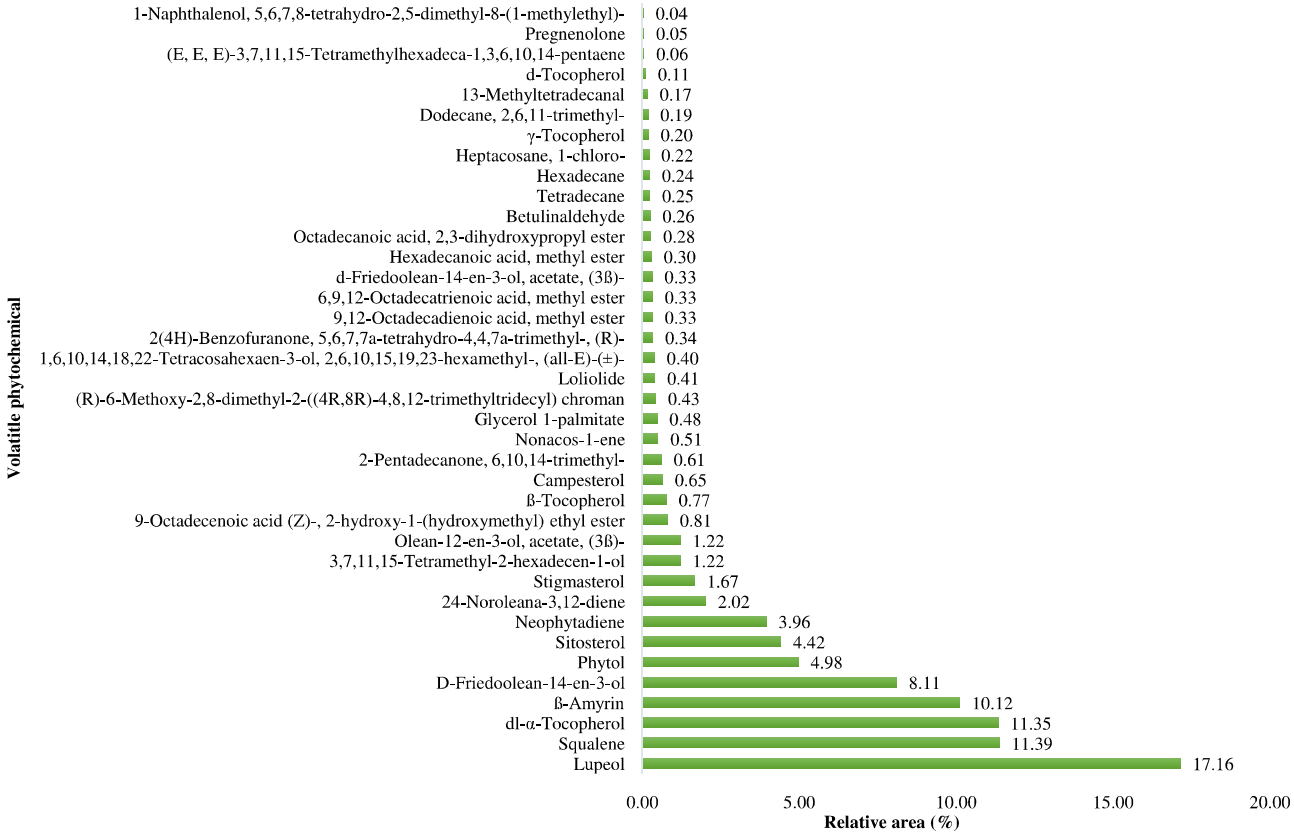

Fig. 1. Phytochemicals compounds and their relative percentage in *S. foetida* leaf detected through nontargeted gas-chromatography mass-spectrometry (GC-MS)

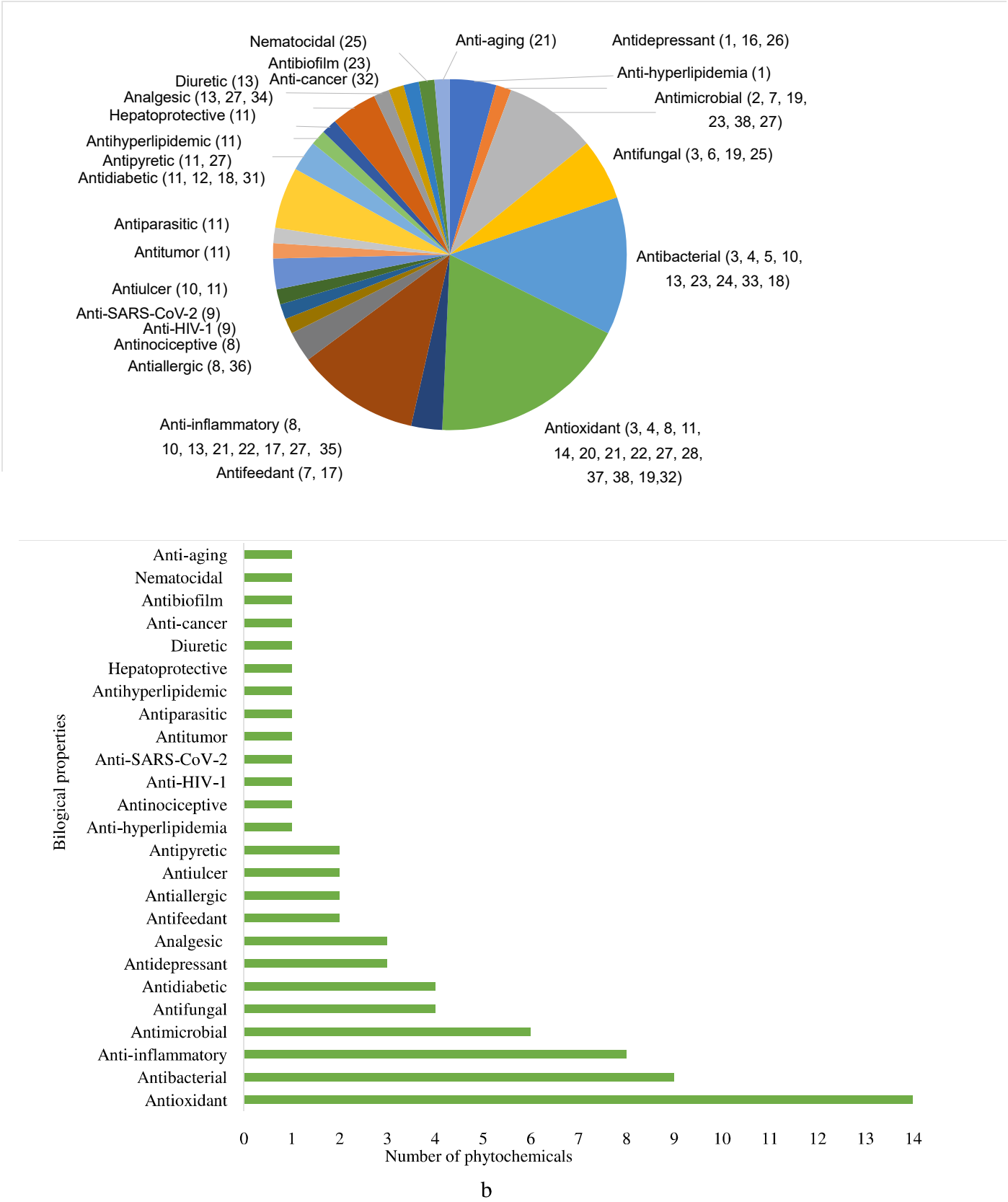

Fig. 2. a) biological activities and phytochemicals associated (for compound name, refer Sl. No., column 1, Table 1) and b) number of compounds exhibiting particular biological activity

Table 1. Phytochemicals compounds of *S. foetida* leaf detected in present study and their corroboration for biological activities with available literature

Compound	Chemical nature/class and biological activity	Reports in other species	Reference
Dodecane, 2,6,11-trimethyl-	Branched alkane; antidepressant and anti-hyperlipidemia	*Taxus chinensis var. mairei*	Wei and Yin (2019)
2(4H)-Benzofuranone, 5,6,7,7a-tetrahydro-4,4,7a-trimethyl-, (R)-	A cyclic ester; antimicrobial activity, flavor and fragrance agents	*Premna paucinervis, Alstonia scholaris*	Francis et al. (2021) Swamy et al. (2019)
Hexadecane	Alkane hydrocarbon; plant epicuticular wax, antifungal, antibacterial and antioxidant	*Tapinanthus bangwensis*	Atewolara-Odule and Oladosu (2016)
13-Methyltetradecanal	Fatty aldehyde; antioxidant and antibacterial	*Celtis australis*	Badoni et al. (2010)
2-Pentadecanone, 6,10,14-trimethyl-	Methyl ketone; antibacterial activity against gram $^{+ve}$ and gram^{-ve} bacteria	*Funtumia africana*	Amos-Tautua et al. (2020)
Hexadecanoic acid, methyl ester	Fatty acid ester; antifungal agent	*Annona muricata* Linn.	Abubacker and Deepalakshmi (2013)
9,12-Octadecadienoic acid, methyl ester	Antifeedant and antimicrobial	*Azadiachta indica*	Khanday and Sharma (2021)
6,9,12-Octadecatrienoic acid, methyl ester	γ-Linolenic acid ester; antinociceptive, antioxidant activities, anti-inflammatory and antiallergic	*Livistona australis*	El-Hawary et al. (2022)
Glycerol 1-palmitate	Monoglyceride; anti-HIV-1 and anti-SARS-CoV-2	*Jatropha curcas*	De Sousa Ferrão and Janeque (2023)
Heptacosane, 1-chloro-	Chlorinated alkane; anti-inflammatory, antibacterial and antiulcergenic	*Syzygium cumini*	Kumar et al. (2009)
Octadecanoic acid, 2,3-dihydroxypropyl ester	Glyceryl monostearate; antioxidant, antitumour, anti-inflammatory, antiparasitic, antiulcer, antimicrobial, antidiabetic, antipyretic, antihyperlipidemic and hepatoprotective	*Manilkara bidentata*	Powder-George and Mohammed (2018)
9-Octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl) ethyl ester	Glyceryl monooleate; antidiabetic	*Nauclea latifolia*	Mgbeje and Abu (2020)
(R)-6-Methoxy-2,8-dimethyl-2-((4R,8R)-4,8,12-trimethyltridecyl) chroman	Tocotrienol isomer; antibacterial, anti-inflammatory, analgesic, diuretic	*Rhus coriaria*	Hamad et al. (2024)
Nonacos-1-ene	Alkene Hydrocarbon; antioxidant	*Anthocleista Djalonensis*	Ogunboyeo et al. (2022)
Campesterol	Phytosterol, associated with cholesterol lowering and cancer prevention	*Strychnos innocua*	Uttu et al. (2023)
Stigmasterol	Phytosterol; antidepressant	*Aegle marmelos*	Ghosh et al. (2022)
1-Naphthalenol, 5,6,7,8-tetrahydro-2,5-dimethyl-8-(1-methylethyl)-	Sesquiterpenoid; antifeedant, anti-inflammatory and antioxidant	*Ardisia solanacea Roxb.*	Anjum et al. (2019)
Pregnenolone	Steroid precursor; antidiabetic and antibacterial	*Lansium parasiticum*	Mutiah et al. (2024)
(E, E, E)-3,7,11,15-Tetramethylhexadeca-1,3,6,10,14-pentaene	Polyene; antimicrobial, antifungal and antioxidant	*Paulownia fortunei, Cosmostigma cordatum*	Ferdosi et al. (2021), Das et al. (2022)
d-Tocopherol	Vitamin E isomer; antioxidant	*Ficus carica*	Konyalıoglu et al. (2005)
ß-Tocopherol	Vitamin E isomer; antibacterial, anti-inflammatory, skin tightening and anti-aging, therapeutic agents against SARS-CoV-2	*Plukenetia volubilis L, Moringa oleifera*	Wang et al. (2018) Siddiqui et al. (2022)
γ-Tocopherol	Vitamin E isomer; anti-inflammatory and antioxidants	*Moringa oleifera*	Sanchez-Machado et al. (2006)
24-Noroleana-3,12-diene	Triterpenoid; antibacterial, antibiofilm and antimicrobial	*Swietenia macrophylla, Boswellia carterii*	Man et al. (2022), Damour et al. (2025)
Betulinaldehyde	Triterpenoid; antibacterial	*Zizyphus rugosa*	Shoeb et al. (2005)
Tetradecane	Antimicrobial, antifungal and nematocidal	*Mangifera indica*	Velumani and Selvi (2019)
Loliolide	Antidepressant,	*Mondia whitei*	Neergaard et al. (2010)

Cont...

Table 1. Phytochemicals compounds of *S. foetida* leaf detected in present study and their corroboration for biological activities with available literature

Compound	Chemical nature/class and biological activity	Reports in other species	Reference
Neophytadiene	Sesquiterpenoids; anti-inflammatory agent, a plant metabolite and an algal metabolite. analgesic, antipyretic, antimicrobial, and antioxidant	*A. pannosum, G. tenax, Plectranthus amboinicus, Eupatorium odoratum, M. dubia*	Aadesariya et al. (2017), Swamy et al. (2017), Raman et al. (2012), Malek et al. (2023)
3,7,11,15-Tetramethyl-2-hexadecen-1-ol	Acyclic diterpene alcohol; antioxidant and antibacterial	*Moringa oleifera*	Suganandam et al. (2022)
Phytol	A constituent of chlorophyll, after fermentation converted to phytanic acid and stored in fats.	*M. dubia, G. pubescens Aegle marmelos*	Murugesan et al. (2013), Hamid et al. (2016) Hossain et al. (2013), Malek et al. (2023)
Squalene	(Triterpene) Monoxygenases inhibitor, antioxidant, antibacterial, cancer preventive, immune−stimulant and anti−tumour	*Strobilanthes glutinosus, Senna tora, M. dubia*	Aziz et al. (2022), Duke (1992), Beulah et al. (2018), Kabila et al. (2022), Malek et al. (2023)
1,6,10,14,18,22-Tetracosahexaen-3-ol, 2,6,10,15,19,23-hexamethyl-, (all-E)-(±)-	Polyisoprenoid alcohol; antidiabetics	*Cordia myxa L., Syzygium cumini, Syzygium malaccense, and Antidesma bunius*	Zubair et al. (2025)
dl-α-Tocopherol	Vitamin E analog; anti-cancer, Antioxidant	*Sarcopoterium spinosum L., M. dubia, Prunus armeniaca, P. persica, P. domestica, Malus domestica*	Bozkurt Sarikaya and Kayalar (2014), Malek et al. (2023), Wojdyto et al. (2022)
Sitosterol	Phytosterol; antibacterial	*Odontonema strictum*	Luhata and Usuki (2021)
D-Friedoolean-14-en-3-ol	Pentacyclic triterpenoid; analgesic	*Osyris lanceolata*	Yeboah and Majinda (2013)
Lupeol	Triterpenoid; anti-inflammatory	*Quercus obtusata*	Sánchez-Burgos (2015)
ß-Amyrin	Triterpenoid; anti-allergic	*Anchientia salutaris var. martiana*	Di Stasi et al. (1999)
d-Friedoolean-14-en-3-ol, acetate, (3ß)-	Acetylated triterpenoid; antioxidant	*Clitoria ternatea*	Nurcholis et al. (2023)
Olean-12-en-3-ol, acetate, (3ß)-	β-Amyrin acetate; anti-microbial and antioxidant	*Ficus religiosa L., Ficus semicordata Buch.- Ham. ex Sm.*	Babu et al. (2023)

compounds are associated with antioxidant property of 14 compounds (Fig. 2a & b). This was followed by antibacterial activity and anti- by 9 and 8 compounds. Antimicrobial activity associated with 6 compounds, whereas antidiabetic and antifungal activities linked to 4 compounds

Antidepressant (1, 16, 26) and analgesic (13, 27, 34) activities were associated with 3 compounds each. Antipyretic (11, 27), antifeedant (7, 17), antiulcer (10, 11) and antiallergic (8, 36) activities involved 2 compounds. Additionally, antinociceptive (8), anti-aging (21), anti-cancer (32), antihyperlipidemic (11), hepatoprotective (11), antitumor (11), antiparasitic (11), diuretic (13), anti-HIV-1 (9), anti-SARS-CoV-2 (9), antibiofilm (23), nematocidal (25) and anti-hyperlipidemia (1) is ascribed to one compound (Fig. 2a & b). Further, meta-analysis pinned out that detected 38 chemical compounds detected in *S. foetida* leaf exhibit 26 different types of biologically beneficial properties (Fig. 2b) which have also been reported from plant species.

CONCLUSION

Total 38 of biologically active compound were reported from *S. foetida* leaves collected from various locations from South Gujarat. The non-volatile compounds findings through GCMS analysis inferred that *S. foetida* leaves has beneficial biological active phytochemicals which may be beneficial to human and animals. Meta-analysis revealed that as many as 26 different types of biologically beneficial properties are exhibited by these detected compounds. Out these14 antioxidant, 9 antibacterial, 8 inflammatory, 6 antimicrobial and 3 each exhibit antidiabetic and antifungal properties, apart from important ones like anti-cancer, anti-HIV-1, anti-SARS-CoV-2, antitumor activities *etc.*, though possessed by a smaller number of compounds. Thus, *S. foetida* leaf is a store house of array of chemical compounds and their derivatives with important biological activities which need to be isolated for further improvement.

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AUTHOR'S CONTRIBUTION

M.L. Sukhadiya: sample collection, laboratory analysis, data arrangement and manuscript draft preparation; N. S. Thakur: research conceptualization, sample collection, data interpretation, table and figure construction, reviewing and editing manuscript; Susheel Singh: GC-MS sample analysis and identification of phytochemicals; R.P. Gunaga: research conceptualization, data interpretation, sampling and statistical procedures; S.K. Sinha: laboratory work and data tabulation; V.R. Patel: interpretation of data, laboratory analysis, methodological inputs.

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Bioethanol Content Estimation in *Lantana camara* at different Altitudinal Gradients in Mussoorie Forest Division, Uttarakhand

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***Abstract*:** The study investigated ethanol yield from different parts of *Lantana camara* at two distinct altitudes: 560 m and 1550 m. The plant parts analyzed include leaves, stems, and a combination of leaves and stems. Ethanol content revealed significant variations based on altitude and plant part. Leaves at 560 m produced a significantly higher ethanol yield (7.5 ml/l) compared to leaves at 1550 m (5.1 ml/l), due to more favorable photosynthesis conditions and higher fermentable sugar accumulation at lower altitudes indicating higher carbohydrate content in leaves at lower altitudes. Conversely, stems showed no significant difference in ethanol yield between the two altitudes (2.7 ml/l and 2.6 ml/l at 560 m and 1550 m, respectively), suggesting that stem metabolic processes and carbohydrate content are less affected by altitude. The combined leaves and stems demonstrated a significant difference, with higher ethanol yields at 560 m (3.2 ml/l) compared to 1550 m (2.9 ml/l), underscoring the altitude sensitivity of leaves in contributing to overall ethanol yield.

***Keywords*:** Ethanol contents, Altitude, *Lantana camara*, Bioethanol

The growing worldwide energy demand, fueled by increasing urbanization, industrialization, and population expansion, has driven home the importance of sustainable and environmentally acceptable energy solutions. Traditional fossil fuels, which have been the main source of energy for many years, are limited and have a major impact on climate change and environmental damage. Finding less polluting and renewable energy sources is imperative in light of this urgent problem (Hahn-Hagerdal et al., 2006). Because it is renewable and has a lower carbon footprint than fossil fuels, bioethanol, a form of biofuel, has become viable option among others (Nigam and Singh 2011). Microorganisms ferment carbohydrates to generate bioethanol, which may be made from various biomass feedstocks such as forestry and agricultural waste, as well as energy crops. A vast range of plant materials, from non-food sources like lignocellulosic biomass to food crops like maize and sugarcane, have been investigated in the hunt for appropriate biomass feedstocks. Lignocellulosic biomass, which includes woody plants, grasses, and leftover materials from agriculture and forestry, is particularly attractive because it is readily available and has little impact on food security (Mohan et al., 2006).

