



SOUVENIR

National Conference on

Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework

(April, 28-30, 2026 | SKUAST-Jammu, Chatha)

Editors

Syed Sheraz Mahdi
Rakesh Sharma
Asif Mohd Iqbal
AK Dhawan



Organizers

Indian Ecological Society, Jammu & Kashmir Chapters



Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu (SKUAST-Jammu) and



Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir (SKUAST-Kashmir)

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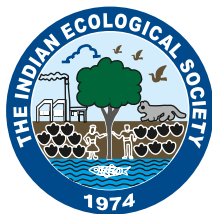


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SOUVENIR



IESCCC-2026

National Conference

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Organized by

Indian Ecological Society, Jammu & Kashmir Chapters

SKUAST-Jammu & SKUAST-Kashmir in Collaboration with Indian Ecological Society, Ludhiana, Punjab

Guidance & Patronage

Dr. B.N. Tripathi

Vice-Chancellor, SKUAST-Jammu

Technical Support

Dr. S.K. Gupta

Director Research, SKUAST-Jammu and

Co-Chairperson National Organizing Committee, IESCCC-2026

Editors

Syed Sheraz Mahdi

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SHIVRAJ SINGH CHOUHAN



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ग्रामीण विकास मंत्री
भारत सरकार
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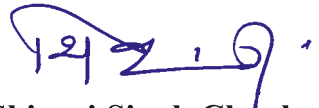
अर्द्ध शा. पत्र क्र. 306/2026,
दिनांक 03/04/2026

MESSAGE

Sustainable and climate-resilient agriculture has become a national priority as India works towards ensuring long term food security, ecological balance and enhanced farmer prosperity. It is heartening to know that the Indian Ecological Society, Jammu & Kashmir Chapter(s) in collaboration with SKUAST-JAMMU and SKUAST-Kashmir is organizing a National Conference on “Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework” from 28-30 April, 2026 at SKUAST-Jammu.

Agriculture continues to play a pivotal role in India’s economy contributing about 18% to the Gross Value Added (GVA) and supporting the livelihoods of over 50% of the country’s population. India has emerged as a global leader in agricultural production, ranking first in milk, pulses and spices and second in rice, wheat, fruits and vegetables. However, over 52% of the net sown area in the country is rainfed, making agricultural systems highly vulnerable to climate change, erratic rainfall and extreme weather events. Addressing these challenges requires strengthening climate-resilient farming systems, ecological approaches to agriculture, efficient natural resource management and innovative technologies.

I commend the efforts of the Indian Ecological Society, SKUAST-Jammu & SKUAST-Kashmir for organizing this important national event. I am confident that the deliberations will lead to meaningful insights and strategies for strengthening sustainable and climate resilient agroecosystems across the country.


(Shivraj Singh Chouhan)

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उपराज्यपाल
जम्मू एवं कश्मीर
MANOJ SINHA
LIEUTENANT GOVERNOR
JAMMU & KASHMIR



सत्यमेव जयते

लोकभवन
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LOK BHAVAN
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MESSAGE

I am happy to know that the Indian Ecological Society, Jammu & Kashmir Chapter, in collaboration with SKUAST-Jammu and SKUAST-Kashmir, is organizing the National Conference on "Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework" from 28th April to 30th April 2026, at SKUAST-Jammu, Chatha.

India's agricultural landscape is at a critical juncture. As one of the world's most climate-vulnerable regions, we face the mounting challenges of rising temperatures, erratic precipitation, and an increasing frequency of extreme weather events.

The Himalayan ecosystems, particularly within Jammu & Kashmir, are not only ecologically sensitive but strategically vital. Here, agriculture is the backbone of rural livelihoods and a primary driver of horticulture-led economic growth. Building resilience in these fragile landscapes requires a seamless convergence of cutting-edge science, innovation, governance, and active community participation.

The conference themes such as sustainable production systems, natural resource stewardship, technological integration, and policy coherence are far more than academic exercises; they are national imperatives aligned with India's commitments under global climate frameworks and Sustainable Development Goals (SDGs).

I am confident that this gathering of eminent scientists, policymakers, innovators, and stakeholders will foster meaningful dialogue and yield actionable strategies to strengthen institutional capacities and promote resilient agroecosystems across the region and beyond.

I extend my greetings to all the participants and best wishes for the success of the conference and the publication of the commemorative souvenir.

Manoj Sinha
(Manoj Sinha)

26th March 2026
Jammu.

Omar Abdullah



सत्यमेव जयते

CHIEF MINISTER
JAMMU & Kashmir



MESSAGE

I am happy to know that the Indian Ecological Society, Jammu & Kashmir Chapter, in collaboration with Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu and Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, is organizing the National Conference on **"Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework"** from 28-30 April 2026 at the main campus of SKUAST-Jammu, Chatha.

Agriculture remains foundational for India's socio-economic fabric. Across the country, agriculture and allied sectors contribute around 18.3 % of gross value added and employ approximately 45.6 % of the workforce, underscoring its vital role in livelihoods and national growth. However, climate variability presents mounting risks to productivity, with projections indicating declines in yields for key staples and increasing vulnerability to extreme weather events unless adaptive strategies are implemented.

In Jammu & Kashmir, agriculture directly or indirectly supports nearly 70% of the population, making climate resilience critical for food security and rural prosperity. Studies in the region confirm that climatic shifts - such as rising temperatures, declining snowfall and erratic rainfall patterns - are perceptible to farmers and are affecting agricultural outcomes, planting seasons, and yield stability in the state.

The theme of this conference - integrating innovation with policy for sustainable and climate-resilient agroecosystems - is therefore both timely and essential. I am confident that the deliberations and outcomes of this conference will catalyse actionable pathways for strengthening climate resilience in agricultural practices, benefiting not only Jammu & Kashmir but the broader Himalayan region and the nation.