Lantana camara, a floral plant species that is frequently referred to as wild sage or lantana, is commonly found in the family of verbenas (Verbenaceae). It is well known for its capacity to thrive in various environments, from arid and degraded soils to tropical rainforests, and for its adaptation to different climatic circumstances and land uses (Sharma et al., 2005, Thakur et al., 2005, 2011). The plant is distinguished by its clusters of tiny, vibrant blooms, ovate leaves, and sturdy, woody branches. *Lantana camara* is frequently found in dense thickets and can reach a height of two meters (Thakur et al., 2017). However, because it frequently displaces native ecosystems and lowers biodiversity, its invasive nature presents ecological concerns (Sundram et al., 2012). *Lantana camara* is regarded as one of the worst invasive plants in the world due to its relentless expansion. It is a powerful invader in many areas because it can flourish in various climates, from the wet tropics to dry settings.

Lantana camara, has caught attention as a potential source for bioethanol because it produces a lot of biomass and can spread quickly (Sharma et al., 2005, Thakur et al., 2007). Although *L. camara* is known for being an invasive plant, it has a significant amount of potential for producing bioethanol. Due to its high lignocellulosic content, researchers can use it as a feedstock for fermentation and enzymatic hydrolysis to produce bioethanol (Kumar et al., 2009, Kumar et al., 2016). Furthermore, using this invasive plant to produce biofuel might both provide a sustainable energy source and lessen its detrimental effects on the ecosystem.

The three primary constituents of lignocellulosic biomass are cellulose, hemicellulose, and lignin. Microorganisms may hydrolyze polysaccharides like cellulose and hemicellulose to produce fermentable sugars, which are then transformed into bioethanol (Hamelinck et al., 2005, Kim and Lee 2007). Conversely, lignin is a complex aromatic polymer that gives plant cell walls structural support, but because of its resistance, it presents a problem for biomass conversion (Sun and Cheng 2002).

The physiology, biomass composition, and growth of plants are all significantly impacted by altitude. Temperature, humidity, solar radiation, and soil composition all change with altitude, and these variations impact the biochemical characteristics of plants (Körner 2007). These environmental gradients may impact plants' suitability for producing bioethanol, leading to notable changes in their lignocellulosic composition. Research has shown that altitude influences the amount of structural carbohydrates needed to make bioethanol, such as cellulose and hemicellulose. To maximize bioethanol production, one must understand how altitude affects *L. camara* biomass composition. To clarify that how altitude affects the biomass composition and bioethanol output of *L. camara*, this study examines the bioethanol potential of the plant taken from two distinct elevations. Considering the information presented above, the current study is being carried out to evaluate the amount of bioethanol that may be obtained by the treatment of lignocellulosic biomass with acid hydrolysis and fermentation.

MATERIAL AND METHODS

Plant biomass collection: The current study was carried out at the research facility of Department of Forestry, Dolphin (PG) Institute of Biomedical and Natural Sciences, Manduwala. The fresh plants were collected from two distinct altitudinal locations that were separated by a vertical distance of 1000 m. The first sample was taken at an elevation of 560 m from Manduwala, Uttarakhand, while the second sample was taken at an elevation of 1550 m from Kolukhet area, Mussoorie Road, Uttarakhand.

Study area: This study covered the two altitudinal transects namely Manduwala (30.3880^0 N, 77.94110^0 E) and Kolukhet (30.4152^0 N, 78.0809^0 E) forest area situated in Mussoorie Forest division, Dehradun Valley of Uttarakhand.

Sample processing: The stems, foliage, and flowers were separated subsequent to their collection. After being cut into 2–3 cm pieces, the stems were left to dry in the sun for three to four days until sufficient dryness for grinding was attained. The biomass from the stems and leaves was crushed separately with a leaf grinder, and a fine powder was produced and sieved. The powdery leaf and stem biomass was quantified individually at 20 g, and composite samples of

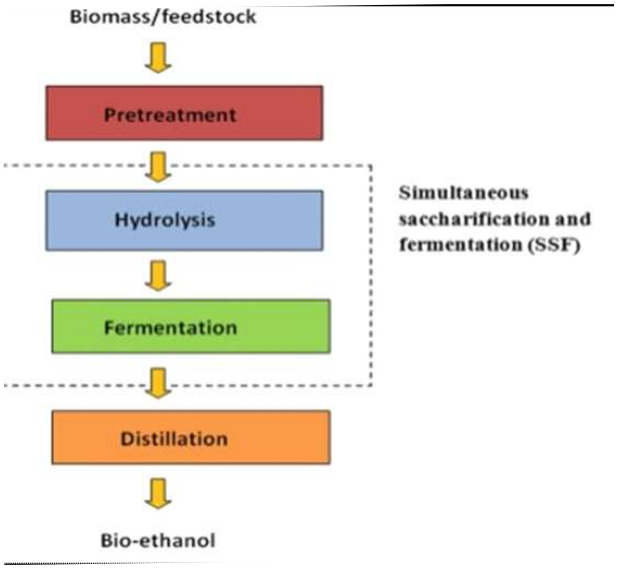

Fig. 2. Flowchart of Ethanol processing

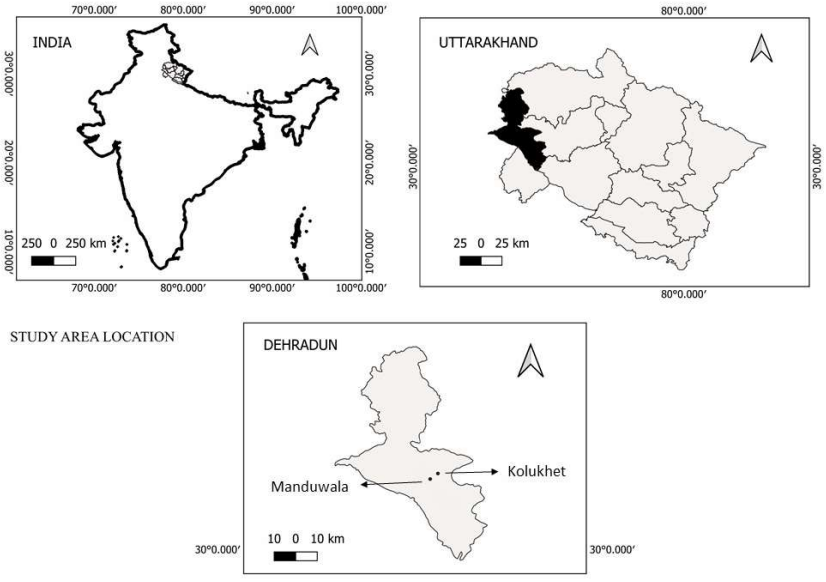

Fig. 1. Location map of study area

10 g each were prepared. These powdered samples were placed in 500 ml conical flasks. A 3% solution of 98% sulfuric acid was then added to each flask. After incubation for 30 minutes, the samples were autoclaved for 20 minutes at 121 °C and 15 PSI. Following autoclaving, the pH of the samples was neutralized with a sodium hydroxide solution (Braide et al., 2016).

Preparation of culture medium for saccharomyces cerevisiae: A total of 20 ml of distilled water was used for dissolving 10 g of nutritional broth in 60 ml of water. The mixture was then autoclaved for 20 minutes at 15 PSI and 121°C. To avoid contamination, saccharomyces cerevisiae was injected under laminar air flow. The injected samples were incubated for 24 hours to facilitate fungal growth. After this period, 20 ml of the fungal culture were added to each biomass sample under laminar air flow.

Ethanol determination: The amount of ethanol present was measured using the potassium dichromate technique. To separate the liquid from the solid, the samples were first centrifuged for five minutes at 5000 rpm. A 250 ml volumetric flask was then filled with 10 ml of the sample. The volume was increased to 100 ml by the addition of water. From this diluted material, a 20 ml aliquot was taken and placed in a conical flask. To prepare 10 ml of acid dichromate solution, a 500 ml conical flask was filled with 125 ml of distilled water. Pure sulfuric acid (70 cc) was carefully added with continuous swirling. After cooling under running water, 0.75 grams of potassium dichromate were added. Using a measuring cylinder, 250 ml of distilled water was poured into each flask for dilution. Each flask was loosely stoppered and heated in a water bath at 40 to 50 degrees Celsius for 10 minutes. After the flasks had been removed from the water bath for twenty minutes, 1 ml of potassium iodide solution (1.2 mol/l) was added to each. The standard thiosulphate solution was placed in a burette, and the contents of the flask were titrated with it. When the brown hue of the solution turned green, 1–2 ml of starch was added. The equivalence point of titration was reached when the blue color of the starch–iodine complex disappeared and was replaced by a clear solution (Table 1a, 1b, 1c, 1d, & 1e) (Shilpa et al., 2013).

Statistical analysis: Statistical tool used to compare ethanol contents among two altitudes and three plant parts (replications) were Heat Map and Scatter plot using “R – software” and the simple statistical analysis of mean (Sharma 1998).

RESULTS AND DISCUSSION

Ethanol yield: Leaf samples from both elevations had the highest ethanol concentrations (7.5 ml/l and 5.1 ml/l), whereas samples from 560 m and 1550 m altitudes had the lowest ethanol contents (2.6 ml/l and 2.7 ml/l, respectively) (Table 2). Darker colors represent higher ethanol concentrations. It also reveals that leaf samples from 560 m showed the highest values, while stems at both altitudes contained the lowest ethanol concentrations (Fig. 3). Further, correlation scatter plot reveals that points aligned closely to a straight line, confirm the strong positive correlation ($r \approx 1.00$). The leaf point is farthest from the origin, reflecting higher ethanol contents (Fig. 4). Altitude greatly influences *L. camara* leaf and leaf-stem ethanol output, but not stem alone.

The ethanol production of leaves at 560 m was substantially greater. A greater buildup of fermentable sugars is probably the result of more favorable photosynthetic conditions at lower elevations. increased carbohydrate content in leaves at lower elevations has also been noted in earlier research (Han et al., 2020). With averages of 2.7 ml/l and 2.6 ml/l at 560 m and, respectively, the ethanol production from stems did not significantly differ between the two elevations. This implies that altitude has less of an impact on the metabolic activities and glucose content of stems. Rao et al. (2015) found steady ethanol production from stem biomass at different elevations, which is consistent with this constancy.

The production of ethanol from the combined leaves and stems varied significantly across the two elevations, with larger yields at 560 m (3.2 ml/l) than at 1550 m (2.9 ml/l). The leaves, which are more susceptible to variations in altitude, account for the majority of the total ethanol output in the combined biomass. In lower altitude regions, *L. camara* leaves produced higher bioethanol yields (Sudha et al., 2014) and attributed this to higher temperatures and sunlight exposure, which increased photosynthetic activity and carbohydrate accumulation in the leaves, resulting in higher ethanol production. Current findings are in line with these conclusions, supporting the notion that lower elevations' climates are better suited for higher leaf ethanol outputs. Furthermore, height affects biomass output and the subsequent generation of ethanol (Gupta and Sharma 2017). Their results demonstrated that improved growth conditions at lower elevations led to larger yields of biomass and ethanol. Current study also indicate greater ethanol yields for leaves at 560 m compared to 1550 m. Rao et al. (2015) concluded that the ethanol output varied little with height, suggesting that altitude had less impact on stems. This study supports our finding that the amount of ethanol produced by *L. camara* stems is constant at both 560 m and 1550 m.

These findings have significant ramifications for the synthesis of bioethanol from *L. camara*. Lower elevations are ideal for optimizing ethanol output, particularly from leaves. It

may be more appropriate to use raw material for the production of bioethanol at elevations of about 560 m. Focusing on leaf harvesting might be more effective given the large yield from leaves at lower elevations. However, stems remain a viable option due to their consistent production regardless of height.

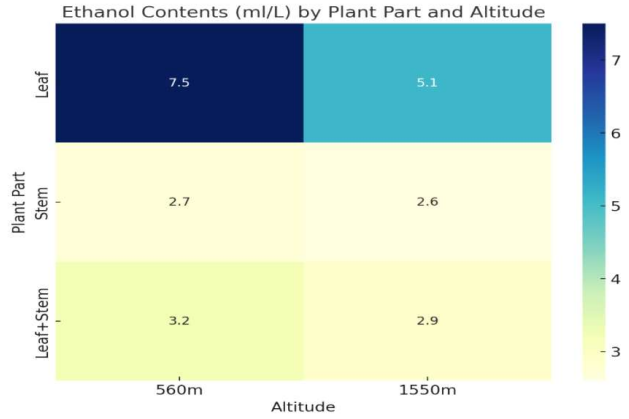

Fig. 3. Ethanol contents by plant part and altitude (Heat map)

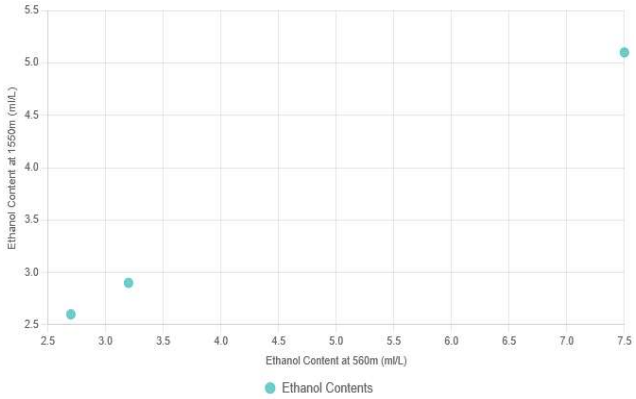

Fig. 5. Scatter plot reflecting ethanol contents in two altitudes

Table 1a. Average volume of Sodium thiosulphate used for titrated samples

Average volume of Sodium thiosulphate used for blank titration	Average volume of Sodium thiosulphate used for samples Altitude					
	560 m			1550 m		
	Leaf	Stem	Leaf + Stem	Leaf	Stem	Leaf + Stem
21.5	17.0	9.6	11.0	15.2	9.6	10.4
22.1	17.6	9.0	11.4	14.8	7.8	9.8
21.8	16.8	8.8	10.8	15.2	9.8	10.0
Average= 21.8	17.2	9.1	11.1	15.1	9.1	10.1

Table 1b. Final volume used to determine alcohol concentration

560 m			1550 m		
Leaf	Stem	Leaf + Stem	Leaf	Stem	Leaf + Stem
(21.8-17.2) = 4.6	(21.8-9.1) = 12.7	(21.8-11.1) = 10.7	(21.8-15.1) = 6.7	(21.8-9.1) = 12.7	(21.8-10.1) = 11.7

Table 1c. Number. of moles of sodium thiosulphate

560m			1550m		
Leaf	Stem	Leaf + Stem	Leaf	Stem	Leaf + Stem
M1V1 = M2V2 M1 (4.6) = 0.03 (1000) Or M1 = 6.52	M1V1 = M2V2 M1 (12.7)= 0.03(1000) Or M1 = 2.36	M1V1 = M2V2 M1 (10.7) = 0.03 (1000) Or M1 = 2.80	M 1 V 1 = M 2 V 2M 1 (6.7) = 0.03 (1000) Or M 1 = 4.48	M 1 V 1 = M 2 V 2 M 1 (12.7) = 0.03(1000) Or M 1 = 2.36	M 1 V 1 = M 2 V 2 M 1 (11.7) = 0.03 (1000) Or M 1 = 2.56

Table 1d. Number of moles of ethanol in sample dilution

560m			1550m		
Leaf	Stem	Leaf + Stem	Leaf	Stem	Leaf + Stem
6.52× 0.25 =1.63 mol	2.36× 0.25 =0.59 mol	2.80× 0.25 = 0.70 mol	4.48× 0.25 = 1.12 mol	2.36× 0.25 = 0.59 mol	2.56× 0.25 = 0.64 mol

Table 1e. Percentage of ethanol produced per 100 ml

560m			1550m		
Leaf	Stem	Leaf + Stem	Leaf	Stem	Leaf + Stem
(1.63 × 46.07)/100 = 0.75 ml	(0.59 × 46.07)/100 = 0.27 ml	(0.7× 46.07)/100 = 0.32 ml	(1.12× 46.07)/100 = 0.52 ml	(0.59× 46.07)/100 = 0.27 ml	(0.64× 46.07)/100 = 0.29 ml

Table 2. Ethanol yield from different plant parts of *Lantana camara* at two altitudes

Plant part	Ethanol contents (ml/l)	
	560 m	1550 m
Leaf	7.5[a]	5.1[a]
Stem	2.7[a]	2.6[a]
Leaf+Stem	3.2[a]	2.9[a]

Mean values followed by same letter within a column are not significantly different at 0.05%

CONCLUSION

The lower elevation of 560 m as opposed to 1550 m, the ethanol output from leaves was higher. This implies that lower elevations may offer more conducive circumstances for *L. camara* leaves to produce ethanol. This oscillation may be caused by variables including temperature, exposure to sunshine, and nutrition availability. Altitude has no discernible effect on the amount of ethanol produced by *L. camara* stems, as seen by the stems' same ethanol output at both elevations. This consistency implies that the metabolic mechanisms in stems that produce ethanol are less susceptible to variations in altitude. Higher altitude results in a statistically significant decrease in ethanol yield for the combined leaves and stems indicating that altitude affects the plant's overall ethanol production, especially when taking the biomass of the entire plant into account. By choosing appropriate growth conditions and concentrating on the most productive plant portions, our findings support the possibility of enhancing the production of bioethanol from *L. camara*.

AUTHORS' CONTRIBUTIONS

Conceptualization, methodology, writing, reviewing and editing by A.K. Uniyal, Vikaspal Singh, Sandhya Goswami, Manish Kumar and Prabhakar Manori, Data collection and analysis by Soumya Pathak. All the authors have read and approved the final manuscript.

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Histological Differentiation of *Swertia* species: An Implication for Raw material Authentication to Avert Adulteration

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Abstract: *Swertia chirayita* (Roxb. ex Fleming) Karst., a critically valued species of the family Gentianaceae, is the principal source of the Ayurvedic drug "chirata" and is extensively utilized in traditional medicine systems due to antimalarial, hepatoprotective, antipyretic, and appetite-stimulant properties. However, increasing demand coupled with overharvesting, habitat degradation, and limited cultivation has rendered the species critically endangered, leading to its frequent adulteration with morphologically similar *Swertia* species. This study aimed to establish a robust histological framework to distinguish *S. chirayita* from common adulterants through comparative anatomical analysis. Key diagnostic features such as stomatal type, epidermal cell structure, and transverse sections of leaf and stem tissues were examined. The identified histological markers offer reliable, reproducible criteria for species authentication, particularly in fresh or partially processed samples, where morphological identification may be ambiguous. These findings contribute substantially to the development of standardized protocols for the authentication and quality assurance of *S. chirayita*, thereby supporting its safe and effective use in phytomedicines.

Keywords: *Swertia chirayita*, Histological differentiation, Species authentication, Adulteration, Herbal medicine, Quality control

Swertia chirayita (Roxb. ex Fleming) Karst., a member of the family Gentianaceae, is a high-altitude medicinal herb indigenous to the temperate regions of the Himalayas, extending from Kashmir to Bhutan and the Khasi Hills of Meghalaya, thriving between 1200 and 3000 meters above mean sea level (Tandon et al., 2010, Bajaj et al., 2017, Mazumder et al., 2023). It is recognized as one of the 32 high-priority medicinal plants by the National Medicinal Plants Board (Kala and Sajwan 2007) and has gained international recognition for its diverse pharmacological activities, including tonic, febrifuge, laxative, stomachic, hypoglycemic, hepatoprotective, anti-inflammatory, antimicrobial, and immunomodulatory effects (Alam et al., 2011, Verma et al., 2013, Ali et al., 2017, Khan et al., 2018). The therapeutic potential of *Swertia chirayita* is primarily attributed to its bitter principles, notably amarogentin and swertiamarin, alongside flavonoids, xanthones, iridoids, and secoiridoid glycosides (Pant et al., 2000, Sharma et al., 2010, Negi et al., 2011, Kumar and Chandra 2013, Kumar and Staden 2016). Swertiamarin has been reported for its hepatoprotective (Wang et al., 2011), anti-diabetic (Vaidya et al., 2013), and anticancer activities (Kavimani and Manisenthlkumar 2000), while amarogentin exhibits potent anti-diabetic properties (Phoboo et al., 2013), anti-cancer (Pal et al., 2012) and anti-arthritic properties (Saravanan et al., 2014). In traditional medical systems, including Ayurveda, Unani, and Siddha, *S. chirayita* holds a prominent position. Historically was included in the Edinburgh Pharmacopoeia (1839) and continues to be recognized in the Indian, British, and American pharmacopeias (Joshi and Dhawan 2005). *S. chirayita* is widely used in the treatment of malaria, hepatic disorders, gastrointestinal ailments, diabetes, and skin diseases (Keil et al., 2000, Joshi 2008, Pant et al., 2010). Additionally, it is employed in managing chronic fever, malaria, anemia, bronchial asthma, hepatotoxic disorders, liver disorders, hepatitis, gastritis, inflammatory conditions, and various digestive disorders, constipation, dyspepsia, skin diseases, anemia, worms, ulcers, epilepsy, ulcers, scanty urine, hypertension, melancholia, and certain types of mental disorders, secretion of bile, blood purification, and diabetes (Banerjee et al., 2000, Rai et al., 2000, Saha et al., 2006, Bhatt et al., 2006, Chen et al., 2011). In addition to its antiviral properties, its anti-hepatitis B virus (anti-HBV) potential has been validated in recent studies, reinforcing its versatility as a therapeutic agent (Zhou et al., 2015). *S. chirayita* is commonly administered in various forms, including concentrated infusions, tinctures, powders, and fluid extracts (Joshi 2008, Phoboo et al., 2008). Its extracts are widely utilized in the cosmetic industry, where they serve as active ingredients in products like facial creams, cleansers, scrubs, hair oils, and skin tonics, including Safi. Herbal formulations such as Ayush-64, Diabecon, Mensturyl syrup, and Melicon V ointment (Edwin and Chungath 1988, Mitra et al., 1996) contain *Swertia chirayita* extract in different concentrations for its antipyretic, hypoglycaemic, antifungal, and antibacterial properties. Ayush-64, incorporates *S. chirayita* and has shown significant effectiveness in managing COVID-19. The formulation was repurposed for mild to moderate cases of COVID-19, showing promising results in

clinical trials (Panda et al., 2022). Moreover, *S. chirayita* also played a vital role as a key ingredient in Traditional Chinese Medicine (TCM) formulations used against SARS-CoV-2 during the early stages of the pandemic in China (Gyawali et al., 2020, Omokhua-Uyi and Staden 2021, Ahmad et al., 2021, Shereen et al., 2021).

Despite its significant medicinal value, *S. chirayita* faces severe threats in its natural habitat due to overexploitation, habitat fragmentation, low seed viability and slow propagation rates and is classified as critically endangered in its native range (Joshi and Dhawan 2005). Overharvesting and widespread habitat destruction have severely depleted wild populations of the species, leading the Government of India to prohibit wild harvesting and prioritize conservation initiatives (Ved and Goraya 2007). In addition, its restricted geographic distribution (Bhat et al., 2013), coupled with persistent seed viability challenges (Badola and Pal 2002, Joshi and Dhawan 2005), further worsens its vulnerability to extinction, underscoring the urgent need for targeted and sustainable conservation interventions.

The rising market demand for *S. chirayita* has led to widespread adulteration, with the species often being substituted by morphologically similar species such as *S. angustifolia, S. cordata, S. alata*, *S. paniculata*, and even unrelated species like *Andrographis paniculata* (Girach et al., 1994, Brahmachari et al., 2004, Latif and Rehman 2014). Such practices compromise therapeutic efficacy, jeopardize consumer safety, and undermine the integrity of herbal formulations. Given the limitations of traditional macroscopic and phytochemical identification methods particularly in processed or powdered materials there is an urgent need for more reliable diagnostic approaches.

Histological profiling, based on stable microanatomical features such as stomatal type, epidermal architecture, mesophyll organization, and vascular arrangement, offers a reproducible and robust tool for precise species authentication. As these anatomical traits largely withstand post-harvest processing, they hold significant potential for pharmacognostic applications. The present study aims to elucidate the detailed histological features of *S. chirayita* and differentiate it from commonly substituted adulterants *viz. S. alata, S. angustifolia, S. cordata* and *S. purpurascens.* By establishing a diagnostic anatomical key, this research seeks to strengthen authentication protocols, enhance quality control standards, and promote the development of safe, standardized herbal formulations.

MATERIAL AND METHODS

Plant materials: Plant samples, including cultivated *S. chirayita* from the University farm in Shilly, *S. alata* and *S. angustifolia* from Dharon Ki Dhar district Solan, Himachal Pradesh (30.881417° N, 77.178488° E) and *S. purpurascens* and *S. cordata* from Hatu district Shimla, Himachal Pradesh (31.244087° N, 77.501339° E (were collected from their respective natural habitats for anatomical studies. The specimens were processed using standard anatomical techniques to examine various morphological features. The study focused on epidermal cell morphology, leaf trichomes, stomatal types and dimensions, and the transverse sections (T.S.) of stems and vertical sections (V.S.) of leaves across these five *Swertia* species.

Sample fixation and preservation: Fresh leaf and stem samples from each species were immediately fixed in a formalin-acetic acid (FAA) solution (ethyl alcohol: acetic acid: formaldehyde in a ratio of 90:5:5) and preserved at room temperature for further analysis.

Sample preparation and staining procedure: Thin sections of leaves and stems were carefully prepared using a sharp razor blade and mounted on slides for microscopic examination. The prepared sections were initially hydrated in distilled water, followed by sequential dehydration in 25 and 50% ethyl alcohol solutions for 5 minutes each. Sections were then stained with aqueous safranine for 5 minutes, followed by dehydration in 75% ethyl alcohol. Afterward, the sections were stained with fast green for 5 minutes. The stained sections were mounted with cover slips and examined under microscope for microscopic analysis.

Microscopic analysis*:* To examine the epidermal cell morphology, fresh leaf peels from the lower epidermis were stained with cotton blue and cleared in lactophenol. The morphological characteristics of the epidermal cells were then documented under a microscope.

Stomatal characteristics: Stomatal size was measured using ocular and stage micrometers on sections from the lower parts of the leaf epidermis. Stomatal types were classified according to system by Fahn (1967). The stomatal index (SI) was calculated from at least 25 readings using the formula:

$$SI = \frac{S}{(E+S)} \times 100$$

Where

SI = Stomatal index

S = No. of stomata/unit area

E = No. of epidermal cells in the same area

RESULTS AND DISCUSSION

The, comparative histological evaluation of five *Swertia* species revealed distinct anatomical markers, thereby strengthening the diagnostic framework for authenticating genuine “chirayita.”

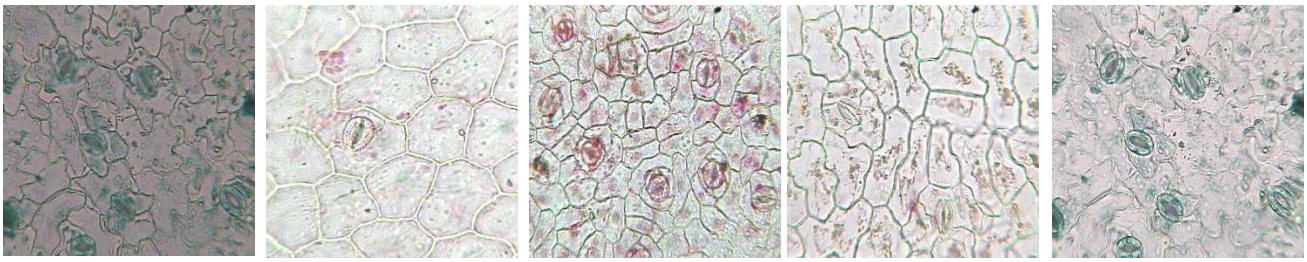
Anatomical Characters

Epidermal cell: Epidermal cell morphology and surface features revealed distinct variations across the studied species (Fig. 1). *S. angustifolia* and *S. purpurascens* displayed prominently wavy epidermal cell outlines, while *S. cordata* showed moderately wavy cells; in contrast, *S. chirayita* and *S. alata* featured angular epidermal cells.

Among these, *S. angustifolia* possessed the largest epidermal cells, serving as a distinguishing anatomical marker. In addition, trichomes both unicellular and multicellular were consistently present among all species, though their density and structural variations further contributed to species differentiation. Similar patterns of taxonomically significant epidermal and trichome variation have been reported by Al-Shami et al. 2022 in *Veronica* species, where detailed comparative analyses of stems, leaves, and petioles revealed distinctive epidermal cell shapes and trichome structures useful for species authentication. These observations are further supported by Chen et al. (2008), and highlighted epidermal cell morphology and trichome characteristics as reliable diagnostic traits for species authentication in medicinal plants.

Stomata type: Stomatal characteristics also play a significant role in differentiation, with *S. chirayita* exhibiting anisocytic stomata, distinct from the anomocytic stomata observed in other species (Table 1). This observation is consistent with previous studies reinforcing the role of stomatal morphology in the authentication of *S. chirayita* (Xue et al., 2000). The stomatal index exhibited variability across species, with *S. angustifolia* demonstrating the highest index and *Swertia cordata* the lowest. *S. chirayita* and *S. purpurascens* displayed similar indices, albeit with slight deviations from previously reported values (Natrajan and Prasad 1972).

These variations emphasize the necessity for diverse methodologies to accurately interpret stomatal indices for species differentiation and quality assessment in medicinal plants. The findings of our study are further substantiated by the work of Jiachun et al. (1993) which presents a comprehensive analysis of the microscopic structure of *Swertia* species. Balekundri and Mannur (2020) emphasized the importance of incorporating robust diagnostic parameters, including anatomical features, to ensure the authenticity of herbal products and mitigate the risk of adulteration and underscores the complementary role of anatomical characterization in maintaining species integrity and quality control in herbal formulations. Li et al. (2013) examined both microscopic and macroscopic traits across eight *Swertia* species, identifying diagnostic features such as epidermal cell wall sinuosity, fiber presence in sepals, and stomatal distribution. These anatomical markers have proven valuable for species authentication and standardization in herbal medicines. Integrating these insights with advanced anatomical techniques, current study refines the criteria for accurately identifying *S. chirayita*, further supporting its authenticity in herbal preparations (Kshirsagar et al., 2019). Rashid et al. (2019) highlighted significant anatomical and phytochemical differences between *S. cordata* and its common adulterant, *S. paniculata*, emphasizing the importance of accurate anatomical authentication. This reinforces the critical role of



(a) *S. alata* (b) *S. angustifolia* (c) *S. chirayita* (d) *S. cordata* (e) *S. purpuras cens*

Fig. 1. Epidermal cells of *Swertia* species

Table 1. Stomatal characteristics of different *Swertia* species

Parameters	Tetramerous species			Pentamerous species	
	S. chirayita	*S. alata*	*S. angustifolia*	*S. purpurascens*	*S. cordata*
Stomata length	32.630.031m	33.770.050m	33.850.037m	34.220.038m	38.980.032m
Stomata breadth	19.630.032m	19.380.032m	21.590.023m	20.940.025m	25.670.023m
Stomata type	Anisocytic	Anomocytic	Anomocytic	Anomocytic	Anomocytic
Stomatal index	23.470.346	20.580.098	31.980.420	24.520.117	18.690.200

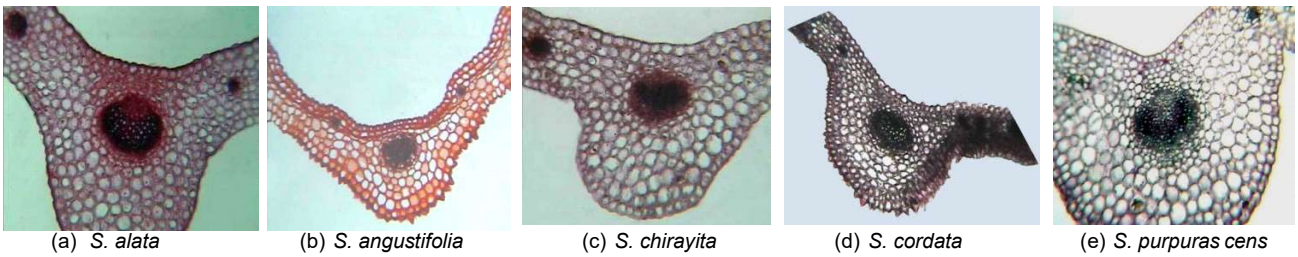
detailed anatomical profiling in ensuring species authenticity, improving quality control, and preventing adulteration in herbal medicine.

Anatomy of leaf: Vertical sections of leaves across all *Swertia* species studied, expressed a consistent anatomical feature: the mesophyll remained undifferentiated, lacking distinct palisade and spongy tissues, and displayed small intercellular spaces (Fig. 2). Bisht et al. (2011) also reported loosely arranged spongy mesophyll cells in *S. chirayita*., *S. angustifolia* exhibited a distinct anatomical characteristic the presence of a well-developed collenchymatous layer which serves as an important marker distinguishing it from *S. chirayita* and other related species.

Additionally, the vascular bundles in *S. angustifolia* were positioned closer to the upper epidermis, contrasting with the more centrally located vascular bundles observed in other *Swertia* species. Such anatomical variations highlight the diagnostic significance of leaf structural traits in species differentiation. The importance of employing simple macroscopic and microscopic evaluations for the authentication of plant materials has also been emphasized by Arathy and Sandhya (2021), particularly in distinguishing genuine *Cinnamomum verum* from its adulterants. Similarly, the unique anatomical features identified in *S. angustifolia* underscore its importance in ensuring accurate identification and maintaining the quality and authenticity of herbal drugs derived from *Swertia* species.

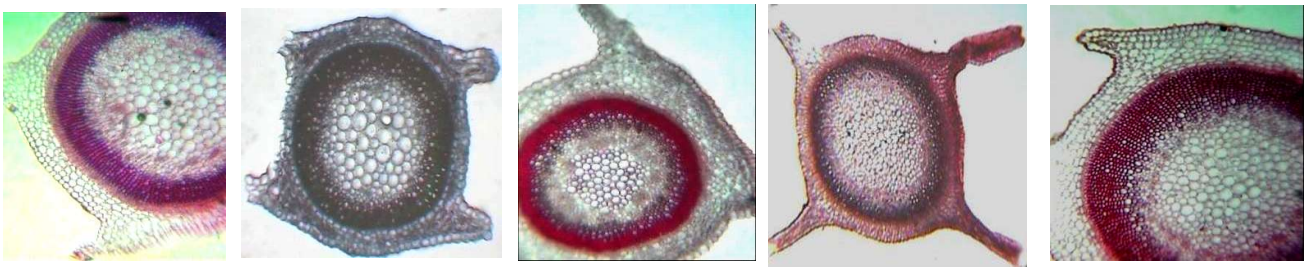
Anatomy of stem: Transverse sections of stem tissues revealed both conserved and distinct anatomical features that are essential for species-level differentiation (Fig. 3). All species exhibited a single layered epidermis, a characteristic feature within the *Swertia* genus, as reported in previous studies (Bisht et al., 2011). A well-developed amphiphloic siphonostele was consistently observed across all taxa, with *Swertia chirayita* displaying the most pronounced configuration, thus reinforcing its role as the reference species for 'Chirata'.

However, in contrast to earlier studies reporting acicular crystals in the cortical region of *Swertia chirayita* (Anonymous 1998, Bisht et al., 2011), no such crystals were detected in the present study. This discrepancy may be attributed to environmental or developmental factors influencing crystal formation. Ergastic cell contents, such as starch grains and prismatic crystals, serve as valuable diagnostic markers in herbal drug identification, including for stem tissues. These features, observed in the stem sections, enhance the reliability of anatomical diagnostics and contribute to distinguishing species based on both macroscopic and microscopic traits (Kumar et al., 2018). Quantitative anatomical parameters, such as tissue thickness in transverse sections (Hassan et al., 2015), cell dimensions, and the size of starch grains, cortical cell and epidermal cells in *Fritillaria cirrhosa* (Singh et al., 2020), further substantiate these diagnostic methods. The presence of a distinct endodermal layer in *S. chirayita* further distinguishes it from other species, potentially reflecting specialized solute transport mechanisms. In contrast, *S. cordata* exhibited radially thickened pericyclic cell walls and enlarged pith



(a) *S. alata* (b) *S. angustifolia* (c) *S. chirayita* (d) *S. cordata* (e) *S. purpuras cens*

Fig. 2. V. S. of leaf (closeup of mid rib region of different *Swertia* species)



(a) *S. alata* (b) *S. angustifolia* (c) *S. chirayita* (d) *S. cordata* (e) *S. purpuras cens*

Fig. 3. T. S. of stem of different *Swertia* species

relative to the cortical parenchyma, providing clear structural markers for identification. *S. angustifolia* displayed a collenchymatous hypodermis, a unique feature that enhances its diagnostic utility. These anatomical distinctions are consistent with the findings of Rashid et al. (2019), who reported significant divergence between *S. cordata* and *S. paniculata*. The frequent misidentification of *Swertia chirayita* (Gentianaceae) and *Andrographis paniculata* (Acanthaceae), two unrelated species with distinct therapeutic profiles, underscores the critical need for reliable diagnostic methods. The comparative anatomical study by Kumar et al. (2022) on raw herbal drugs of *Abrus precatorius* and *Glycyrrhiza glabra* emphasizes the importance of integrating both macroscopic and microscopic characteristics for distinguishing closely related species. Similarly, the anatomical profiling of *Swertia chirayita*, incorporating both exomorphic and endomorphic traits, provides essential data for accurate species delimitation and ensures the authenticity and integrity of raw materials used in herbal formulations (Selvam 2011).

CONCLUSIONS

The study provides a useful approach for detecting adulteration in fresh leaf and stem samples of *Swertia chirayita*. However, its applicability may be limited when dealing with dry and thoroughly mixed samples, where distinguishing morphological or anatomical features becomes difficult. In such cases, additional methods or modifications would be required for reliable purity assessment. Future research should focus on evaluating and adapting the methodology for dry samples, as this would significantly enhance the practical utility of the study for trade and quality control of medicinal plants.

AUTHOR'S CONTRIBUTION

Aruna Mehta: Sample collection, histological studies, analyzed microscopic observations and manuscript drafting; Sunil Marpa: data interpretation, manuscript writing and review; Kumari Bandana: literature review, data interpretation and manuscript preparation; Yourmila Kumari: discussion and manuscript editing; Garima: manuscript writing, formatting and referencing; Kashish: figure organization and manuscript proofreading.

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Variation in *Sterculia foetida* Seed Oil Content among different Landscapes in South Gujarat *vis-a-vis* Oil Phytochemical and Fatty Acid Composition

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***Abstract*:** The present study aimed to find out the variation in *Sterculia foetida* seed oil content across different landscapes (L_1 & L_8-arboreal; L_2-agricultural and L_3-L_7-city avenue plantations) of South Gujarat, India and its oil phytochemical and fatty acid composition. The sampling locations were comprised of eight landscapes falling in three districts namely Narmada (lies in the Satpura mountain ranges and the Narmada River basin), Navsari and Valsad (Arabian Sea coast). Findings deduced significant ($P \leq 0.05$) variation in *S. foetida* seed oil content among the landscapes and it ranged from 38.43 to 53.23% with overall average of 44.16%. Further, the gas-chromatography mass-spectrometry analysis revealed 11 volatile compounds in oil. Based on relative percentage most abundant were 9-Octadecanone (88.67), stigmasterol (78.74), 2-Decanone (78.02) and nonanoic acid (76.55). Gass chromatography analysis of Total Fatty Acid Methyl Esters (FAME) of *S. foetida* seed oil revealed 6 compounds. Among them maximum amount (57.06%) was of palmitoleic acid. The total saturated fatty acids, monounsaturated fatty acids and poly unsaturated acids were 19.48%, 18.37% and 62.13%, respectively. Corroboration of detected kernel oil phytochemicals and fatty acids, in the present study, with available literature expressed that these compounds have many biological properties indicating it beneficial for human being.