I commend the organizers for their dedication to advancing sustainable agriculture and resilience-focused policy and extend my best wishes for the success of this important scientific endeavour.


(Omar Abdullah)

Javid Ahmed Dar
(Minister)
Government of Jammu & Kashmir



Minister for Agriculture Production Rural Development
& Panchayati Raj, Cooperative & Election Department



D. O. No. PS/MM/JAD/1042

Dated: 07.04.2026

MESSAGE

It gives me great pleasure to know that the Indian Ecological Society, Jammu & Kashmir Chapter(s) in collaboration with SKUAST-Jammu and SKUAST-Kashmir is organizing a National Conference on "Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework" from 28-30 April, 2026 at the Main Campus, Chatha, SKUAST-Jammu.

Agriculture remains the backbone of the economy of Jammu & Kashmir, supporting the livelihood of nearly 70% of the population. Recent assessments indicate that more than 60 percent of cultivated land in J&K is rainfed, making farming systems more vulnerable to climate change. At the same time, the region holds immense opportunities for sustainable intensification, organic and natural farming, climate-smart technologies, efficient water management and resilient cropping systems. In this context, strengthening sustainable and climate-resilient agroecosystems through scientific innovations, efficient resource management and supportive policy frameworks is crucial for ensuring long-term agricultural sustainability and improved farmer incomes.

I commend the efforts of SKUAST-Jammu for organizing this important conference. I am confident that the deliberations will generate valuable insights and policy recommendations for promoting sustainable agriculture and climate resilience in Jammu & Kashmir and beyond.

I extend my best wishes for the success of the conference.

(Javid Ahmad Dar)



डॉ. एम. एल. जाट

सचिव (डेयर) एवं महानिदेशक (भाकृअनुप)

Dr. M. L. Jat

SECRETARY (DARE) & DIRECTOR GENERAL (ICAR)

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MESSAGE

Indian agriculture faces mounting climate risks, with over 52% of the net sown area being rainfed and nearly 85% of farmers being small and marginal. Scientific assessments indicate that climate change may reduce yields of major cereals by 10-25% by mid-century if adaptive measures are not mainstreamed. At the same time, agriculture accounts for about 14% of national greenhouse gas emissions, underscoring the need for resource-efficient and climate-smart production systems.

Building resilient agro ecosystems through conservation agriculture, sustainable intensification, efficient water and nutrient management, and systems-based innovations has demonstrated the potential to enhance productivity while reducing environmental footprints by 20-30% in diverse agro-ecologies. Integrating such science-based innovations with enabling policy frameworks is critical for scaling impact.

In this context, Indian Ecological Society, Jammu & Kashmir Chapters in collaboration with SKUAST-Jammu and SKUAST-Kashmir is organizing a National Conference on “Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework” from 28-30 April, 2026 at main campus, SKUAST-Jammu, Chatha.

The theme of this conference is timely and strategically important. I am confident that the deliberations will generate actionable insights to strengthen research-extension-policy convergence and accelerate India’s transition towards sustainable and climate-resilient agriculture.

I congratulate organizers for this important initiative and wish the conference every success.

(M.L. Jat)

Dated the 13th March, 2026
New Delhi



Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu

Dr B.N. Tripathi

Ph.D. FRCPath (England)

FNAAS | FNAVS | DICVP

Vice-Chancellor



MESSAGE

It is a matter of great pride and privilege for Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu (SKUAST-Jammu) to host the National Conference on "Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework" from 28-30 April, 2026. The conference is being organized by the Indian Ecological Society, Jammu & Kashmir Chapter, in collaboration with SKUAST-Jammu and SKUAST-Kashmir.

In the face of increasing climate variability and ecological uncertainties, the need for resilient and sustainable agricultural systems has become paramount. As a leading institution in agricultural education, research, and extension, SKUAST-Jammu is committed to developing innovative, climate-smart solutions tailored to the fragile Himalayan agroecosystems.

This conference assumes added significance with the organization of special technical sessions in collaboration with internationally and nationally reputed institutions such as CIMMYT, BISA, IRRI, and ICAR-IGFRI. These collaborations will greatly enrich the scientific discourse by bringing global perspectives, cutting-edge research, and practical insights into climate-resilient agriculture, natural resource management, and sustainable fodder systems.

The event will serve as a vibrant platform for scientists, policymakers, industry experts, and young researchers to exchange ideas, foster collaborations, and deliberate on policy frameworks that can ensure long-term sustainability, food security, and livelihood enhancement.

I warmly welcome all the distinguished delegates to SKUAST-Jammu and am confident that the deliberations will lead to meaningful outcomes and actionable strategies for strengthening climate-resilient agroecosystems.

I extend my best wishes to my organizing team and participants for the grand success of this conference.

(B.N. Tripathi)

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"An institute for sustainable agriculture for food and nutritional security"



Prof. Nazir Ahmad Ganai
Vice-Chancellor



MESSAGE

It is a matter of great pleasure that the Indian Ecological Society, in collaboration with Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu and Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, is jointly organizing the National Conference on "Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework (IESCCC-2026)" from 28–30 April 2026 at SKUAST-Jammu, Chatha.

Agriculture continues to remain the backbone of India's economy, supporting nearly half of the population and contributing significantly to the national GDP. However, the sector today stands at a critical juncture, confronted with the intensifying challenges of climate variability, rising temperatures, erratic precipitation, and increasing frequency of extreme weather events. The Himalayan agroecosystems, including those of Jammu & Kashmir, are particularly fragile and disproportionately vulnerable to these changes. Emerging scientific evidence suggests that the Himalayan region is warming at a rate higher than the global average, with far-reaching implications for agricultural productivity, water security, and the livelihoods of farming communities.