***Keywords*:** Hazel sterculia, Oil content, Oil composition, Phytosterol, Fatty acid

Unveiling of the Planning Commission Government of India report on 'Pathways and Strategies for Accelerating Growth in Edible Oils Towards Self Reliance (*Atmanirbharta*), highlighted that over the past decades, per capita consumption of edible oil in the country has seen a dramatic rise, reaching 19.70 kg/year. This spate in demand has pointedly overtaken domestic production, leading to a substantial reliance on imports to meet both domestic and industrial needs. In 2022-23, India imported 16.50 million tonnes (MT) of edible oils, with domestic production fulfilling only 40-45% of the country's requirements. This situation presents a considerable challenge to the country's goal of achieving self-sufficiency in edible oils. Under a business-as-usual scenario, the national supply of edible oil is projected to increase to 16 MT by 2030 and 26.7 MT by 2047 (Patel et al., 2024). Oilseeds and edible oils are two of the most sensitive essential commodities. India is one of the largest producers of oilseeds in the world and this sector occupies an important position in the agricultural economy, accounting for the estimated production of 39.66 million tonns of nine cultivated oilseeds during the year 2023-24 (November-October) as per Final Advance Estimates released by the Ministry of Agriculture at end of 2024. India contributes about 5-6% of the world oilseeds production. Export of oil meals, oilseeds and minor oils was about 5.44 million tons in the financial year 2023-24 valued at ₹ 29,587 crores (Patel et al., 2024). Vegetable oils are an integral part of producing manufactured food both domestically and on an industrial scale. The vegetable oil market is increasing upward with a compound annual growth rate (CAGR) of 3.25% during the forecast period 2019-2024 all around the world.

Therefore, it is necessary to find alternative sources of vegetable oil (Bose et al., 2021) and tree born edible oils (Hegde et al., 2019) to fulfil the insufficiency in the market. In addition to major oilseeds crops, 3 million tonnes of vegetable oil are being harnessed from secondary sources like cottonseed, rice bran, coconut, Tree Borne Oilseeds (TBOs) and oil palm which is categorized as secondary sources of oils should be included as primary source as it gives the highest per ha oil yield (4-5 t/ha). There are an array of plant species including perennial trees which have been evaluated for edible seed oil and after oil extraction cakes are used as a concentrate for livestock feeding or other purposes like manuring (Akande et al., 2016, Hegde et al., 2019).

Sterculia foetida L., commonly known Hazel sterculia and wild almond. It is found from Eastern tropical Africa to North Australia, through Malaysia, Burma, Bangladesh, India, Sri Lanka and Malacca (Mujumdar et al., 2000). The generic name is based on the Latin word 'stercus', meaning 'manure', which refers to the smell of the flowers and leaves of some species. Fruits ripen in February, nearly 11 months after the 1st appearance of the flowers. Mature trees produce

approximately 200-350 kg of seed per year (Orwa et al., 2009). *S. foetida* seeds are safe to eat and contain significant amounts of carbohydrates, protein, lipids, minerals and macro and micronutrients (Galla 2013). Seeds yield a considerable amount an edible non-drying oil, is found in both the testa and the kernel and been found to be a good biofuel (Bose et al., 2021). Due to low moisture content, *S. foetida* seed have a prolonged shelf life. The oil has anti-diabetic, anti-dermatophytic, antimicrobial, anti-cancer, anti-obesity, antifertility, and antifeedant properties. On a small scale, oil from the seed is extracted and used in medicine to treat itches and other skin diseases internally and externally as a paste. The wood is boiled with seed oil and applied externally to treat rheumatism. By sensitizing receptors, seed oil may aid in the reduction of belly fat and insulin resistance. Based on all the tested parameters, oil may serve as an alternative, viable source of safe edible oil (Sarkar et al., 2021, Bose et al., 2021 Farsana et al., 2022). There is a dearth of information in India on its seed kernel and its oil nutritive value. Therefore, the present study was proposed to fulfil this lacking pertaining to physico-chemical, micro-macro nutrient, secondary metabolite, volatile phytochemical, oil content and oil composition of *S. foetida* across landscapes of south Gujarat extending from Arabian cost to Satpura mountain ranges India.

MATERIAL AND METHODS

Study area and fruit collection: *S. foetida* fruits were collected from distantly located eight different landscapes falling in three districts namely Narmada (falls in Satpura mountain ranges and Narmada River basin), Navsari and Valsad (along Arabian Sea coast) of south Gujarat, India.

Geographical location of landscapes and growth attributes of selected trees are given in Figure 1 and Table 1, respectively. In each landscape five trees were marked and height and diameter at breast height (DBH) was measured and average values are given in table 1. *S. foetida* fruits were collected in bulk (January 2024) from each landscape and brought to the laboratory and seeds were extracted.

Nut morpho-metric attributes: Under each replication (n=5) 100 nuts were taken and data on morph-metric attribute *i.e.* seed length and width, and seed weight was recorded.

Seed kernel oil content (%): The nuts were de-shelled manually to extract the kernel. The kernels were then dried in hot air oven at 65(±5)^0 C for 72 hrs. The dried kernels were crushed and grounded fine using grinding mixer. Oil was extracted (using 25 g kernel powder) by using the Soxhlet

Fig. 1. A) Geographic location of *S. foetida* landscapes and B) *S. foetida* tree in arboreal landscape (insight: fruit, seed and seed kernel from top to bottom, respectively)

Table 1. Geographical location, and average growth and seed morphometric attributes of *S. foetida* in different landscapes of south Gujarat

Land-scape (L)	Altitude (m)	Latitude (N)	Longitude (E)	Tree eight (m)	DBH (cm)	SL (mm)	SWdt. (mm)	SWt. (g)	MC (%)
RPL-L_1	67	21°85'81"	73°51'87"	22.50	45.06	19.23^{c}	12.46^{bcd}	1.85^{cd}	12.25^{de}
NVS-1-L_2	33	20°92'23"	72°90'52"	21.20	68.30	22.04^{a}	13.32^{a}	2.37^{a}	16.77^{a}
NVS-2-L_3	34	20°97'03"	72°93'42"	10.60	32.80	20.28^{b}	12.28^{cd}	1.91^{c}	13.41^{cd}
NVS-3-L_4	33	20°93'67"	72°94'01"	15.30	49.90	19.20^{c}	12.04^{cd}	1.73^{e}	15.80^{ab}
NVS-4-L_5	39	20°94'63"	72°93'49"	18.80	51.70	19.47^{c}	12.10^{cd}	1.76^{de}	16.45^{e}
VLD-1-L_6	30	20°60'42"	72°91'38"	12.40	46.60	21.94^{a}	11.97^{d}	1.89^{c}	15.43^{abc}
VLD-2-L_7	33	20°60'82"	72°90'83"	8.60	34.19	21.62^{a}	12.98^{ab}	2.28^{a}	14.06^{bcd}
VLD-3-L_8	32	20°60'46"	72°91'37"	21.50	36.00	20.26^{b}	12.68^{abc}	2.03^{b}	10.37^{a}
Mean	-	-	-	-	-	20.50	12.48	1.98	14.32
SEm (±)	-	-	-	-	-	0.18	0.22	0.03	0.77

(DBH= Diameter at Breast Height); RPL=Rajpipla; NVS=Navsari; VLD=Valsad; DBH=Diameter at breast height; SL=Seed length; SWdt.=Seed width; SWt.=Seed weight; MC=Moisture content; Letter different in same vertical column are significantly different according to Duncan's multiple range test ($P \leq 0.05$)

method with hexane as per the standard procedure followed for the estimation of oil in oilseeds and TBOs (Bose et al., 2021).

Oil phytochemical and oil fatty acid profile: *S. foetida* seed oil phytochemicals were detected through Gas Chromatography-Mass Spectrometry (GC-MS) partly following Sukhadiya et al., (2021) whereas fatty acids were estimated following standard method of AOAC (2000).

Statistical analysis: All respective data sets were analyzed as per standard statistical procedure using Complete Randomized Design (CRD) and F-test was done and ANOVA was constructed with following model Yij = μ + ti + eij, where Yij = an observation, μ = overall mean effect, ti = true effect of the (Ti) treatment, eij = error term of the (Yj) unit receiving (i) treatment, i = a particular treatment, j = a particular replicate as described by Snedecor and Cochran (1980). Treatment means were compared at *P≤0.05*. Further, Duncan's multiple range test (DMRT) was adopted to compare the sets of means of each factor (Sheoran et al., 1998).

RESULTS AND DISCUSSION

Seed morpho-metric and biomass attributes: *S. foetida* seed morpho-metric attributes namely seed length, width and weight varied significantly (*P ≤ 0.05*) among the eight studied landscapes (Table 1). Maximum seed length (22.04 mm), width (13.32 mm) and weight (2.37 g/seed) was recorded for seeds of L_2 landscape (NVS-1-L_2). Shortest seed length (19.20 mm) and least seed weight (1.73 g/seed) was found in seed of NVS-3-L_4. The minimum seed width (11.97 mm) was of seeds from L_6 landscape (VLD-1-L_6). Overall, seed length, width and seed weight had average values of 20.50 cm, 12.48 cm and 1.98 g, respectively.

Oil content: The perusal of data (Fig. 2) expressed that percentage of *S. foetida* seed oil content varied significantly (*P ≤ 0.05*) among eight different landscapes. Maximum oil content (53.23%) was found in VLD-3-L_8 landscape seeds, which was statistically at par with RPL-L_1 landscape having 47.51% oil. NVS-3-L_4 landscape seeds kernel yielded minimum oil content (38.43. Overall, in all the landscapes an average of 44.16% oil content was obtained.

Oil phytochemicals: The phytochemicals detected through gas-chromatography mass-spectrometry (GC-MS) in SFSK and kernel are presented in table 2. The chromatograms showing retention time and relative abundance of volatile phytochemical compounds detected in kernel oil are depicted in Figure 3. In total, 11 phytochemicals could be identified extracted kernel oil. Among them phytochemicals *viz.,* 1-Decyne, Cyclopropane pentyl, Nonanal, 2-Decanone, Nonanoic acid, n-Hexadecanoic acid, 9-Octadecanone, 12-Tricosanone, Squalene, Stigmasterol and β-Sitosterol were detected with relative area 14.29, 39.61, 53.18, 78.02, 76.55, 48.11, 88.67, 19.28, 57.43, 78.74 and 48.43%, respectively (Table 2).

Oil fatty acid composition: Fatty acids are composed of a hydrocarbon chain with a methyl group and a terminal carboxyl group. Fatty acids are major components of triacylglycerols, phospholipids and other complex lipids. Triacylglycerols and hence fatty acids are the main contributors to dietary fat in humans. The properties of dietary fat are primarily determined by the composition of its fatty acids, which may be SFA (no double bonds), MUFA (one double bond) or PUFA (greater than one double bond).

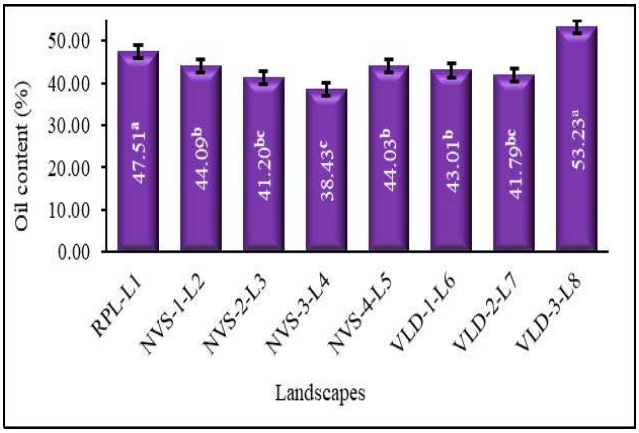

Fig. 2. Variation in *S. foetida* seed oil content (%; SEm=±1.023) among different landscapes of south Gujarat; L=Landscape; RPL=Rajpipla; NVS=Navsari; VLD=Valsad. Letter different in vertical bar are significantly different according to Duncan's multiple range test (*P ≤ 0.05*)

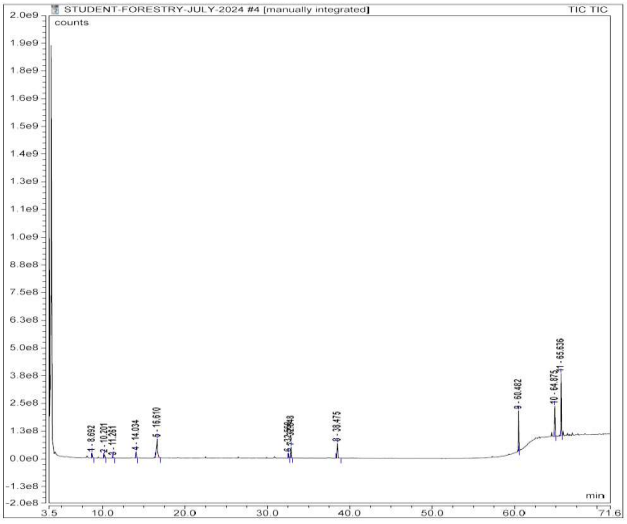

Fig. 3. GC-MS chromatogram showing retention time and relative abundance of volatile phytochemical compounds detected in *S. foetida* kernel oil

Different foods contain different amounts of fat and different types of fatty acids and these may be affected by processing, storage, and cooking methods. Its widespread distribution in dietary fats and oils, palmitic acid is the most common fatty acid in many diets. The optimal fatty acid composition of the diet is an important factor which can play an important role in disease prevention and promote health. The Joint Food and Agriculture Organization/WHO expert consultation on fats and oils in human nutrition (FAO/WHO 1994) concluded that 'Adequate amounts of dietary fat are essential for health'. Fatty acids also can affect the expression of genes encoding for enzymes which are involved in lipid metabolism and to interact with nuclear receptor proteins that bind to DNA, therefore fatty acids can alter the transcription of regulatory genes (Calder 2015).

Based on FAME chromatogram (Figure 4a, b) and Table 3 data demonstrated in that *S. foetida* seed oil exhibited 6 compounds. Among them maximum percentage (57.06%) was of palmitoleic acid. Others were 1.22% palmitic acid, 5.07% oleic acid, 15.41% linoleic acid, 18.26% arachidic acid and 2.96% eicosadienoic acid. The current investigation demonstrated that total saturated fatty acids, monounsaturated fatty acids and poly unsaturated acids were 19.48, 62.13 and 18.37%, respectively. The results deduced that maximum monounsaturated fatty acids were detected in different landscapes of south Gujarat selected in present study.

In response to edaphoclimatic factors plant organs tend

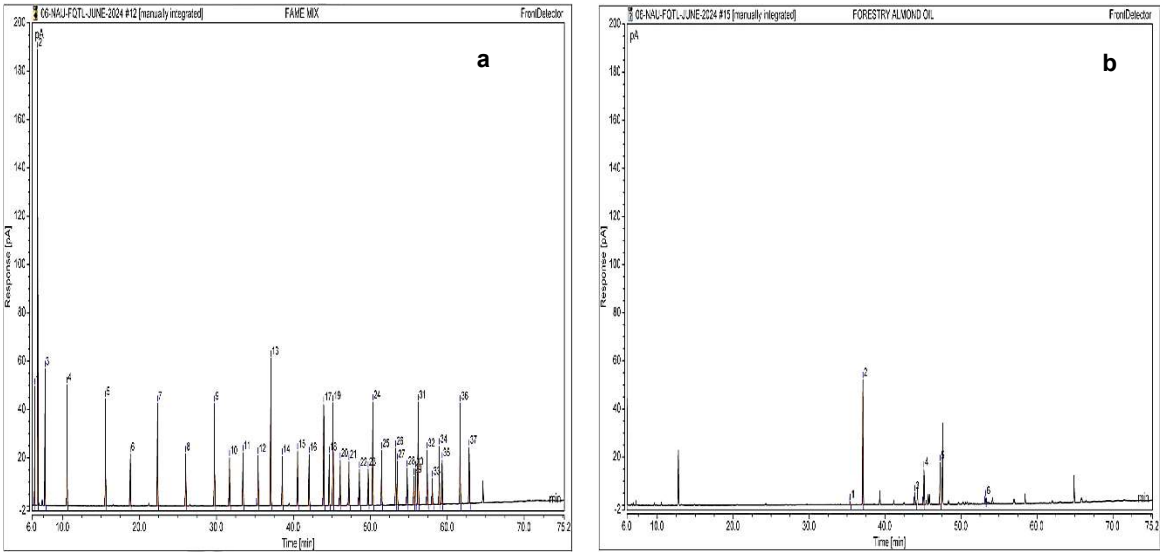

Fig. 4. a) Chromatogram of fatty acid methyl ester (FAME) for standard and b) chromatogram of fatty acid methyl esters (FAME) of *S. foetida* seed kernel oil

Table 2. *S. foetida* kernel oil phytochemicals detected through Gas chromatography-mass spectrometry (GC-MS)

Compound	Chemical formula	Molecular weight (g/mol)	Retention time (min)	Relative area (%)
1-Decyne	$C_{10}H_{18}$	138.25	8.692	14.29
Cyclopropane, pentyl-	C_8H_{16}	112.21	10.201	39.61
Nonanal	$C_9H_{18}O$	142.24	11.261	53.18
2-Decanone	$C_{10}H_{20}O$	156.27	14.034	78.02
Nonanoic acid	$C_9H_{18}O_2$	158.24	16.610	76.55
n-Hexadecanoic acid	$C_{16}H_{32}O_2$	256.42	32.560	48.11
9-Octadecanone	$C_{18}H_{36}O$	268.48	32.848	88.67
12-Tricosanone	$C_{23}H_{46}O$	338.61	38.475	19.28
Squalene	$C_{30}H_{50}$	410.73	60.482	57.43
Stigmasterol	$C_{29}H_{48}O$	412.70	64.875	78.74
β-Sitosterol	$C_{29}H_{50}O$	414.70	65.636	48.43

Table 3. Fatty acid composition of *S. foetida* kernel oil

Fatty acid	Retention time (min)	Relative area (%)
Palmitic acid (C16:0)	35.40	1.22
Palmitoleic acid (C16:1 [cis-9])	37.08	57.06
Oleic acid (C18:1)	43.92	5.07
Linoleic acid (C18:2)	45.13	15.41
Arachidic acid (C20:0)	47.24	18.26
Eicosadienoic acid (C20:2)	53.26	2.96
SFA		19.48%
MUFA		62.13%
PUFA		18.37%

SFA=Saturated fatty acids; MUFA=Monounsaturated fatty acids; PUFA=Polyunsaturated fatty acid

to change their morphometric attributes (Zobel and Talbert 1984, Sukhadiya et al., 2021). The study indicated that overall, seed length, width and seed weight had average values varied significantly. These variations in morpho-metric attributes among the studied landscapes reflects prevailing influence of both genetic and environmental factors on the individuals of these landscapes (Elmagboul et al., 2014, Finch-Savage and Bassel 2016, Malek et al., 2024).

The SFSKs contain golden yellow oil (Habib et al., 2013). Oil from seed kernels have been reported to show high quality and oxidative stability during storage. Thus, seed kernels could be used as a potential source of edible oil in the food industry (Chanyawiwatkul et al., 2018). The oil content obtained in the present study is in conformity with earlier studies (Chanyawiwatkul et al., 2018, Devarajan et al., 2022) in this species. However, Bose et al. (2021) reported higher oil content (58.70%) whereas, Farsana et al. (2022) have reported lower oil content (34%) compared to our findings.

These variations may be ascribed to varied climatic and geological conditions, and genetic variability in *S. foetida* trees growing in different landscapes in present study (Sukhadiya et al., 2021, Malek et al., 2024). Further, oil yield in many oil-yielding species use to be seed moisture content driven. The higher oil content of VLD-3-L_8 is apparent from the fact that this landscape seed source showed lower moisture content and conversely oil content was less in seeds from NVS-1-L_2landscape which exhibited higher MC. These findings are in congruence with earlier similar inferences made by Orhevba et al. (2013).

Different compounds extracted from the plants possess various properties that which have significant effects on the health and nutrition of humans and livestock (Almodaifer et al., 2017). *S. foetida* seed and oil has anti-diabetic, antidermatophytic, antifungal, antifungal, insecticide, anticancer, anti-obesity, antibiotic, antiviral, hormonal, carcinogenic and antitumoral properties (Kale et al., 2011, Jafri et al., 2019, Subashini et al., 2020, Farsana et al., 2022). Seeds are safe to eat raw or cooked without any toxicity in humans or animals (Alam et al., 2021). A number of flavonoids, phenolics, steroids, coumarins, phenylpropanoids and cerebrosides have been found in the roots, leaves, seeds and barks of this species (Cuong et al., 2019) and triterpenoids, steroids, and fatty acids have also reported (Pham et al., 2021). Phytosterols (stigmasterol, β-sitosterol and squalene) exhibit various beneficial properties, including analgesic, immune-regulating, anti-inflammatory, antioxidant, anticancer, and anti-aging effects, as well as the ability to prevent cardiovascular diseases (Zhao 2016, Chen et al., 2017, Zhang et al., 2022, Luana et al., 2024). β–Sitosterol is one of the main dietary phytosterols belonging to the class of organic compounds known as stigmastanes (Sharma et al., 2021). The provenances studied in the present study could be source for further improvement to get kernel oil with higher beneficial volatile compounds.

Vegetable or tree born oil fatty acids are important compositional attributes as they have antioxidant, antibiotic, antifungal, insecticide anti-tumor activity *etc.* (Subashini et al., 2020, Farsana et al., 2022). Palmitic acid was reported as dominant fatty acid (52%) in this species seed oil (Vipunngeun and Palanuvej 2009). However, in Indian seed oil it was found 11.87% (Kale et al., 2011) comparatively, it was lowest (1.22%) in the current research. In same species the total saturated fatty acids and unsaturated fatty acids amounted up to 15.80% and 33.35% (Kale et al., 2011). Total 27.32% saturated fatty acids and 5.30% mono-unsaturated fatty acids, 55.95% poly-unsaturated fatty acids reported in *S. foetida* seed oil (Chanyawiwatkul et al., 2018), which is comparatively different from the present study. Ghazani et al. (2014) indicated that the extraction methods and solvent used also had the impact on fatty acid composition in oil. *S. foetida* oil fatty acids have been found to have antioxidant, antibiotic, antifungal, insecticide and anti-tumor activity (Kavitha et al., 2015, Subashini et al., 2020, Farsana et al., 2022).

CONCLUSION

The present findings deduced significant variations in *S. foetida* seed morpho-metric varied significantly across the landscapes. The kernel oil content was in good percentage and gas-chromatography mass-spectrometry revealed 11 volatile compounds in extracted oil, which have been reported to have many beneficial biological properties particularly stigmasterol and β-sitosterol. Total Fatty Acid Methyl Esters (FAME) analysis of oil revealed 6 compounds

with maximum percentage of palmitoleic acid and these have been reported to have antioxidant, antibiotic, antifungal, insecticide and anti-tumor activity.

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AUTHOR'S CONTRIBUTION

M.R. Prajapati: sample collection, laboratory analysis, data arrangement and manuscript draft preparation; N.S. Thakur: research conceptualization, data interpretation, table and figure construction, reviewing and editing manuscript; A.A. Mehta: laboratory sample analysis, oil extraction, data interpretation; manuscript reviewing; Y.A. Garde: data tabulation and statistical interpretation.

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Influence of Type and Depth of Bark Incision on Gum Yield and Bark Recovery in *Lannea coromandelica*

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***Abstract*:** Gum tapping from forest trees played a vital role in supporting both rural livelihoods and a multiple of industries in India. *Lannea coromandelica* produces commercial gum called *Jhingan* and is commonly found in the moist and dry deciduous forests. In order to explore and understand how different methods of making cuts in the bark as well as varying cut depths on gum yield and bark recovery in *L. coromandelica,* a field study was conducted at Sirsi, Karnataka. Healthy trees were selected for the experiment and each was subjected to four types of bark incisions like notch, vertical, horizontal and slant cut, with four different depths: 0.5, 0.75, 1.0, and 1.5 cm. The horizontal cuts led to the highest gum yield (1520.7 g/m²), closely followed by notch cuts (1423.6 g/m²). In contrast, vertical and slant cuts produced significantly less gum yield. This species bark is thicker, hence deeper cuts, especially those at 1.5 cm, gave the highest gum output (1653.6 g/m²) with faster bark recovery (72%). The vertical and horizontal incisions allowed the best bark recovery (70% and 69%, respectively); while shallowest depth (*i.e.,* 0.5 cm and 1.0 cm) showed the lowest bark regeneration rate (<50%). These findings suggest that while deeper, horizontally placed cuts in *L. coromandelica* can maximize gum extraction, and also increases the risk of long-term damage to the tree.

***Keywords*:** Bark incision, Bark recovery, Gum yield, Jhingan, *Lannea coromandelica*

India is one of the world's top exporters of natural gums and resins, exporting goods worth USD 127 million in 2022 and USD 89 million in 2023 under HS Code 1301. However, despite this, the country imported nearly USD 241 million worth in 2023 alone, mostly from countries like Afghanistan, Indonesia, and Mali (Anon 2024). This mismatch highlights the need to boost domestic production, improve quality standards, and build stronger value chains.

The gum trade depends heavily on the species like *Anogeissus latifolia* (Gum Ghatii) and *Sterculia urens* (Gum Karaya), however, others like gums from *Acacia senegal*, *Boswellia serrata*, *Commiphora wightii* and *Lannea coromandelica* also contribute significantly to total gum production (Ramawat et al 2014, Sinha et al 2021). For many forest-based communities, gum collection is more than a livelihood therefore, programs like the minimum support price for NTFPs and TRIFED's Van Dhan Yojana have been introduced to support these communities by promoting fair trade and sustainable practices (ICAR 2021, Volza 2024). Improved tapping techniques raised the price of gum in gum karaya from ₹30 to ₹125 per kilogram (FAO 2021). Despite of these efforts, traditional tapping methods are often inefficient and can harm trees. Elements such as cut design, depth, season, tree size, and even chemical stimulants like ethephon all influence how much gum a tree produces and how well it recovers afterward (Nayak and Prajapati 2020).

Lannea coromandelica (Houtt.) Merr. is a lesser-explored but promising gum yielding species distributed in deciduous forests and can grow up to 24 meters height. It is commonly found throughout India and the Andaman Islands, especially in dry deciduous forests and hilly areas up to 1,500 meters above sea level. This tree is known for producing Jhingan gum during the dry season from March until the onset of monsoon (Vasishth 2017). *Jhingan* gum is used in a wide range of applications from textile sizing and ink production to varnishes, plastering, and even clarifying sugarcane juice, where its performance rivals' synthetic agents like Lytron-X 886 (Nayak and Prajapati 2020). Unfortunately, current harvesting methods often lead to low yields and stress the trees. Factors like tapping depth, method, tree age, and use of stimulants all play a role in determining both productivity and long-term sustainability (Nayak and Prajapati 2020, Dhaka et al., 2017, Sinha et al., 2021). Current practices of bark harvesting from wild populations which include girdling, bark stripping from large portion of trunk/branches or chopping off trees, followed in India are largely unsustainable (Pandey and Mandal 2012). While harvesting or damaging bark, it is essential to consider how a tree species recovers from the wound made by blazing in order to develop species-specific bark harvesting systems and parameters such as strip geometry, rotation period, age of the tree (diameter of trees), and proportion of individuals subjected to bark harvesting in a population as key parameters to be considered while developing sustainable bark harvesting and conservation including population status and genetic diversity of a species (Pandey and Mandal 2012, Hanumantha 2020, Hanumantha and Vasudeva 2022, Thakur et al., 2023). The forests face growing pressure from

human activity and over extraction, species like *Lannea coromandelica* are at risk. This makes it all the more urgent to adopt standardized, tree-friendly tapping practices that align with broader goals of conservation, sustainable forest use and rural development (FAO 2021, ICAR 2021). With this backdrop, the present investigation was carried out to understand the influence of incision (cut) type and its depth on gum production, bark recovery and pest and disease occurrence in *L. coromandelica*.

MATERIAL AND METHODS

The study was conducted near Banavasi Road, Sirsi, Uttara Kannada district of Karnataka, India. The study area belongs to the geocoordinates- latitude of 14°36"17.10" N and longitude of 74°51'05.19" E with altitude of 613 m above mean sea level. Climatologically, the area receives a mean annual rainfall of approximately 3000 mm, with average temperatures ranging from 20 to 33°C. The region is characterized by lateritic soils and undulating topography with an average elevation of 500 meters above sea level.

Out of fifty *Lannea coromandelica* trees marked in the field, ten healthy trees of similar size class and free from pests and diseases were selected for the gum tapping experiment. Four different tapping methods and four different incision depths were implemented to evaluate their effects on gum yield. The treatments were replicated across trees. Gum was collected once every 15 days and total gum production was calculated per square meter following the protocol described by Prasad et al (2016). On every visit, per cent bark recovery was visually scored for per cent bark regeneration and photographic evidence was taken. After incision, observations of insect/pest attack if any on cut position was also noted (Hanumantha and Vasudeva 2022). Tree growth parameters such as height (7.0-12.0 m), girth (47.0-160.0 cm), bole height (1.7 to 5.0 m) and crown width (3.7-7.0 m), were recorded in the marked trees (Table 1).

Tapping Methods

Type of incision: To assess the effect of different tapping methods on gum yield, four types of incisions *viz.,* notch cut (conventional method), vertical cut, horizontal cut and slant cut, were applied on five trees. Before making the cuts, dead bark was removed (10 cm² area) from four different sides of each tree trunk, one for each cut type. Five treatments were imposed on the standing trees, which included T_1- Notch method: 10 notches,T_2 - Vertical cut: 5 vertical lines, T_3 - Horizontal cut: 5 horizontal lines. T_4 - Slant cut: 5- Slanted lines (Plate 1).

Depth of incision (cut): To study the effect of different incision depths on gum yield, five trees were selected during the June–September period. Dead bark (10 cm²) was removed from four different sides of the trunk, and incisions of varying depths 0.5 cm (D_1), 0.75 cm (D_2), 1.0 cm (D_3), and 1.5 cm (D_4) were made on the cleared bark areas.

The gum exudates were collected at 15-day intervals from both (type and depth of cut) the treatments. Later collected gum is processed, dried, weighed, and expressed in g/m².

Bark recovery: After implementing treatments on selected tree bark recovery (regeneration) was recorded in response to different tapping methods and depths after four months.

Statistical analysis: The collected data were subjected to one-way analysis using a completely randomized design (CRD). Mean values of gum yield and bark recovery were compared at P< 0.05 significance level by using critical difference (values calculated for each parameter. OPSTAT software was used for statistical computation and result interpretation (Sheoran et al., 1998).

RESULTS AND DISCUSSION

Influence of type of incision on gum yield and bark recovery: Among the various types of incisions/cuts (Plate 1), the highest gum yield was recorded in the horizontal cut (1520.70 g/m²), followed by the notch cut and it was the least in vertical cut (795.2 g/m²). The yield from the horizontal cut from the notch cut did not differ significantly between vertical and slant cuts (Table 2). Hence for production of more gum in *Lannea cormoandelica,* horizontal or notch cuts would be best as compared to slant and vertical cut. Prasad et al (2081) also reported higher gum yield in the notch cut (1033.36 g/m²) for *Butea monosperma*. The superior performance of horizontal cuts is likely due to the orientation and better exposure of gum canals along the cambial layer in *Lannea coromandelica* and enhanced exposure facilitates greater exudation. Even tapping direction in plants

Table 1. Biometric attributes of selected standing trees of *Lannea coromandelica*

Tree code	Height (m)	Girth (cm)	Clear bole height (m)	Crown width (m)
LL-1	10.0	160.0	2.0	5.0
LL-2	9.0	68.0	3.5	4.0
LL-3	10.0	97.0	1.7	7.0
LL-4	10.5	70.0	5.0	7.0
LL-5	12.0	65.0	3.0	6.0
LL-6	10.0	95.0	3.0	4.5
LL-7	10.5	110.0	2.5	6.5
LL-8	7.0	47.0	1.5	3.7
LL-9	7.5	55.0	4.0	4.0
LL-10	8.5	68.0	2.5	3.7

concerning sunlight is a very important factor in gum yielding. Adam et al. (2009) reported the effect of direction of the wound on gum production in *Accacia senegal*. The study revealed that the gum yield was increased to 60 per cent when the taping was in eastern and western site towards direct sunlight, as because these two sites receive the maximum amount of sunshine which help in rapid drying of the exudates accompanied by the high temperature facilitating high gum production. Gessmalla et al. (2015) on *Boswellia papyrifera* also confirmed the suitability of eastern and western sides for tapping the maximum amount of gum. Along with the side direction, tapping position also had a valuable impact on the production of gum. The different position of tapping on *Acacia seyal* leads to different production of gum. The tapping on the higher stem and upper branches causes lower production of gum than the middle and lower stem of the plant (Kamal et al., 2004).

Significant variation for recovery of bark was observed among different types of incision. The highest bark recovery was n vertical cuts (70%), followed by horizontal. However, t was slow in notch (38%), and slant cuts (37%) (Table 2). Bark recovery for vertical and horizontal incision was significantly higher than for notch and slant cuts. Pandey et al. (2011) also observed 48 per cent bark recovery in strip bark harvesting in *Holarrhena antidysenterica*. Higher recovery in vertical and horizontal methods may be attributed to clean incision that minimize the cambial damage, thus, promoting faster bark regeneration (Hanumantha 2020, Sinha et al., 2022).

Influence of depth of incision (cut) on gum yield and bark recovery: Significant variation in gum yield among different depths studied was where maximum gum yield was recorded in the 1.5 cm deep cut (1653.6 g/m²), followed by 1.0 and 0.75 cm depth and was the least in 0.5 cm depth incision (683.6 g/m²) (Table 3). The bark thickness varies in different species, where thickness of the bark to be considered was 1.5 to 2 cm to make wounds on gum canals cut/incision for longer depths in *Lannea coromandelica*, since 1.5 cm deep incision resulted in higher gum yield. Vasishth (2017) also reported maximum gum yield in 5 cm borehole tapping during summer in *Lannea coromandelica*. The increased yield in the 1.5 cm cut may be attributed to penetration beyond the bark's surface into gum ducts, enhancing gum exudation. However, sustainability must be weighed against potential damage to tree health. Prasad et al. (2016) conducted similar work in *Butea monosperma* and reported that the maximum gum yield occurred in 1.0 cm deep cut (31.06 g/m^2) than 0.5 cm and 1.5 cm deep cuts (22.06 g/m^2 and 25.21 g/m^2, respectively). The variation in gum yield between these two species could mainly attributed to the thickness of the bark. The recovery of bark, it varied significantly among different depths of incision/cut. The highest bark recovery was noted in the D_4 treatment where incision was made up to 1.5 cm depth (72%), followed by D_3 *i.e.,*1.0 cm depth incision (71%), however, slow recovery was observed in D_2 (42.69%) and D_1 (47%) (Table 3). Pandey and Mandal (2012) reported about

Table 2. Influence of different type of cuts on gum yield and bark recovery in *L. coromandelica*

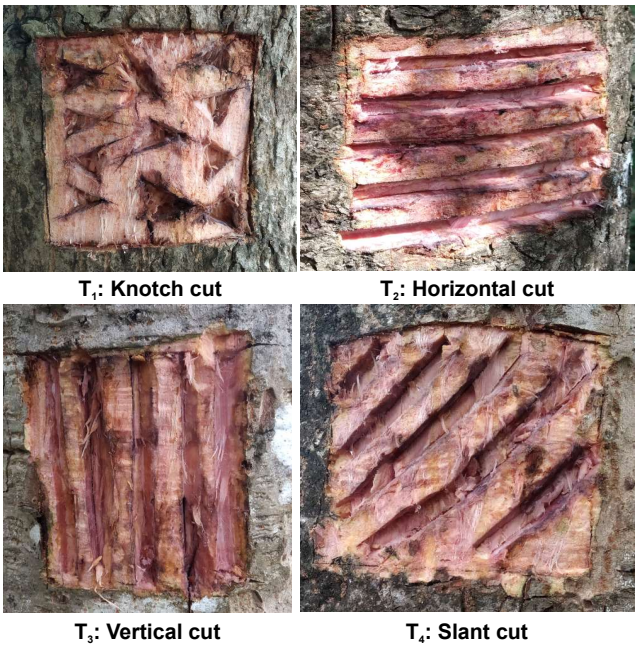
Treatment-Type of Incision	Gum yield (g/m²)	Bark recovery (%)
T_1 – Notch cut	1423.60	38.00 (38.02)
T_2 – Vertical cut	795.20	70.00 (56.94)
T_3 – Horizontal cut	1520.70	69.00 (56.36)
T_4 – Slant cut	900.30	37.00 (37.42)
		2.04
CD (p=0.05)	110.56	6.18
CV (%)	35.24	9.69

*Values in parentheses are arc sine-transformed values

Table 3. Influence of different depth of incision (cut) on gum yield and bark recovery in *Lannea coromandelica*

Treatment-Depth of incision	Gum yield (g/m²)	Bark recovery (%)
D_1 – 0.5 cm	683.60	47.00 (43.27)
D_2 – 0.75 cm	804.60	46.00 (42.69)
D_3 – 1.0 cm	1435.94	71.00 (57.59)
D_4 – 1.5 cm	1653.60	72.00 (58.15)
CD (p=0.05)	58.89	5.46
CV (%)	19.03	8.01

Parentheses are arc sine-transformed values



T_1: Knotch cut **T_2: Horizontal cut**

T_3: Vertical cut **T_4: Slant cut**

Plate 1. Different types of incisions/cuts applied on *Lannea coromandelica* trees for gum production

38 per cent bark recovery in strip bark harvesting method in *Terminalia arjuna* using shallow incisions.

Many authors reported that several factors such as type and width of the cut, humidity, anatomical features, *etc* may have influence on the recovery of bark. Hanumantha and Vasudeva (2022) reported maximum bark recovery (51.01%) in narrow patches (25×6 cm) than broader patches (10×15 cm) with 41.11 per cent bark recovery in *Cinnamomum zeylanicum* after 12 months. Maintenance of higher humidity of the exposed surface is the single most important factor that enhances the bark recovery (Juan et al 2006). Since the narrower strips have larger perimeter, the number of living cells in the xylem that contribute towards wound closure would be higher than in the broader strips and longitudinal strips with only outer and middle bark should be removed without damaging the inner bark for quicker regeneration (Pandey 2015). However, the anatomical details of bark regeneration in *Lannea coromanelica* are still unclear.

CONCLUSION

Study concludes that incision types and depth of cut influences the gum flow and gum production in *L. coromanelica*. The study suggested to follow horizontal cuts at a depth of around 1.0-1.5 cm for obtaining maximum gum yield and faster recovery of bark in view of sustainable yield and long-term tree health. Moving forward, research should also explore seasonal effects, physiological responses over time, and the economic aspects of tapping in this species.