In this evolving context, agricultural universities are uniquely positioned to lead the transition towards climate-smart, resilient, and sustainable agricultural systems. Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir has, over the years, established itself as a leading institution in temperate agriculture and mountain ecosystem research. The University has made notable contributions in the development of improved crop varieties, sustainable natural resource management, and climate-resilient production systems. Its pioneering efforts in the revival and scientific validation of traditional crops such as Mushkbudji rice, advancement of temperate horticulture, and development of location-specific technologies for fragile ecosystems stand as important milestones. Through an integrated approach encompassing research, education, and extension, the University continues to strengthen farm productivity, livelihood security, and resilience across Jammu & Kashmir and other Himalayan regions.

I am confident that this conference will serve as an important platform for scientists, academicians, policymakers, and stakeholders to deliberate on emerging challenges, share cutting-edge research, and co-create innovative pathways for sustainable agricultural transformation. The insights and policy recommendations emerging from this forum will be instrumental in shaping future research agendas and enabling robust policy frameworks for climate-resilient agriculture.

I congratulate the organizers for this timely and significant initiative and extend my best wishes for the grand success of the conference.

(Prof. Nazir A. Ganai)



DIRECTORATE OF RESEARCH

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Dr. S.K. Gupta
Director Research



MESSAGE

At a time when agriculture is increasingly challenged by climate change, resource degradation, and ecological imbalances, the need for science-led, resilient and sustainable agro-ecosystems has become more urgent than ever. This conference is a timely initiative aimed at bringing together leading scientists, policymakers, industry stakeholders, and young researchers to deliberate upon innovative solutions and robust policy framework for climate-resilient agriculture.

The Indian Ecological Society, through its J&K Chapter, has been actively promoting ecological research and sustainable natural resource management in the region. The society in collaboration with SKUAST-Jammu and SKUAST-Kashmir, is committed to foster interdisciplinary dialogue and translating scientific knowledge into actionable strategies for the farming community, particularly in the ecologically sensitive Himalayan region.

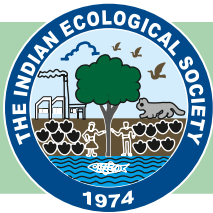
I as President of the Indian Ecological Society (Jammu Chapter) and Director Research, SKUAST-Jammu welcome to hold the National Conference on ***“Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework”*** at Chatha from **28-30 April, 2026**.

I am particularly pleased that this conference features special technical sessions in collaboration with premier international and national institutions such as CIMMYT, BISA, IRRI, and ICAR-IGFRI. Their participation will greatly strengthen the scientific discourse by integrating global best practices with local realities, especially in areas of climate-resilient cropping systems, natural resource management, and sustainable fodder production.

I am confident that the deliberations during this conference will not only generate meaningful scientific insights but also pave the way for strategic partnerships and policy interventions that will contribute towards sustainable agricultural development and enhanced livelihood security.

I congratulate organizing team for their dedicated efforts and extend warm welcome to all delegates. I wish the conference a grand success and impactful outcomes.

(S.K. Gupta)



THE INDIAN ECOLOGICAL SOCIETY PUNJAB AGRICULTURAL UNIVERSITY LUDHIANA-141 004, INDIA

Dr A.K. Dhawan
President
Indian Ecological Society



MESSAGE

The agricultural production is particularly vulnerable to climate change, which has altered environmental factors such as temperature, precipitation and wind speed, which in turn affected the crop growth cycle, the frequency of extreme weather events, the occurrence patterns of pests and diseases and ultimately influence the crop yield and quality. Seasonal shifts have disrupted planting and harvesting pattern, forcing farmers to shift to resource-intensive alternative farming systems. These challenges highlight the urgent need for adaptive strategies such as climate-resilient crops, improved irrigation systems, and sustainable land management practices. Climate change also influences the food chain by damaging the ecology, that sustains it.

The Indian Ecological Society (IES), established in 1974 at Punjab Agriculture University Ludhiana (PAU), is one of the pioneering organizations of India. The Society is engaged in advances in ecological sciences and environmental protection. Complementing the present scenario of climate shift, the IES, along with its SKUAST-J and SKUAST-K Chapters, is organizing a National Conference on “Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework” at SKUAST-J, Jammu (J&K).

The conference will highlight the various issues pertaining to climate change and energy transitions, digital tools for sustainable agri-food systems, climate-smart organic farming, role of ecosystem services in agrifood systems, energy and water efficient innovations for agrifood systems, breeding adaptation and tolerance systems, novel approaches in pest management. Energy transitions that replace fossil fuels with renewable energy sources can mitigate climate change and must also occur in agrifood systems.

I, on behalf of IES, extend a hearty welcome to all the delegates. I am sure, the deliberations in various sessions will lead to recommendations, to meet the challenges of food security and productivity, in a sustainable manner, maintaining environment quality.

Akhan

(A.K. Dhawan)



Dr. Syed Sheraz Mahdi
Organizing Secretary



From the desk of Organizing Secretary

It is a matter of great honor and privilege that I have been entrusted with the responsibility of organizing the National Conference on *“Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework”* being held from **28-30 April, 2026** at Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu (SKUAST-Jammu), under the aegis of the Indian Ecological Society, Jammu & Kashmir Chapter, in collaboration with SKUAST-Jammu and SKUAST-Kashmir.

The enthusiastic response to this conference, reflected in **around 210 extended abstracts, 50 research papers, 22 invited expert / lead talks, and participation from premier national and international institutions**, underscores the relevance and urgency of the theme. The inclusion of **special technical sessions in collaboration with CIMMYT, IRRI, BISA, and ICAR-IGFRI** further strengthens the scientific depth of the event by integrating global expertise with regional priorities, particularly for the Himalayan agroecosystems.

This conference is envisioned as a platform to foster meaningful dialogue on innovative research, climate-resilient technologies, and policy frameworks essential for sustainable agricultural development. The active engagement of **research institutions, funding agencies, and industry partners** highlights the growing synergy required to address the challenges posed by climate change.

I express my sincere gratitude to Hon'ble Vice-Chancellor, collaborating institutions, partners, and all contributors for their guidance and support. I also acknowledge the dedicated efforts of our organizing team.

I extend a warm welcome to all delegates and wish the conference great success.

(Syed Sheraz Mahdi)



Dr. Rakesh Sharma
Organizing Secretary

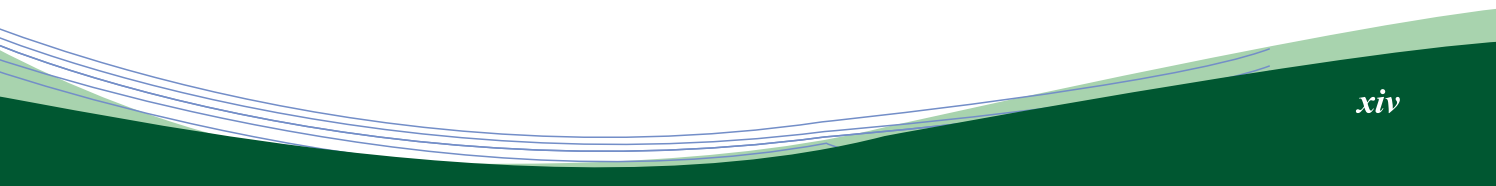


From the desk of Organizing Secretary

Climate change has ecological, economic and social consequences and its dynamic and unpredictable nature already poses and will continue to pose challenges for agriculture. There is growing concern over impact of climate change in India and expected to worsen water scarcity due to rising temperatures, erratic rainfall, reduced groundwater recharge and declining water levels. It is expected that climate change is likely to reduce yields of major crops such as rice and wheat unless adaptive measures are adopted. Additionally, emerging pests and diseases pose serious risks to crop production. To address these challenges, several policy initiatives have been undertaken by the Indian Council of Agricultural Research (ICAR) and Government of India. But, there is need to put more emphasis for technological and institutional development to increase awareness among the farming community and extension agencies for effectively utilizes climate-resilient practices. The basic aim of organising this national conference is to address the current issues and devise research priorities based on evidences for strengthening climate resilience across India's diverse farming systems.

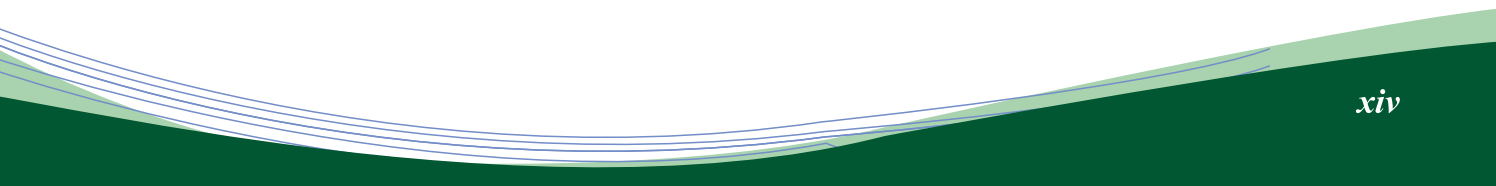
I hope that this three days national conference on “**Sustainable and Climate Resilient Agroecosystems: Innovations and Policy Framework**” will come out with meaningful deliberations that will help the policy planners to device future road map to address this global challenge in effective manner.

(Rakesh Sharma)



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Chapter-1

Climate Change Adaptation and Mitigation Strategies in India

Ch. Srinivasa Rao and Abhinav Rathi

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ABSTRACT

Agriculture contributes to 17-18% of the total GDP and also generates more than half of the total employment in the country making India an agrarian society and agriculture dependent country. The population of India is expected to be 1.59 billion by 2050 which will put in demand for 450 million tons (Mt) of food grain per year. Such an unprecedented demand will steeply increase the prices of food commodities over the years. Climate sensitive sectors like agriculture, forestry and coastal ecosystems will be most adversely affected by these changes. According to Intergovernmental Panel on Climate Change (IPCC), the climate change is already negatively affecting the agricultural growth and developing countries like India are highly vulnerable to ensuing negative impacts. Over the past 100 years, there has been 0.6 °C increase in atmospheric temperature in India. The country is already experiencing an increased frequency and intensity of extreme weather events like heavy precipitation, droughts, floods, hailstorms, cold waves, heat waves, increased mean maximum temperatures and pest infestations impacting the crops and threatening the food security and livelihoods of millions of farmers. Climate change induced warming has already reduced the production of rice and wheat in some parts of the country and it is estimated that the future warming trend could further reduce the yields by 4.5 to 9% during 2020-39 and may have 0.7 to 1.35% negative impact on the GDP. Thus, it is important to enhance the resilience of agro-ecosystems to climate change in India and develop science-driven technological solutions duly supported by policy level decisions.

Introduction

Climate change is a real and undeniable threat to entire civilization. It is primarily driven by human activities, such as the burning of fossil fuels (coal, oil, and natural gas), deforestation, industrial processes, and agricultural activities, which release greenhouse gases (GHGs) into the atmosphere. These GHGs include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases which trap heat in the Earth's atmosphere, leading to the greenhouse effect and global warming. The GHGs emitted due to human activities are the primary cause of climate change (IPCC, 2021). At present, the atmospheric CO₂ concentration is over 400 ppm. The anthropogenic climate change has already slowed down agricultural productivity growth by 21 per cent in last 50 years (Crippa *et al.*, 2021). The CO₂ equivalents of other GHGs have also reached to 489 ppm. Apart from CO₂, N₂O and CH₄ levels have also increased by 20 and 150%, respectively compared to 1750 levels (Arunanondchai *et al.*, 2018). The average surface temperature of planet earth has increased by 0.89°C since 1901 (IPCC AR5). Further, the global mean temperature is anticipated to increase by 1.8 to 4.0°C by the end of this century (Wheeler and Braun 2013). Emissions of GHGs in the atmosphere and global warming are theoretically related and current emission trends suggest that earth surface temperature has been continuously rising with increase in heat wave frequencies and number of warmer days and nights. Thus, climate change is perceived to bring in increased temperatures, altered precipitation pattern with increased frequency and severe extreme weather events (Fig. 1). Jammu & Kashmir with difficult terrain with important biodiversity; is effected negatively with extreme climatic events.