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Growth Rings and Climate Patterns: Evaluating the Dendrochronological Review of Central and Peninsular India

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Abstract: Dendrochronology has emerged as a vital tool for reconstructing past climates and understanding tree-climate interactions, yet its application in Peninsular India remains limited and uneven. This review synthesizes published studies from the region, covering 20 tree species across 14 families, and reveals a striking dominance of *Tectona grandis*, which accounts for more than 96% of research efforts. Teak has proven to be a robust proxy for monsoon rainfall and drought events, owing to its distinct growth periodicity and strong climatic sensitivity, but the overwhelming reliance on a single species restricts broader ecological inference. Other promising taxa such as *Toona ciliata*, *Magnolia champaca*, and *Dalbergia latifolia* remain underexplored despite demonstrated dendrochronological potential. Spatially, research is disproportionately concentrated in moist deciduous and evergreen forests, while dry deciduous ecosystems, which may capture stronger precipitation seasonality signals, are underrepresented. Methodologically, most studies emphasize dendroclimatology and ring dating, with limited integration of wood anatomy, density, and isotopic approaches that could deepen climate signal extraction. Collectively, these gaps highlight the urgent need for expanding species coverage, diversifying ecological settings, and adopting interdisciplinary methodologies to strengthen tree-ring science in India. Advancing such efforts will not only refine monsoon reconstructions but also enhance regional climate resilience strategies, water management planning, and long-term ecosystem monitoring under global climate change.

Keywords: Dendrochronology, Climate, Broadleaf trees, Precipitaion, Central and Penisular India

Dendrochronology is the branch of science that studies tree rings and gives detailed information about tree age, growth pattern, past environmental conditions, forest fire, soil distribution, insect pest outbreaks, and wood density of tree species in past ecological conditions (Schweingruber 2012). Tree ring data on environmental conditions through their growth pattern and later used as a collection of historical data in past environments. Tree ring width gives information about growth patterns and long-term environmental deal with past variation time scales yearly (George 2014). This information is critical to understand the climate change in particular vegetation areas (Babst et al., 2018, Upadhyay and Tripathi, 2019) to understand the relationship between their growth pattern and climate condition (Gaire et al., 2020). This scientific discipline leverages the annual growth increments, or tree rings, to reconstruct past environmental conditions, with dendroclimatology specifically utilizing ring-width variations to infer historical climate variability. Beyond radial growth, dendroanatomy, which involves the analysis of xylem-cell features, offers a more nuanced understanding of the complex xylogenetic processes and their responses to environmental fluctuations (Pandey 2021). The intricate relationship between tree-ring characteristics and environmental parameters, including climatic variables, forms the foundation for dendrochronological interpretations, elucidating the historical context of ecological dynamics (Gartner et al., 2002). The formation of these annual rings, encompassing both earlywood and latewood, is intrinsically linked to seasonal growth patterns and can be meticulously cross dated to specific years, thereby creating robust chronologies for various interdisciplinary applications. This precise dating technique allows for an annual, and seasonal, resolution of past events, making it an invaluable tool for archaeological and environmental reconstructions (Towner 2015). Tree-ring records provide an effective proxy method for examining paleoclimatic conditions, as the annual growth ring width reflects surrounding climatic variability, establishing a temporal record of past trends and specific events (Carroll and Jules 2005).

A greater number of dendrochronological studies on the related history of particular forest areas, as well as climatic conditions past and present, have been carried out in various geographical regions of India (Bhattacharyya and Shah 2009, Shah et al., 2014, Pandey et al., 2016). Tree ring research in India mostly focuses on forestry aspects like wood quality, wood productivity, and growth patterns. Tree ring is mainly used for the reconstruction of climate and environmental issues.

Historical development of dendrochronology in India: Dendrochronological research in India began in the mid-20th century with preliminary studies focusing on tree-ring analysis in temperate forests of the Himalayas. Initial works by (Pant and Borgaonkar 1983) laid the foundation for tree-ring studies in India, emphasizing their potential for climate

reconstruction. Further advancements were made by (Yadav et al., 2006), who established long-term chronologies using conifer species such as *Cedrus deodara* and *Pinus roxburghii*. These early investigations primarily focused on the Himalayan region due to the presence of long-lived conifer species, which are particularly well-suited for dendrochronological studies. However, the application of these methodologies to the tropical and subtropical forests of Central and South India presented unique challenges, primarily due to less pronounced seasonality and the presence of complex growth patterns in many deciduous and evergreen species (Muhammad et al., 2021).

The establishment of tree-ring chronologies in India has facilitated reconstructions of past climatic patterns, particularly variations in temperature and precipitation. Studies by Bhattacharyya et al. (2007) and Shah et al. (2013) have demonstrated the impact of monsoonal variability on tree growth patterns, providing valuable insights into historical drought occurrences and temperature fluctuations.

Applications of dendrochronology in India: The primary applications of dendrochronology in India can be categorized into three main areas: climatic reconstructions, hydrological studies, and archaeological research. Dendrochronological records have been instrumental in reconstructing past climatic trends. Studies by Borgaonkar et al. (2010) have linked tree-ring width variations to monsoon strength, highlighting prolonged drought periods over the past few centuries. Such reconstructions are crucial for predicting future climate scenarios and understanding long-term climate variability.

Tree-ring analysis has also been employed to study historical water availability and river discharge patterns. Studies in the Western Himalayas and Central India have revealed correlations between tree growth and river flow, aiding in water resource management and flood prediction (Shah et al., 2014).

Dendrochronology has been applied in dating ancient wooden structures and artifacts in India. Studies by Bhattacharyya et al. (2009) have successfully dated timber used in historic temples and traditional buildings, providing chronological benchmarks for architectural history. Dendrochronology has proven to be a versatile tool in India, extending its applications beyond climatic reconstructions to include ecological and hydrological studies (Khan et al., 2013).

Challenges and future prospects: Despite significant advancements, dendrochronology in India faces several challenges. The tropical climate of India, characterized by less distinct seasonal variations in tree rings, poses difficulties in accurate dating (Quesada-Roman et al., 2022). Furthermore, the limited availability of suitable tree species for dendrochronological analysis restricts the scope of research. Addressing these limitations necessitates exploring alternative proxies, such as intra-annual density fluctuations, and expanding research to understudied regions and species (Tayyab et al., 2023) (Muhammad et al., 2021).

Future research should focus on expanding tree-ring networks across diverse ecological regions. Dendrochronology and Radiocarbon dating are the investigation of sedimentary records for studies on ecology or climate (Quarta et al., 2021). Collaborative efforts between Indian and international research institutions can enhance methodological approaches and improve the precision of climate reconstructions. India's climate-specific due to being impacted by seasonal wind patterns such as the Winter Monsoon and Summer Monsoon, along with related rainfall and temperature changes. The Indian economy depends on Variations of the monsoon, but the documents of monsoon data are not satisfactory for creating accurate climate projection systems. To more effectively analyze the long-term turn data of tree rings is a very important role in climate reconstructions and providing detailed information creates data for many centuries of (Bhattacharyya and Shah 2009). Three research institutions, viz., the Birbal Sahni Instute of Palaeoscience. IISC, IITM are currently the main centers in India for pursuing various aspects of tree-ring studies(Bhattacharyya and Shah 2009).

MATERIAL AND METHODS

Study area: India is a vast subcontinent with diverse geographical and cultural regions. Central India and Peninsular India possess unique physical, climatic, and socio-cultural characteristics. Central India serves as a transitional zone between the northern and southern parts of the country, while Peninsular India forms the southernmost geographical unit, surrounded by water on three sides (Singh 2020). Central India primarily includes the states of Madhya Pradesh and Chhattisgarh**,** along with portions of Uttar Pradesh and Maharashtra. Tropical dry and moist deciduous forests dominate it (Singh et al., 2024). Central India is home to tree species such as *Tectona grandis* (teak), *Shorea robusta* (sal), and *Dendrocalamus strictus* (bamboo) (Chandrakar et al., 2021, Dixit 2022), which show potential for dendrochronological studies.

Central India, encompassing states such as Madhya Pradesh, Chhattisgarh, and parts of Maharashtra, experiences a tropical climate with three seasons: summer, monsoon, and winter (Singh et al., 2025). The summer season (March to June) is characterized by high

temperatures, often exceeding 40°C, particularly in May (IMD 2021). Peninsular India consists of Maharashtra, Karnataka, Andhra Pradesh, Telangana, Tamil Nadu, Kerala, and Goa. The Arabian Sea bounds it to the west, the Bay of Bengal to the east, and the Indian Ocean to the south (Majumdar, 2022). It lies between 18° N and 26° N latitude and 75° E and 85° E longitude. This region encompasses diverse geographical features, including the Maikal and Satpura Ranges, Vindhya Hills, and river valleys of the Narmada, Mahanadi, and Godavari. The forests of Peninsular India fall under Moist and Dry Deciduous, Evergreen, and Mangrove Forests (ISFR 2021, Agrawal et al., 2010).

The forest types are Moist Deciduous and Tropical Dry Deciduous, with some patches of Thorn and Mixed Forests (Champion and Seth 1968). Peninsular India has a tropical monsoon climate with moderate seasonal variations. The region is influenced by both the southwest and northeast monsoons, with the latter providing significant rainfall to the eastern coast, particularly in Tamil Nadu (Sreekala et al., 2022). Unlike Central India, Peninsular India experiences relatively stable temperatures throughout the year, ranging from 20°C to 35°C, with coastal regions maintaining higher humidity levels (IMD 2021). The Western Ghats play a crucial role in orographic rainfall, making Kerala and coastal Karnataka among the wettest regions in India, with annual rainfall exceeding 2500 mm (Chandrashekar et al., 2018).

Central India and Peninsular India exhibit distinct climatic patterns due to their geographical locations, topographical features, and proximity to water bodies. This paper examines the climatic conditions of these two regions, highlighting seasonal variations, temperature ranges, and monsoonal influences. A major distinction between the two regions is the absence of a severe winter in Peninsular India, attributed to its proximity to the equator and moderating influence of the surrounding seas. In contrast, Central India experiences greater temperature variability due to its continental location. The climatic differences between these regions significantly impact agriculture, water availability, and overall ecosystem dynamics.

The methodology for reviewing the dendrochronological potential of Central India and peninsular India was designed to systematically collect and analyze data from existing studies. This review not only focuses on tree-ring research within Central India and peninsular India but also compares findings from other Indian regions where similar species have been studied, providing a broader perspective on dendrochronology's applicability.

Data collection: A comprehensive literature search was conducted using academic databases such as Google Scholar, Web of Science, Scopus, Science Direct, Wiley Online Library, ResearchGate, and Springer Link. Additional sources, including books, government reports, theses, and dissertations, were reviewed to ensure an exhaustive dataset (Acosta-Hernandez et al, 2017).

Search terms included combinations of keywords such as "Dendrochronology," "tree-ring analysis," "Central India," “Peninsular India”, "Western Ghats," "tropical deciduous forests," "climate reconstruction," and "tree growth-climate relationship." The review covered literature published between 1992 and 2024 to incorporate recent advancements in dendrochronological research.

Inclusion and exclusion criteria: Studies were included if they: Focused on dendrochronological research in Central India or peninsular India regions with similar tree species (e.g., Western Ghats, Eastern Ghats). Provided detailed methodologies for tree-ring sampling and analysis. Examined relationships between tree-ring growth and climatic parameters such as rainfall, temperature, or drought indices. Studies were excluded if they did not involve dendrochronology, lacked clear methodological details, or focused solely on other ecological aspects, such as biodiversity. Duplicate studies and those with overlapping datasets were also excluded.

Data extraction and verification: A standardized Excel format was used to systematically extract data. Key data points included the tree species studied, sampling locations, core extraction methods, tree-ring measurement techniques, climatic variables analyzed, and primary findings. Comparative fields captured similarities and differences in tree growth-climate relationships between Central India to peninsular India

Scientific names and tree species classifications were verified using authoritative botanical databases such as Plants of the World Online (https://powo.science.kew.org/). This step ensured consistency in species identification, especially for species studied across different regions of India.

Data analysis and reporting: Descriptive statistics were calculated to summarize the spatial and temporal coverage of studies, species diversity, and the range of climatic variables examined. Comparative analyses were conducted to evaluate how similar tree species in different regions (e.g., *Tectona grandis* in Central India versus the *Western Ghats*) respond to climatic factors.

The findings were synthesized into an inventory highlighting the dendrochronological Studies of Central India and peninsular India its. This inventory included details on tree species, study locations, methodologies, and key results. The comparative analysis provided insights into regional differences and commonalities in tree-ring growth responses.

RESULTS AND DISCUSSION

State-wise analysis of dendrochronological research in the Indian peninsular region reveals distinct patterns in both publication frequency and species focus (Fig. 1). Kerala accounts for the highest number of publications (13 articles), though only two species have been studied, reflecting repeated work on a narrow taxonomic base. Karnataka, with seven published articles, demonstrates the widest species coverage (17 species), indicating greater exploration of taxonomic diversity (Fig. 1). Maharashtra has an equal number of publications (7) but concentrated exclusively on a single species, primarily teak. Andhra Pradesh (5 articles), Tamil Nadu (1 article), and Madhya Pradesh (1 article) have relatively fewer studies, each limited to one species (Fig. 1). This distribution suggests a geographic and taxonomic imbalance, with research clustered in a few states and often restricted to teak or other widely distributed hardwoods, underscoring the need to diversify both regional and species coverage in future dendrochronological investigations.

Dendrochronological research has been conducted across three distinct vegetation types (Fig. 2). Notably, 48.28% of these studies have focused on Tropical Moist Deciduous, making them the predominant subject of investigation. This is followed by Tropical Evergreen Forests, which account for 34.48% of the studies (Fig. 2). Conversely, Tropical Dry Deciduous Forests have received considerably less attention, comprising only 31.03% of the total research conducted in the Indian peninsular region (Fig. 2).

A total of 20 tree species, belonging to 14 different families, were used in dendrochronological studies conducted across the Indian Peninsula (Fig. 3). Among these, the family Fabaceae had the highest species richness, contributing 3 species (14.3%), suggesting its notable presence in dendrochronological research (Fig. 3). Families such as Lamiaceae, Magnoliaceae, Meliaceae, and Myristicaceae each contributed 2 species (9.5%), reflecting moderate species-level representation. The remaining nine families, Anacardiaceae, Bignoniaceae, Combretaceae, Euphorbiaceae, Lythraceae, Malvaceae, Moraceae, Sapindaceae, and Ulmaceae, were each represented by a single species (4.8%) (Fig. 3). However, despite this taxonomic diversity, the dominance of Lamiaceae was overwhelming when analyzed in terms of article representation (Fig. 4).

Lamiaceae alone accounted for 96.55% of the total studies (Fig. 4), reflecting a concentrated research focus on this family, largely attributable to the frequent selection of *Tectona grandis*, which was utilized in 96.55% of the reviewed studies (Fig. 5). In contrast, other families such as Meliaceae (10.34%) and Magnoliaceae (6.90%) were only marginally represented (Fig. 5). All other families, including Fabaceae, despite higher species richness, appeared in only 3.45% of the articles each (Fig. 5). *Toona ciliata* and *Magnolia champaca* were the second most frequently studied species, each appearing in 6.90% of the articles (Fig. 5). All other species, including *Terminalia alata*, *Dalbergia latifolia*, *Gmelina arborea*, and *Mangifera indica*, were each reported in only 3.45% of the studies (Fig. 5). These results

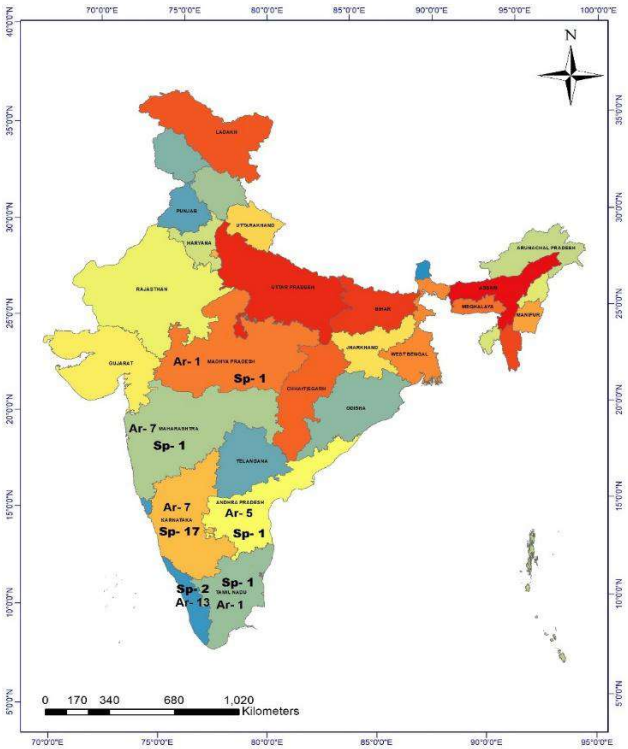

Fig. 1. State-wise analysis of Dendrochronological studies performed in the Central and peninsular region of India. AR -articles, SP- species

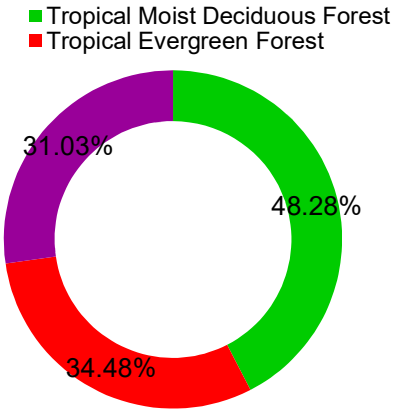

Fig. 2. Percentages of studies classified according to the type of forest ecosystem following Champion and Seth's forest classification system

reveal a clear research preference for specific species, especially teak, based on dendrochronological suitability, while also highlighting the underutilization of several other ecologically important taxa in growth ring analysis.

The reviewed studies were categorized based on their primary area of application within dendrochronological research across the Indian peninsular region (Fig. 6). A majority of the studies (65.52%) focused on dendroclimatology, reflecting a strong emphasis on climate-growth relationships in tree-ring research (Fig. 6). Dendrochronology as a core dating method accounted for 27.59% of the studies, while more specialized applications such as dendroanatomy and studies involving growth ring and specific gravity were each represented by only 3.45% of the literature (Fig. 6). This distribution highlights a notable research inclination toward climate-focused dendrochronological analysis, with limited exploration into wood anatomical and density-related investigations (Fig. 6).