Climate change will exert severe pressure on global food production systems. Global population is expected to be 9.5 billion by 2050 (Godfray *et al.*, 2010) and such an unprecedented increase in population will raise the demand by more than 70% in global crop production (Foley *et*

al., 2011, Abhilash *et al.*, 2016). Further, medium-term climate change (2020-2039) could reduce the crop yield by 4.5 to 9%. This could seriously affect the food security of the nation as there would be 69.8% increase in demand for food grain production for a burgeoning population of 1.6 billion people by 2050 (Pathak, 2015). Rising temperatures, spurred by a 1.1°C (2°F) increase since the late 19th century, intensify heat waves, posing risks of heat-related illnesses and straining water resources and agriculture. Alterations in precipitation patterns result in heightened droughts and heavy precipitation, disrupting water supplies, agriculture and ecosystems, fostering food insecurity and displacement (Pathak *et al.*, 2021).

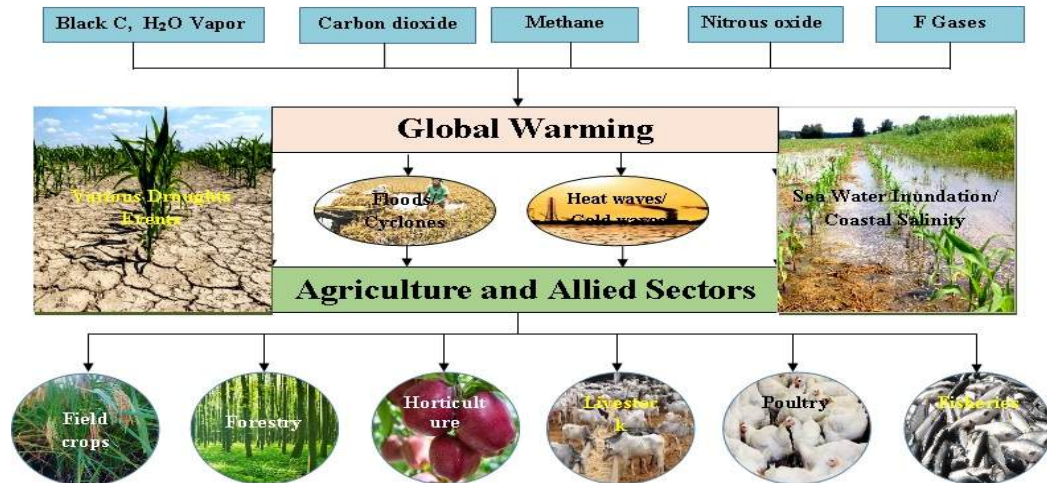


Fig. 1: Causes and impacts of climate change in agriculture.

Impact of Climate change on Agriculture

- 1. Decline in Crop Yields:** Climate change poses a measurable and growing threat to global food production. Unique crops growth in J&K is often affected with crop losses during extreme events. On average, each degree Celsius of warming reduces the world's per capita food supply by approximately 120 calories per day, representing a 4.4% decline relative to current dietary consumption levels. Under high-emissions scenarios, global caloric yields from staple crops are projected to be around 24% lower by 2100 compared to a climate-stable baseline - a decline that persists even when farmer-level adaptation is taken into account. These long-term projections are complemented by nearer-term estimates: a 2025 systematic literature review determined that without timely and effective adaptation interventions, global agricultural food production could decline by as much as 14% by 2050, with serious implications for food security across both developed and developing nations (Hultgren *et al.*, 2025).
- 2. Threat to Food Security Across All Dimensions:** Climate change is anticipated to exert pressure on every core dimension of food security - spanning availability, accessibility, utilization, and stability - through a combination of gradual shifts in baseline climatic conditions and an accelerating rise in the frequency, severity, and duration of extreme weather events. The cascading consequences of these disruptions are expected to reverberate well beyond the farm gate, influencing commodity prices across food, fiber, and energy markets, compressing agricultural incomes, and placing additional strain on already fragile ecosystems at both the national and international levels (Crimmins *et al.*, 2023).

- 3. Regional Crop Losses - Sub-Saharan Africa & South Asia:** Regional projections paint a particularly troubling picture for some of the world's most food-vulnerable populations. Across Sub-Saharan Africa, staple crop yields are forecast to contract by 10-20% by 2050 under prevailing climate trajectories, placing significant strain on rural economies and food systems that are already operating under considerable stress. At the country level, Ethiopia offers a sobering illustration, where maize yields alone could fall by approximately 15% by mid-century as a direct consequence of rising temperatures and increasingly erratic rainfall patterns. A similarly concerning outlook extends to South Asia, where intensifying heat stress and the disruption of established monsoon cycles are projected to reduce rice and wheat production by 10-15% by 2050 - a decline with profound livelihood implications for the millions of smallholder farmers whose food and income security depends almost entirely on these two crops (Abebaw *et al.*, 2025).
- 4. Water Scarcity and Irrigation Stress:** Water availability represents one of the most critical pressure points at the intersection of climate change and agriculture. As summer temperatures rise, accelerating soil moisture loss makes drought management increasingly challenging, while water sources for irrigation simultaneously diminish - creating a paradoxical situation where demand peaks precisely when supply is most constrained (USEPA, 2024). This vulnerability is further compounded by agriculture's overwhelming dependence on freshwater, accounting for approximately 70% of all global freshwater withdrawals, alongside the reality that land degradation through soil erosion and salinization has already compromised the productivity of up to one-third of the world's arable land (Kummu *et al.*, 2016).
- 5. Increased Pest, Weed, and Disease Pressure:** Climate change is increasingly creating favorable conditions for the proliferation of weeds, pests, and fungal pathogens, as warmer temperatures, elevated moisture levels, and rising atmospheric CO₂ collectively lower the biological barriers that naturally constrain these threats (Deutsch *et al.*, 2018). Crop pests alone already account for approximately one-sixth of global farm productivity losses, and as climate conditions continue to shift, their prevalence and impact across cropping systems, livestock, and fisheries is projected to intensify significantly, with a higher likelihood of catastrophic outbreak events that could overwhelm existing pest management frameworks (FAO, 2021).
- 6. Soil Degradation:** J&K witnessed recently, beyond its direct effects on crop productivity, climate change exerts broad-ranging pressure across the entire agricultural system, simultaneously intensifying water scarcity, accelerating soil degradation, amplifying nitrogen and phosphorus pollution, increasing pest pressure and associated pesticide use, and driving measurable losses in biodiversity - all while elevating emissions of potent greenhouse gases such as nitrous oxide and methane that further entrench the cycle of environmental deterioration (Yang *et al.*, 2024).
- 7. Impacts on Livestock Productivity:** Livestock is important economic activity in J&K. Livestock productivity faces compounding threats under climate change, both directly through heat stress and indirectly through the deteriorating nutritional quality of feed and forage (Rojas-Downing *et al.*, 2017). While elevated atmospheric CO₂ may marginally boost the growth of pasture plants, this apparent benefit is offset by a concurrent decline in forage nutritional quality, compelling cattle to consume greater quantities of feed to meet the same dietary requirements — a dynamic that, when combined with increasingly extreme temperatures and precipitation disrupting crop growth, places mounting pressure on the long-term viability of grazing systems and rangeland productivity worldwide (USEPA, 2024).

8. **Nutritional Quality of Food Declining:** Although elevated atmospheric CO₂ is often associated with enhanced plant growth, this benefit carries a significant nutritional trade-off - higher CO₂ concentrations have been shown to systematically reduce the levels of protein and essential minerals in widely consumed staple crops including wheat, soybeans, and rice, posing a largely underrecognized but serious threat to human dietary health and nutritional security at the global scale (Myers *et al.*, 2014).
9. **Droughts, Famines, and Extreme Weather Events:** Climate change has triggered a cascade of interconnected environmental disruptions - encompassing recurrent droughts, flooding, desertification, wetland loss, and surging pest and disease incidence - that have collectively undermined agricultural productivity and freshwater availability across vulnerable regions (IPCC, 2022). Nowhere is this more evident than in East Africa, where escalating drought and heatwave frequency has driven wheat yields down by as much as 25% in certain areas over recent decades, with climate-induced crop losses in Ethiopia alone contributing to an estimated 5–10% contraction in the country's annual agricultural GDP (Abebaw *et al.*, 2025).
10. **Climate-Agriculture Feedback Loop:** A comprehensive global study from the University of Minnesota has uncovered a deeply troubling feedback dynamic, wherein the mounting pressure that climate change exerts on food production drives the adoption of agricultural practices that in turn further accelerate warming - a self-reinforcing cycle that, left unaddressed, could fundamentally undermine the Paris Agreement's critical threshold of limiting global temperature rise to 1.5°C-2°C (Yang *et al.*, 2024).
11. **Historical Evidence: Half a Century of Documented Harm:** A 2025 landmark study spanning five decades of agroclimatic data revealed that the majority of the world's cropping regions have simultaneously undergone rapid warming and progressive atmospheric drying, a dual climatic shift that has already translated into significantly diminished global yields across three of the five major crops examined - underscoring that the agricultural consequences of climate change are not merely projected future risks but measurable present realities (Lobell & Di Tommaso, 2025).

Adaptation Strategies for climate change

1. **Tolerant crops:** Patterns of drought happening may need various sets of adaptive forms (Srinivasarao and Gopinath, 2016). To reach deficient downpour conditions, early maturing and drought-tolerant cultivars of green gram (BM 2002-1), chickpea (Digvijay and Vijay), and pigeon pea (BDN-708) were brought on selected farmer's fields in Aurangabad district of Maharashtra (rainfall of 645 mm), which provided 20-25 % higher yield than the indigenous cultivars. In the same way, drought-tolerant, early maturing cultivars of pigeon pea (AKT-8811) and sorghum (CSH-14) were introduced in the villages of Amravati district, Maharashtra (rainfall of 877 mm) (Srinivasarao *et al.*, 2016).
2. **Tolerant breeds in livestock and poultry:** Local or indigenous breeds have the notion to forage for themselves which is a learned character. In nomadic systems, the animals show their owners when to move in search of new grasslands. Indigenous breeds have unique characters that are adapted to very specific eco-systems across the world. These unique characters are resistance to droughts, thermoregulation, ability to walk long distances, fertility and mothering instincts, ability to ingest and digest low-quality feed, and resistance to diseases. These livestock breeds may not be highly productive in terms of meat or milk production, but are highly adaptive to the unpredictable nature and have low resource

footprints. These critical features are what makes these breeds grant considerably to food security and livelihood systems of humans who inhabit these areas in different ways without affecting the weak ecosystem.