The temporal distribution of dendrochronological studies in the Indian Peninsula (Fig. 7) reveals a sporadic publication

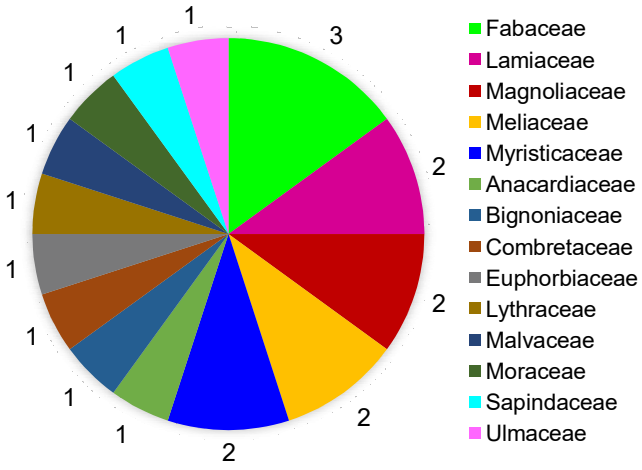

Fig. 3. Family-wise distribution of tree species selected for dendrochronological study in the Indian peninsular region

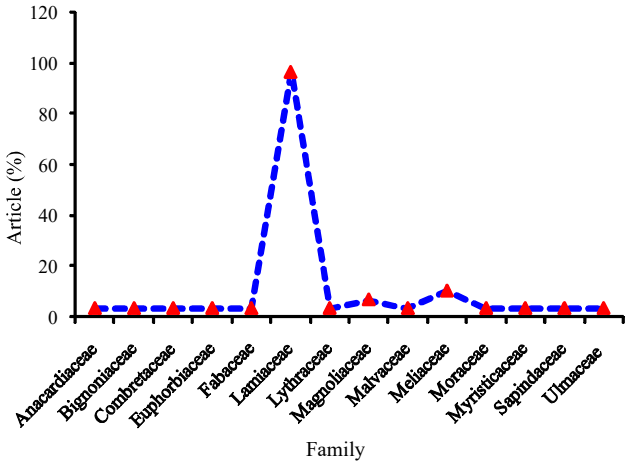

Fig. 4. Dendrochronological studies performed in the Indian peninsular region, categorized by taxonomic family

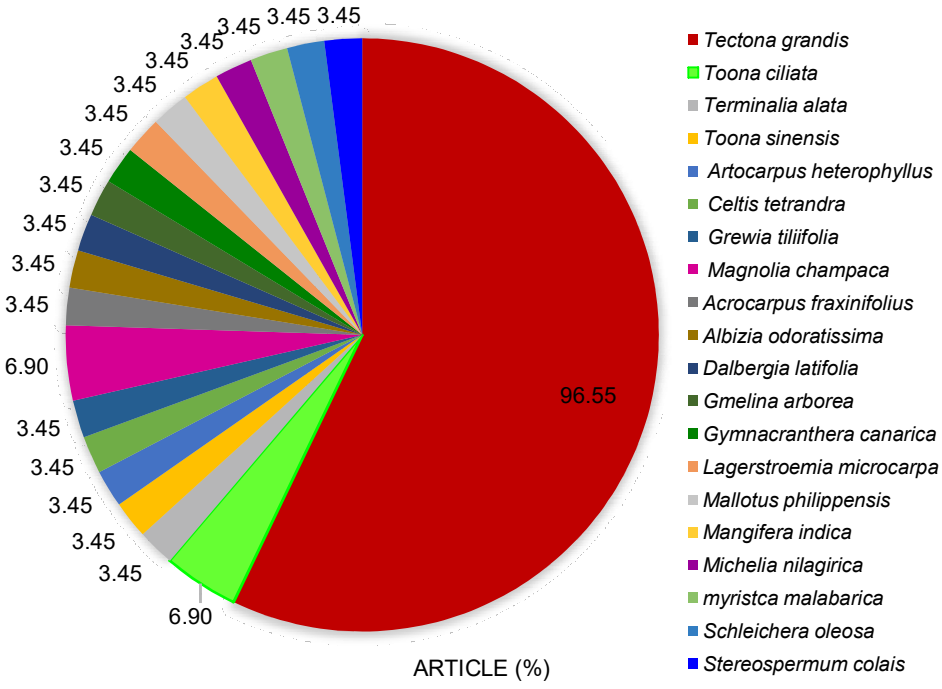

Fig. 5. Dendrochronological studies performed in the Indian peninsular region, categorized by tree species

trend from 1992 to 2023, characterized by notable fluctuations in research output. Early contributions were sparse, with only one article each in 1992, 1996, 1997, 2000, and 2005. A gradual increase is observed from 2007 onwards, with two studies published each in 2007, 2008, and 2010 (Fig. 7). The peak research activity occurred in 2011, with four publications, followed by a slight decline in subsequent years. Secondary peaks were noted in 2012 and 2016 (three articles each), indicating intermittent surges in interest. The period after 2018 has reflected a moderate and consistent output, with one to two publications per year (Fig. 7). Overall, the data suggest that dendrochronological research in the Indian peninsula has expanded over the past two decades, albeit with irregular intervals of heightened activity.

This review reveals that dendrochronological research in Peninsular India remains heavily skewed in terms of species selection, forest type coverage, and research applications.

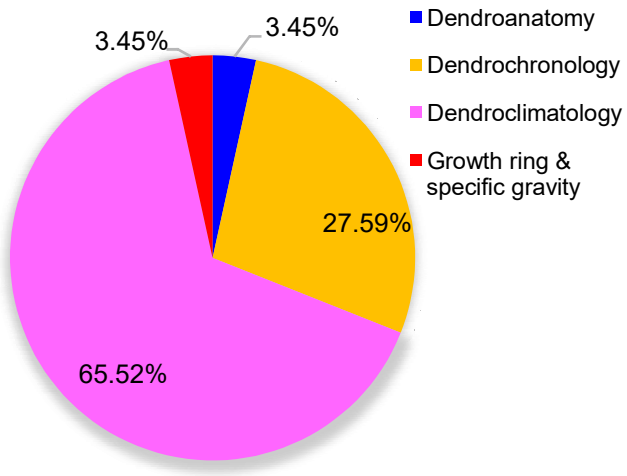

Fig. 6. Dendrochronological studies conducted in the Indian peninsular region, categorized by area of application

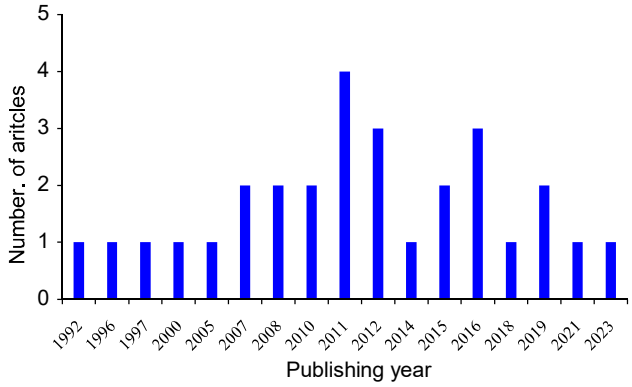

Fig. 7. Dendrochronological studies published in Indian peninsula, grouped by year of publication

Despite sampling 20 species across 14 families, the vast majority of studies (>96%) rely on *Tectona grandis*. Analyses conducted in Central India have demonstrated strong positive correlations between teak tree-ring widths and both monsoonal rainfall and soil moisture indices, establishing teak as a highly reliable proxy for past precipitation (Ram et al., 2008). Similarly, investigations in the Western Ghats confirmed ability of teak to reliably reflect drought years based on ring-width chronologies (Deepak et al., 2017). Further, Sinha (2012) provided empirical evidence linking teak ring-width variations to local rainfall and temperature, reinforcing teak's strong monsoon sensitivity. This focus is understandable given teak's pronounced annual layering, cambial dormancy from October–December, reactivation by pre-monsoon rains, and maximal growth during June–July (Priya and Bhat, 1999). In addition, a study by Upadhyay et al. (2019) evaluated the dendrochronological potential of teak and developed short tree-ring chronologies, which further substantiates its reliability as a climate-sensitive species for dendroclimatic reconstructions.

In contrast, *Toona ciliata* and *Magnolia champaca* appear in only 7.14% of studies, and many species, such as *Terminalia alata*, *Dalbergia latifolia*, *Mangifera indica*, and *Gmelina arborea* are each featured in just 3.57% of articles. While *T. ciliata* has shown dendrochronological potential, local chronologies in northeast India spanning several decades have been constructed and used for climate-growth interpretation (Shah and Mehrotra 2017), its adoption remains limited. This narrow taxonomic focus may limit the ecological and physiological modulation of growth responses captured in current chronologies.

The geographic distribution of studies reveals a clear imbalance, with the majority of research concentrated in Tropical Moist Deciduous (41%) and Evergreen Forests (31%), while Dry Deciduous Forests are noticeably underrepresented at 28%. This uneven pattern may reflect ease of access to wetter forests or the perception that tree rings in moist environments exhibit clearer annual boundaries. However, such spatial skew carries the risk of omitting critical climate signals inherent to drier biomes, forests characterized by stronger precipitation seasonality, which can result in distinct cambial dormancy and annual ring formation (Rozendaal and Zuidema 2011). Broader reviews of tropical dendrochronology emphasize that while many tropical tree species form annual rings, the strength and clarity of these rings are heavily influenced by local climate patterns, particularly the presence and duration of a dry season (Quesada-Roman et al., 2022). Consequently, focusing predominantly on moist and evergreen zones may limit the capture of growth responses tied to moisture-stress

dynamics and seasonal drought common in dry deciduous regions.

The majority (64.29%) of studies focus on dendroclimatology, with ring dating alone accounting for 28.57% and anatomical or specific gravity investigations each at 3.57%. This reflects Indian dendrochronology's historical prioritization of monsoon reconstruction over exploring internal wood structure. Yet recent evidence from Indian teak trees shows wood density and latewood content vary significantly with age and climate, particularly in mature wood, indicating potential for richer signal interpretation through density and anatomical approaches (Sinha et al., 2014, Bhat 1995).

CONCLUSION

This review underscores that dendrochronological research in Peninsular India, though promising, remains narrowly focused in terms of species, forest types, and methodological scope. The dominance of teak-centered studies has advanced monsoon reconstructions but limits understanding of diverse climate-growth relationships across other ecologically and economically important tree species. Similarly, the underrepresentation of dry deciduous forests restricts insights into growth responses linked to seasonal water stress, which are highly relevant in the context of intensifying climate variability. Moving forward, expanding research beyond teak to include multipurpose and endemic taxa, broadening geographic coverage to neglected forest types, and integrating anatomical, density, and isotopic analyses are crucial steps to strengthen the reliability and applicability of dendrochronological findings. Such advancements would position Peninsular India as a key contributor to global tropical dendrochronology, enhance our ability to interpret past climate variability with greater confidence, and support adaptive strategies for forest management, water security, and biodiversity conservation. The future of dendrochronology in India thus lies in fostering interdisciplinary approaches and building robust, multi-species, multi-ecosystem chronologies that truly capture the climatic and ecological complexity of the region.

AUTHOR'S CONTRIBUTIONS

V. B.: Conceptualized the review framework and contributed to data collection. S.S.: led the literature compilation, data analysis, and synthesis of results, drafted and revised the manuscript, and provided overall supervision and guidance throughout the study. A.K.S.: contributed to the study design, critically reviewed the manuscript for scientific accuracy, and provided expert input. S.R.C.: prepared the map, assisted in data organization, and reference management. All authors read and approved the final version of the manuscript.

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Forest Remedies: Plant-based Health Practices of the Siddi Tribal in Karnataka

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Abstract: This study investigates the ethnobotanical knowledge of the Siddi tribal community inhabiting the Western Ghats region of Karnataka, India, a distinct Afro-Indian group with ancestral roots in East Africa. Field documentation across four settlements such as Kerehosalli, Bilki, Hunsemane and Kotemane in Yellapur taluk were conducted. Data were collected from 28 families using semi-structured interviews, participatory observations and focus group discussions. This resulted in the identification of 60 plant species, of which 56 were used for medicinal purposes and 11 as food. The leaves are the most commonly utilized plant part, with pastes, decoctions and juices being the primary methods of preparation. Remedies were administered either orally or externally, based on the type of ailment. The Siddi community exhibits a practical, non-ritualistic approach to healing, with knowledge widely shared and passed down orally. Many plants serve dual functions as food and medicine, illustrating a holistic understanding of health where diet and treatment are interconnected. This practice underscores a sustainable relationship with the surrounding forest ecosystem, promoting both biodiversity conservation and cultural resilience. However, threats such as environmental degradation, habitat loss and cultural assimilation pose risks to the preservation of this traditional knowledge. The study highlights the urgency of documenting and protecting such indigenous knowledge systems through collaborative efforts, ethical research practices and policy interventions guided by frameworks like the Nagoya Protocol. Overall, research underscores the significance of traditional ethnomedicinal and ethnofood practices in ensuring sustainable development, public health and the continuity of tribal heritage.

Keywords: Ethnobotany, Ethnofood, Siddi tribe, Plant-Based Healthcare and Karnataka

The Afro-Indian community, referred to as the Siddis, represents a distinctive diasporic group in India with ancestral origins tracing back to East Africa. As per 1981 Census, the Siddi population in India is estimated at approximately 54,291 individuals (Karmwar and Srivastava 2025). Historical accounts document the establishment of two prominent Siddi kingdoms along the western coast of India-Janjira and Jaffrabad-around the 12th century A.D. Over time, descendants of African origin settled across various Indian states including Karnataka, Gujarat, Maharashtra, Andhra Pradesh and Telangana. They have come to be known by different appellations such as Siddi, Sidi, Siddi Badshah and Habshi. Today, many members of this community are largely assimilated into the broader Indian population in terms of language, appearance and cultural practices (de Silva Jayasuriya 2015). Despite this integration, limited research has explored the influence of India's pluralistic medical systems particularly Ayurveda and biomedicine on the traditional ethnomedicinal practices of the Siddis.

In Karnataka, the Siddis are primarily concentrated in the districts of Uttara Kannada, Dharwad and Belagavi, where they have historically settled in forested and hilly regions. Linguistically, they communicate in a mix of Konkani, Kannada and Siddi dialects and largely adapted to the regional socio-cultural context. The community continues to preserve unique elements of African heritage, particularly in their music, dance (notably the *Dhamal*) and spiritual healing practices. Traditional medicinal knowledge remains integral to their healthcare system, with a strong reliance on plant-based remedies and indigenous health beliefs passed down through generations. The forested landscapes of the Western Ghats have played a pivotal role in shaping the Siddis' ethnobotanical knowledge, as they depend on the local flora for treating a range of ailments including fever, gastrointestinal disorders and respiratory disorders.

In a progressive move to support the documentation and study of such traditional knowledge systems, the Government of India granted Ms. Seema Solanki of the University of Kent, United Kingdom, access in 2021 to the ethno-medicinal knowledge of the Siddi community in Gujarat (Karmwar and Srivastava 2025). The Karnataka Siddis are similarly recognized for their extensive and longstanding ethnomedicinal practices. In Haliyal Taluk, Uttara Kannada, Makanur et al. (2024) documented the use of medicinal plants by the Siddis in addressing a wide range of ailments such as diabetes, kidney stones, snakebites, dengue fever, piles, gastric disorders, fever, skin problems and wounds. These traditional remedies continue to serve as

an essential part of community health management, even as their transmission to younger generations shows signs of decline. Such documentation is crucial not only for cultural preservation but also for contributing to pharmacological research. This initiative aligns with the principles of the Nagoya Protocol, an international agreement under the Convention on Biological Diversity, which seeks to ensure the fair and equitable sharing of benefits arising from the utilization of genetic resources. It promotes transparency and safeguards against the unauthorized appropriation of traditional knowledge for intellectual property rights (IPR) without proper acknowledgment or benefit-sharing with the originating communities.

This development underscores a growing international commitment to the protection of indigenous rights and the promotion of collaborative, ethical research. It also positions the Siddi community including those in Karnataka as vital stakeholders in preserving and advancing traditional knowledge systems and promoting cultural resilience in the face of modernization. Therefore, the present study was undertaken to document the ethnobotanical knowledge including ethnofood practices of the Siddi tribal community inhabiting the Western Ghats region of Karnataka, India.

MATERIAL AND METHODS

Description of the study area: The present study was carried out among the Siddi tribal community residing in the Western Ghats region of Karnataka, India. The Siddis are primarily concentrated in the districts of Uttara Kannada with notable settlements in Yellapur taluk at four tribal settlements namely Kerehosalli**,** Bilki**,** Hunsemane and Kotemane. This region is part of the ecologically sensitive Western Ghats, recognized as one of the eight biodiversity hotspots" of biological diversity in the world (Miltenberger et al., 2018). The geographical coordinates of the study area range approximately between 14°38′N to 15°01′N latitude and 74°25′E to 75°25′E longitude. Situated at an elevation of approximately 500–900 meters above sea level, the area is characterized by dense tropical evergreen and semi-evergreen forests, hilly terrain and high annual rainfall, especially during the monsoon season (June to September). Temperatures in the region typically range between 15°C in winter and 32°C in summer, with high humidity levels prevailing through most of the year.

The Siddi settlements are generally located near forest fringes, agricultural lands and water bodies, where they engage in subsistence farming, wage labour and collection of non-timber forest products (NTFPs). The flora-rich landscape provides a wide array of ethnomedicinal plants used traditionally for treating various ailments. The Siddi people have inherited rich traditional ecological knowledge (TEK), particularly in herbal medicine, dietary practices and healing rituals, derived from centuries of interaction with their forest environment.

Data collection and methodology: Prior to the commencement of fieldwork, formal approval was obtained from leaders and village elders of the Siddi settlements. The purpose and scope of the study were explained in detail to gain their trust and voluntary participation. All data collection was carried out with the informed consent of the participants, adhering strictly to ethical standards for working with indigenous communities.

The field study was conducted across four selected villages**,** with seven families surveyed in each (total 28 families). The informants were selected using a combination of randomized household interviews, purposive sampling and the snowball method**,** which allowed the identification of key knowledge holders within the community (Thakur et al., 2025). These included traditional healers, elders, homemakers and community members with intergenerational knowledge of medicinal and edible plants. Data collection was carried out using semi-structured interviews, supplemented with focus group discussions, participatory observations and informal conversations. A semi-structured questionnaire was designed to explore the ethnobotanical knowledge of the Siddi community, specifically focusing on plant usage for the categories, such as medicinal purposes, food, cultural practices and architecture. Certain core questions were posed uniformly to all respondents, others were asked spontaneously, depending on the direction of the conversation and the respondent's area of knowledge. This approach provided a more flexible and in-depth understanding of traditional plant use. Ethnobotanical information such as plants used as medicine and plants consumed as food were documented.

For each plant, detailed data were recorded, including the local name, scientific name, plant family, plant part used, method of preparation, mode of application, and ailment or use. Plant specimens cited by informants were collected directly from the field with their assistance, labelled with local names, and photographed to ensure accurate documentation. These specimens were processed into herbarium samples for preservation and further study. The scientific names and families were carefully verified and documented, with taxonomic identification carried out using authoritative botanical references such as The Flora of British India (Hooker 1890), Flora of India (Singh et al., 2000), The Flora of the Presidency of Bombay (Cooke 1903), Flora of Karnataka (Karnataka Biodiversity Board 2019) and other regional floras published by the Botanical Survey of India.

RESULTS AND DISCUSSION

The comprehensive ethnobotanical survey among the Siddi tribes of Karnataka revealed the use of 60 plant species distributed across 33 families, primarily for medicinal and dietary purposes (Fig. 1). The highest number of species were recorded from fabaceae, lamiaceae and apocynaceae. Among the plants documented, the most frequently used parts were leaves (43.43%), followed by roots, seeds, bark and fruits (8.08%). The most common methods of preparation included paste (29.29%), kashaya/decoction (25.25%) and juice (24.24%), while powder, raw consumption and oil application were also reported. The primary route of administration was oral (61.62%), followed by external application.

Ethnomedicinal practices among the Siddi community: The Siddi community residing in the forested regions of Uttara Kannada district continues to rely extensively on traditional ethnomedicinal knowledge for the maintenance of health and the treatment of diverse ailments. This knowledge system, shaped through generations of lived experience and close interaction with the local ecology, is rooted in the use of both wild and cultivated plant species. Unlike the ritualistic healing practices observed among certain other tribal groups, the Siddis of Karnataka follow a pragmatic, plant-based medical tradition in which knowledge is shared collectively within the community, particularly among elders and women, rather than being confined to specialized healers (Karmwar and Srivastava 2025). Bhandary et al. (1995) documented a total of 98 medicinal preparations derived from 69 plant species used by the Siddis of Uttara Kannada and this included 40 novel medicinal applications of already known species. Among these, the use of *Calamus thwaitesii* stem sap as an antifertility remedy, the flowers of *Ichnocarpus frutescens* and the rhizome of *Hedychium coronarium* in the management of diabetes stand out as particularly noteworthy practices. The ethnobotanical repertoire of the Siddis was also distinct from that of neighbouring tribes such as the Gowlis, underscoring the uniqueness of their medical heritage.

The most frequently used plant parts were leaves, followed by roots, barks, seeds and fruits. Leaves were predominantly utilized due to their ease of collection, rapid preparation and multipurpose therapeutic benefits. Az-Zahra et al. (2021) confirmed that leaves are predominantly utilized in traditional medicine therapy. Preparation methods included juices, decoctions (kashayas), pastes, powders, oils and raw consumption. Applications varied based on the condition being treated, with oral ingestion commonly used for internal ailments such as fever, diabetes, gastric problems and anemia, while external application (e.g., pastes, oils) was employed for skin diseases, wounds, bone fractures and joint pains.