3. **Feed management:** Betterment of feeding systems as an adaptation measure could indirectly improve the efficiency of livestock production. Some of the given feeding methods include altering feeding time or frequency, and modification of diet composition, including agroforestry species in the animal diet and training producers in production and conservation of feed for various agro-ecological zones. These measures can decrease the risk from variations of climate by encouraging higher intake or compensating low feed consumption, decreasing excessive heat load, reducing animal malnutrition, and mortality and reducing the feed insecurity during dry seasons respectively.
4. **Water management:** Water smart technologies like a furrow-irrigated raised bed, micro-irrigation, rainwater harvesting structure, cover crop method, greenhouse, laser land leveling, reuse wastewater, deficit irrigation, and drainage management can support farmers to decrease the effect of variations of climate. Various technologies based on a precision estimation of crop water needs, groundwater recharge techniques, adoption of scientific water conservation methods, altering the fertilizer and irrigation schedules, cultivating less water requiring varieties, adjusting the planting dates, irrigation scheduling, and adopting zero-tillage which may help farmers to reach satisfactory crop yields, even in deficit rainfall and warmer years. Hence, many international organizations, national governments' research institutions, farmers' organizations, NGOs, and private agencies throughout the world are focusing their efforts on the design, development of cost-effective and environmentally friendly water-conserving devices and improved water application practices to enhance water use efficiency and water productivity.
5. **Agro-advisory:** Response farming is an integrative approach and could be called farming with advisories taken from the technocrats depending on local weather information. The success of response farming, viz., decreased danger, and enhanced productivity has been already taken in Tamil Nadu and many other states. Response farming could be a viable choice for climate change adoption strategies, as the variations of climate is not a sudden one. The main cause for the success of response farming is because of both location and time-specific technologies. It is time to take forward the success of response farming to the entire farming community.
6. **Soil organic carbon:** Different farm management practices can increase soil carbon stocks and stimulate soil functional stability. Conservation agriculture technologies (reduced tillage, crop rotations, and cover crops), soil conservation practices (contour farming) and nutrient recharge strategies can refill soil organic matter by giving a protective soil cover, and an environment favorable to vigorous plant growth. Integrated nutrient management deals with the application of organic and inorganic fertilizers, in addition to farmyard manure, vermicompost, legumes in rotation, and crop residue for sustaining soil health for the long term. Feeding the soil instead of adding fertilizers to the crop without organic inputs is the key point for the long-term sustainability of Indian agriculture (Srinivasarao *et al.*, 2014).

Climate Change in J & K and Impacts

- 1. Climate-Induced Risks in Jammu & Kashmir:** Climate change in Jammu and Kashmir is driving accelerated glacier melting, erratic precipitation, and rising temperatures, leading to severe water scarcity, increased flash floods, and agricultural disruption. Key impacts include a 1.45°C–2.32°C temperature rise, reduced snowpack, heightened forest fire frequency, and threats to apple production from unseasonal rains.
- 2. Tourism Reduction due to Natural Disasters:** Important source of income for J&K is through tourism; which is often affected to extreme climatic events.
- 3. Glacier and Water Resource Loss:** Rapidly receding glaciers and reduced snowfall, particularly in winter, have caused reduced water levels in rivers and streams, threatening water security.
- 4. Agri and Food Systems:** Erratic rainfall, drought-like conditions, and increased winter temperatures affect apple farming and other traditional livelihoods, reducing productivity. Apple growing regions are moving to upper regions of Himalayas due to increasing temperature.
- 5. Natural Disasters:** Changing precipitation patterns have increased the frequency of flash floods, landslides, and glacial lake outburst floods (GLOF).
- 6. Wildlife Stress:** Forests are facing increased vulnerability to fire due to rising temperatures and prolonged dry periods, impacting biodiversity.
- 7. Human Life and Health:** Nomadic populations (Gujjars and Bakarwals) are experiencing distress from unseasonal snow, while rising temperatures increase risks of health issues like infectious disease transmission to higher altitudes.
- 8. Economic Impact:** The region's tourism industry is suffering from reduced snowfall, limiting winter sports and altering the landscape.

Climate Change mitigation strategies

Mitigating climate change involves reducing greenhouse gas emissions into the atmosphere and increasing carbon dioxide removal. To limit global warming to below 1.5°C, global greenhouse gas emissions must reach net-zero by 2050, or by 2070 for a 2°C target. Achieving this requires unprecedented, far-reaching, and systemic transformations across energy, land use, urban planning, transportation, buildings, and industrial sectors. Climate change also exacerbates humanitarian crises caused by heat waves, wildfires, floods, tropical storms, and hurricanes, leading to displacement, loss of life, and property damage. It disproportionately affects marginalized communities with limited access to resources, including indigenous peoples, women, and low-income populations. Climate-induced migration, driven by sea-level rise, extreme weather events, and conflicts over natural resources, is expected to increase, potentially leading to statelessness for some individuals.

- 1. Reduction of methane emissions from Agriculture field:** Some of the best practices for low methane emissions agri- food system could be by using intermittent irrigation for irrigated medium and lowland rice, and alternate wetting-drying cycles for rainfed rice, Maintain sulfate in reduced zones of acid sulfate soil, Implement dry-direct seeded rice instead of wet-direct seeded rice in medium to upland ecologies, Promote aerobic decomposition of rice straw during winter/ summer to reduce CH₄ emissions in subsequent wet seasons, Optimize planting time to reduce CH₄ emissions, considering diurnal temperature variations.