Several plants with multiple applications were recorded (Table 1). Survey conducted to document the medicinal plants utilized by the Siddhi community of Haliyal taluka in

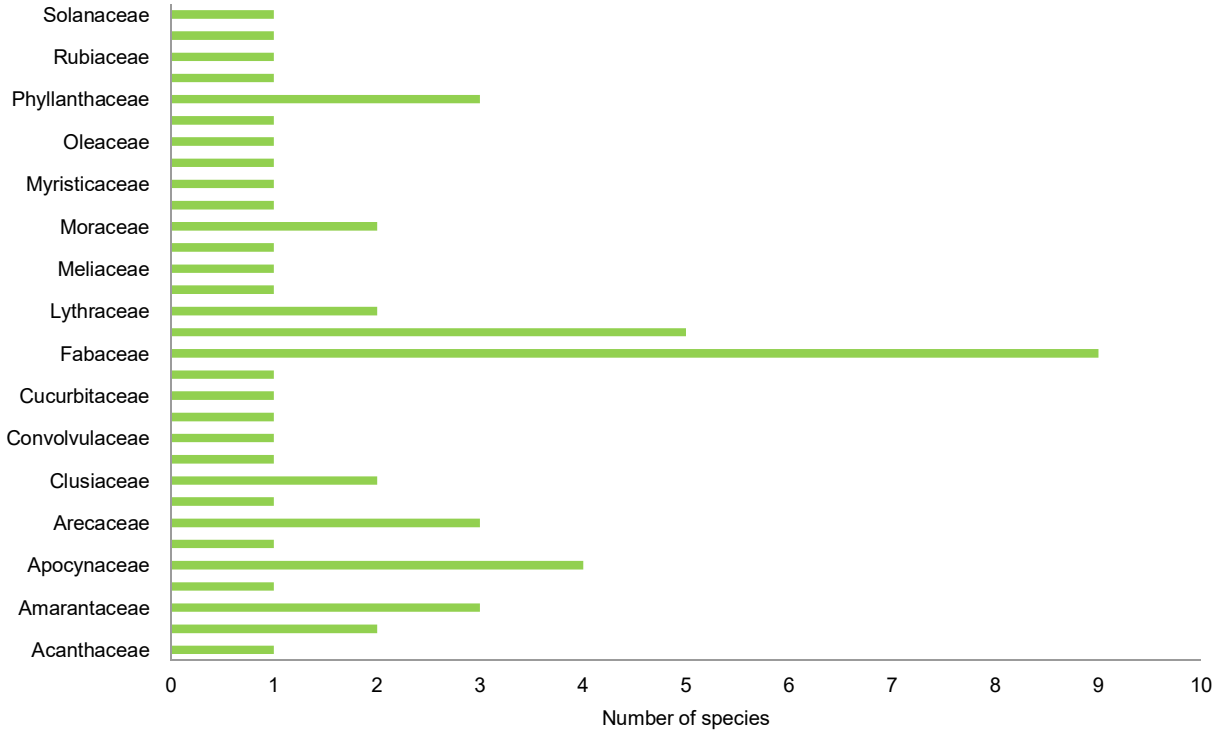

Fig. 1. Distribution of medicinal plant species across different families used by Siddi tribes

Table 1. List of medicinal plants used to treat different ailments by Siddi tribes

Scientific name	Family	Local name	Parts used	Preparation method	Mode of application	Ailment treated
Abrus precatorius	Fabaceae	Bili gulaganji	Leaves	Juice	Orally	Anaemia
Achyranthes aspera	Amarantaceae	Uttarani gida	Leaves	Paste with buttermilk	Orally	To avoid heavy bleeding
Acorus calamus	Acoraceae	Baje	Root	Chewing of root	Orally	Toothache
Adina cordifolia	Rubiaceae	Heddi	Leaves	Paste	Externally	Gangrin
Alstonia scholaris	Apocynaceae	Haalmara, Maddale	Bark	Bark squash	Orally	Stomach pain and worms
Amaranthus cruentus	Amarantaceae	Kemparive soppu	Seeds	Paste	Externally	Furuncle
Amaranthus viridis	Amarantaceae	Arive soppu	Leaves	Curry	Externally	For vitamins
Azadirachta indica	Meliaceae	Kahibevu	Leaves	Kashaya	Orally	For good health, Stomach pain
Caesalpinia bonduc	Fabaceae	Gajjaga	Seeds	Paste	Externally	Cold in children
Calycopteris floribunda	Combretaceae	Kumsanballi	Leaves	Juice	Orally	Asthma and cough, cold
Caryota urens	Arecaceae	Baine mara	Root	Lotion	Externally	Rheumatic swellings, snake bites
Cassia fistula	Fabaceae	Keppate soppu	Leaves	Lotion	Externally	Toothache
Cassia fistula	Fabaceae	Keppate soppu	Leaves	Paste	Externally	Mumps
Cassia tora	Fabaceae	Thogate soppu	Leaves	Curry	Orally	Furuncle
Cocos nucifera	Arecaceae	Tengu	Ambu	Raw	Externally	To stop bleeding from wound
Cocos nucifera	Arecaceae	Tengu	Shell	Lotion	Externally	Ring worms
Cocos nucifera	Arecaceae	Tengu	Bark	Oil	Externally	Ear pain
Cocos nucifera	Arecaceae	Tengu	Fruit	Oil	Externally	Wounds
Colocasia esculenta	Arecaceae	Kesu	Leaves and stem	Curry	Orally	Body pain and digestion
Costus igneus	Costaceae	Naladagadde	Rhizome	Juice	Orally	Gastric and stomach pain
Diospyros kaki	Ebenaceae	Kaaki hannu	Root	Kashaya	Orally	Stomach pain and gastric
Embelia ribes	Primulaceae	Vaivadang	Root	Juice	Orally	Cough
Entada scandens	Fabaceae	Ganapekayi	Seed	Paste	Applied to hair	Prevents greying hair
Evolvulus alsinoides	Convolvulaceae	Nelahatthi gida	Root	Raw	Externally	Headache
Ficus asperrima	Moraceae	Garagatti mara	Bark	Juice	Orally	Fever
Ficus glomerata	Moraceae	Hatthimara	Root	Fluid extract	Orally	Act as coolant
Garcinia indica	Clusiaceae	Muragalu	Fruit	Juice	Orally	Dizziness
Garcinia indica	Clusiaceae	Muragalu	Rind	Tablet	Orally	Chest pain
Garcinia indica	Clusiaceae	Muragalu	Seeds	Oil	Externally	Piles
Hemidesmus indicus	Apocynaceae	Doodwala	Root	Juice	Orally	Diabetes, act as coolant
Jasminum malabaricum	Oleaceae	Kaadu mallige	Flower	Soaked overnight	Externally	Cataract, eye problems
Justicia adhatoda	Acanthaceae	Belisalaga	Leaves	Warming of leaves	Externally	Backpain
Justicia adhatoda	Acanthaceae	Belisalaga	Leaves	Kashaya	Orally	Fever and cold
Lawsonia inermis	Lythraceae	Madarangi	Leaves	Decoction	Externally	Sterility
Lawsonia inermis	Lythraceae	Madarangi	Leaves	Paste	Externally	Gangrin
Leucas aspera	Lamiaceae	Totlu tumbe	Leaves	Paste	Orally	Cough, asthma
Millettia pinnata	Fabaceae	Karanji	Stem fibers	Raw	Externally	Fever
Mimosa pudica	Fabaceae	Naachike mullu	Leaves	Lotion	Externally	Wounds
Mimosa pudica	Fabaceae	Naachike mullu	leaves	paste	Externally	Bone fracture, Toothache
Mimosa pudica	Fabaceae	Naachike mullu	Root	Paste	Orally	Sterility

Cont...

Table 1. List of medicinal plants used to treat different ailments by Siddi tribes

Scientific name	Family	Local name	Parts used	Preparation method	Mode of application	Ailment treated
Momordica charantia	Cucurbitaceae	Hagalkayi	Leaves	Juice	Orally	Stomach worms in children, Constipation
Momordica charantia	Cucurbitaceae	Hagalkayi	Raw fruit	Paste	Externally	Itching
Musa paradisiaca	Musaceae	Baale	Unripened banana	Unripened banana	Orally	Kidney stone
Myristica fragrans	Myristicaceae	Jaakayi	Seed	Paste	Apply on wounds	Pain kill, Declotting
Ocimum gratissimum	Lamiaceae	Rama tulsi	Leaves	Oil	Externally	Ear pain
Ocimum tenuiflorum	Lamiaceae	Bili tulsi	Leaves	Kashaya	Orally	Cold and cough
Ocimum sanctum	Lamiaceae	Tulasi	seed	Juice	Orally	Acidity
Parthenium hysterophorus	Asteraceae	Parthenium	Leaves	Raw leaves	Externally	To stop bleeding from wound
Phyllanthus acidus	Phyllanthaceae	Avalaar mara	Bark	Paste	Externally	Ring worms
Phyllanthus emblica	Phyllanthaceae	Nellikayi	fruit	Dried and powdered	Orally	Stomach pain
Phyllanthus niruri	Phyllanthaceae	Nelada nellikayi	Leaves	Kashaya	Orally	Asthma, cough and cold
Pistia stratiotes	Araceae	Antharagange	leaves	juice	Orally	Cold and cough
Plectranthus amboinicus	Lamiaceae	Pathregida	Leaves	Decoction	Orally	Stomach pain, body pain, digestion and cough in children
Psidium guajava	Myrtaceae	Perle	Leaves	Juice	Orally	Stomach pain
Psidium guajava	Myrtaceae	Perle	Leaves	Paste	Orally	For lice
Pterocarpus marsupium	Fabaceae	Honge mara	Bark	Kashaya	Orally	Fever
Punica granatum	Lythraceae	Dalimbe	Peel	Powder	Externally	Remove pimple and good skin
Rauwolfia serpentina	Apocynaceae	Gadapathal	Root	Lotion	Externally	Ring worm
Rhynchostylis retusa	Orchidaceae	Seethe hoovu	Fleshy Leaves	Fluid extract	Externally	Ear pain
Rosa sinensis	Malvaceae	Daswala	Leaves and flowers	Paste and juice	Externally	Act as coolant
Sapindus emarginatus	Sapindaceae	Antwala	Pulp	Paste	Applied to hair	Prevents greying hair
Semecarpus anacardium	Anacardiaceae	Guddegerannu	Seed	Lotion	Externally	Wounds
Solanum virginianum	Solanaceae	Haladi badanekayi	seeds	Steam	Externally	Cavities
Solanum virginianum	Solanaceae	Mullubadane	Root	paste	Externally	Ring worms, dermatitis
Tabernaemontana divaricata	Apocynaceae	Nanjatle	Leaves	Kashaya	Orally	Throat pain
Tabernaemontana divaricata	Apocynaceae	Nanjatle	Root	Lotion	Externally	Wounds
Tabernaemontana divaricata	Apocynaceae	Nanjatle	Root	Kashaya	Orally	Cold and cough
Tabernaemontana divaricata	Apocynaceae	Nanjatle	Root	paste	Externally	Poisonous snakebite
Tinospora cordifolia	Menispermaceae	Amruthaballi	Leaves	Decoction	Orally	For good health, diabetes, body pain and fever
Trigonella foenum-graecum	Fabaceae	Menthya	Seeds	Kashaya	Orally	Diabetes

Uttara Kannada district, Karnataka, revealed 45 medicinal plant species representing 29 families, being employed as remedies for 38 distinct ailments. Among the recorded families, apocynaceae contributed the highest number of species, followed by fabaceae, lamiaceae and rutaceae, highlighting their central role in the Siddhi ethnopharmacopoeia (Makanur et al., 2024). In the same way, this investigation recognized fabaceae as the most commonly cited flora family. For example, *Alstonia scholaris* bark was used to treat stomach pain and intestinal worms, while *Mimosa pudica* had diverse applications, including treatment for wounds, toothache, sterility and bone fractures. The versatility of certain species like *Azadirachta indica* (Neem) and *Tinospora cordifolia* (Amruthaballi), known for their immune-boosting and preventive properties, indicates the community's awareness of both curative and prophylactic health strategies. Some of these plant-derived compounds serve as natural defence mechanisms, that acts as toxins to deter herbivores and predators, while others exhibit pharmacologically active properties that are beneficial to human health and form the basis of traditional medicinal practices (Amsalu et al., 2018). Such utilization patterns have also been reported by local communities in protected areas from Himalayas, another biodiversity hotspot (Thakur et al., 2011, 2017, Kumari Monika et al., 2024).

This ethnomedicinal tradition aligns with similar studies across the Western Ghats, highlighting the broader regional dependency on local flora for primary healthcare. The ethnomedicine combines herbal remedies (dava) and spiritual healing (dua), reflecting both local influences and African roots (Solanki 2020). Furthermore, the integration of medicinal plants into daily life demonstrates the community's adaptive strategies to limited biomedical access, reinforcing the resilience and self-sufficiency of traditional knowledge systems. These communities have cultivated a sustainable and symbiotic relationship with their surrounding ecosystems, drawing on a wide range of locally available plant species for medicinal purposes while simultaneously upholding ecological integrity and biodiversity conservation (Turner et al., 2022).

Ethnofood practices and nutritional knowledge: Parallel to their medicinal use of plants, the Siddis also depend on a diverse range of wild and semi-domesticated plants for food. The study documented 11 food plant species across 9 families and 10 genera, primarily comprising leafy vegetables, fruits and seeds. Leafy greens such as *Amaranthus cruentus* and *Amaranthus viridis* are especially important for their iron and vitamin content and are widely consumed in traditional dishes like curries and dumplings (Table 2).

The consumption of *Cassia tora* (Thogate soppu) with its bitter and detoxifying nature indicates an indigenous understanding of its therapeutic value in daily diet, especially for purging toxins. Similarly, *Moringa oleifera* (Nuggekayi), a globally recognized superfood, is commonly used, reflecting a convergence of traditional and contemporary health values. Many of the food plants also serve medicinal purposes. For instance, *Colocasia esculenta* (Kesu) is used not only for nutrition but also for managing body pain and digestion. *Momordica charantia* (Hagalakayi), used as both food and medicine, is indicative of the dual-purpose application of flora in Siddi lifeways, emphasizing a holistic approach to health where the boundary between food and medicine is fluid.

Their food system is further supplemented by wild foraging, subsistence agriculture and consumption of forest-based non-vegetarian resources (e.g., fish, crabs and wild meats), indicating a diversified diet adapted to ecological

Table 2. Plants used as food by Siddhi tribes

Scientific name	Local name	Family	Parts used
Amaranthus cruentus	Kempu arive	Amaranthaceae	Leaves
Amaranthus viridis	Arive soppu	Amaranthaceae	Leaves
Artocarpus heterophyllus	Halasu	Moraceae	Fruit
Basella alba	Basale soppu	Basellaceae	Leaves
Caryota urens	Baine mara	Arecaceae	Seeds
Cassia tora	Thogate soppu	Fabaceae	Leaves
Colocasia esculenta	Kesu	Araceae	Leaves
Cucurbita moschata	Kumbalakayi	Cucurbitaceae	Leaves
Justicia adhatoda	Beli salaga	Acanthaceae	Leaves
Momordica charantia	Hagala kayi	Cucurbitaceae	Leaves, Fruit
Moringa oleifera	Nuggekayi	Moringaceae	Leaves, Fruit

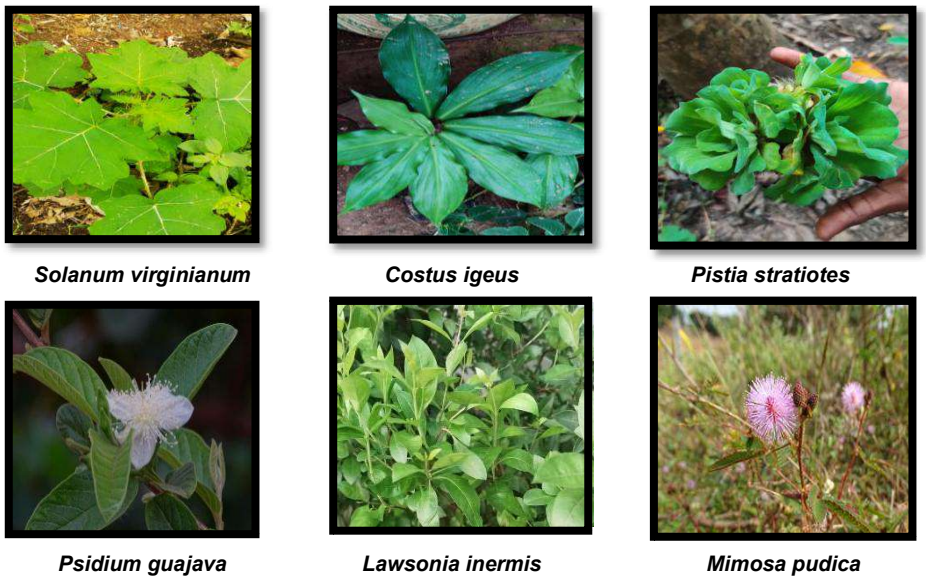

Plate 1. Representative plant species documented during field survey

availability and seasonal abundance. The sustainable gathering and use of these resources underline a deep ecological knowledge and cultural continuity**.** However, increasing anthropogenic pressures, habitat degradation and climate change pose significant threats to these ecosystems, potentially disrupting this delicate balance and the traditional knowledge associated with it (Bisht et al., 2020).

The growth and transformation of indigenous therapeutic knowledge within tribal communities have been profoundly shaped by the complex interplay of cultural, environmental and spiritual systems (Hamzah et al., 2023, Haq et al., 2023). These communities regard traditional medicine not merely as a utilitarian practice, but as a vital cultural heritage intrinsically woven into their social and ancestral fabric (National Research Council 2002). The present findings underscore the urgent need to preserve and promote such traditional knowledge, not only as a means of safeguarding cultural identity, but also as a foundational element in advancing sustainable development. Indeed, the preservation of ethnomedicinal wisdom is essential for ensuring the continuity and resilience of tribal cultures in the face of rapid modernization and socio-ecological change (Reddy et al., 2023).

In response, a range of stakeholders, including researchers, local communities and cultural institutions, are actively engaging in collaborative efforts to protect endangered indigenous healing practices. These initiatives encompass systematic documentation, intergenerational transmission of knowledge, training programs for both practitioners and emerging scholars and the development of adaptive frameworks that support the long-term evolution and revitalization of this invaluable knowledge system.

CONCLUSION

The present study highlights the rich ethnobotanical heritage of the Siddi tribal community in Yellapur taluk of Uttara Kannada district, Karnataka, revealing their deep reliance on forest biodiversity for both medicinal and nutritional needs. A total of 54 medicinal and 11 food plant species were documented, showcasing a practical and experience based system of traditional medicine that is widely shared among community members, especially elders and women. The frequent use of leaves, along with versatile preparation methods such as decoctions, pastes and juices, reflects the community's intimate knowledge of plant properties and their adaptability in the face of limited biomedical access. Many plants serve dual purposes as both food and medicine, exemplifying the Siddis' holistic approach to health and sustainable resource use. Despite their assimilation into the broader Indian socio-cultural landscape, the Siddis have retained significant elements of their traditional knowledge, passed down orally through generations. However, increasing threats from habitat degradation, climate change and cultural erosion underline the urgency of documenting and preserving this knowledge system.

AUTHORS' CONTRIBUTIONS

Bindu Shree M Y conducted the field investigations and contributed to species identification. Nandhakumar S and Sushma C Meti conceptualized the study and drafted the

initial manuscript. Anusha Sanjay Revankar performed species identification and assisted in data interpretation and manuscript preparation. Clara Manasa P A revised and refined the manuscript. The study was carried out under the overall supervision and guidance of Suryanarayana V.

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