2. **Reduction of nitrous oxide emissions from Indian Agriculture:** Best management practices may be employed such as application of coated ammonium citrate significantly reduce N₂O emission in arable soils, Application of bio char, Zero and Minimum tillage, Nitrification inhibitors like (1) 2-chloro-6-(trichloromethyl) pyridine (nitrapyrin), (2) dicyandiamide (DCD), and (3) 3,4-dimethylepyrazole phosphate (DMPP), neem cake, neem oil etc., Deep placement of urea in the reduced zone of paddy fields, Site specific nutrient management and Split application of nitrogenous fertilizers either based on critical physiological stages of the crop or using tools like Leaf color chart and SPAD meters.
3. **Minimizing CO₂ emissions in Indian Agriculture:** Transformative changes in India's agriculture are needed to reduce greenhouse gas emissions while maintaining production levels and sustaining ecosystem services. One of the most widely recommended interventions is conservation or zero tillage, which minimizes the oxidation of organic matter and retains carbon in the soil (Babu *et al.*, 2023). However, key practices such as agroforestry, biochar application, laser-assisted precision land leveling, direct seeding of rice, intercropping, use of solar energy, efficient management of irrigation water, soil nutrients, livestock feed, and manure and improved crop and livestock management help in sequestering carbon in both biomass and soil, offering substantial potential for capturing atmospheric CO₂ and storing it in agricultural landscapes (Gopinath *et al.*, 2025). From a policy standpoint, it is estimated that by 2030, business-as-usual GHG emissions from the agricultural sector in India would reach 515 megatonnes CO₂ equivalent per year, with a technical mitigation potential of 85.5 megatonnes CO₂ equivalent per year through adoption of various mitigation practices, and approximately 80% of this mitigation potential could be achieved through cost-saving measures alone (Sapkota *et al.*, 2019). India's government has reinforced these efforts through initiatives such as the National Mission on Sustainable Agriculture (NMSA) and the Carbon Credit Trading Scheme (CCTS).

Collectively, the convergence of agronomic innovation, digital monitoring systems, and supportive policy frameworks of Indian Government such as *National Action Plan on Climate Change (NAPCC)*, *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)*, *Paramparagat Krishi Vikas Yojana (PKVY)*, *Soil Health Card Scheme*, *National Mission on Sustainable Agriculture (NMSA)*, *Crop Insurance Program based on Weather (WBCIS)* and *Pradhan Mantri Fasal Bima Yojana (PMFBY)* may contributor to national climate mitigation goals.

Conclusions

Agriculture sector is facing a undeniable threat i.e. Climate change, which is a serious threat to agriculture production, food security and achievement of the Sustainable Development goals (SDGs). So, to tackle climate related issues within the agriculture sector climate change adaptation and mitigation strategies should be implemented. Progressively rising Earth's temperature further results in unforeseen changes in weather situations that are distressing the agriculture sector and the Indian economy. Climate change could reduce agricultural income by 15 to 25%. Adaptation of appropriate mitigation technologies such as the cultivation of tolerant breeds to overcome the climate stresses; water and nutrient management for efficient productivity and resource utilization; agro advisories for timely crop monitoring; conservation agricultural practices to build soil organic carbon and to build congenial environment for plant growth, manure management, etc., are crucial to address the climate change and achieve sustainable development goals (SDG) in India. However, location suitable policies/schemes and strategies play a pivotal role in sustaining the production system of the country.

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Chapter-2

Greenhouse Gas Emissions in South Asian Cereal Systems: Processes, Drivers, and Mitigation Pathways

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ABSTRACT

South Asia's cereal-based agriculture, particularly the rice–wheat system, is central to food security for more than 1.8 billion people but is also a major source of greenhouse gas (GHG) emissions. This chapter synthesizes current understanding of emission dynamics in rice, wheat, and maize systems and evaluates mitigation opportunities. Methane (CH₄) emissions are primarily associated with flooded rice due to anaerobic soil conditions, while nitrous oxide (N₂O) emissions arise largely from nitrogen fertilization in wheat and maize. Carbon dioxide (CO₂) emissions are linked to land-use change, intensive tillage, and energy use for irrigation. The rice–wheat system is particularly significant because alternating flooded and dry phases create complex interactions in soil carbon and nitrogen cycling, resulting in high global warming potential. Key mitigation options include alternate wetting and drying, direct-seeded rice, improved nitrogen management, conservation agriculture, and better residue management. These practices can reduce emissions while sustaining productivity, but adoption is constrained by economic, institutional, and knowledge-related barriers in smallholder systems. Scaling climate-smart practices will require integrated approaches combining technology, policy support, and extension services. Improving input-use efficiency and aligning incentives can support sustainable intensification. Overall, transitioning to climate-smart cereal systems offers a practical pathway to reduce emissions, enhance resilience and ensure long-term food security in South Asia.

Keywords: Greenhouse gas emissions; Rice–wheat system; South Asia; Methane emissions; Nitrous oxide; Climate-smart agriculture; Sustainable intensification; Conservation agriculture; Nitrogen use efficiency; Water management

1. Introduction

South Asia is one of the most densely populated and agriculturally intensive regions in the world, supporting more than 1.8 billion people and accounting for a substantial share of global cereal production. The region's food systems are heavily dependent on rice (*Oryza sativa*) and wheat (*Triticum aestivum*), which together dominate cropping patterns and underpin food and livelihood security. In recent decades, maize (*Zea mays*) has also expanded rapidly, particularly in India and Nepal, driven by increasing demand from the livestock, poultry, and bioenergy sectors (FAOSTAT, 2023; Pingali *et al.*, 2022). The Indo-Gangetic Plain (IGP), extending across Pakistan, northern India, Nepal and Bangladesh, represents one of the most productive agricultural landscapes globally. Its success has been closely linked to the Green Revolution, which introduced high-yielding varieties, irrigation infrastructure, and increased fertilizer use. While these interventions significantly enhanced productivity, they have also intensified environmental pressures, particularly in the form of greenhouse gas (GHG) emissions and natural resource degradation (Ladha *et al.*, 2021; Jat *et al.*, 2022).

Agricultural systems in South Asia are major contributors to global GHG emissions, particularly methane (CH₄) and nitrous oxide (N₂O), which have global warming potentials approximately 27–30 and 273 times greater than carbon dioxide (CO₂), respectively, over a 100-year time horizon (IPCC, 2021). Flooded rice systems create anaerobic soil conditions that promote methanogenesis, making rice cultivation a dominant source of CH₄ emissions in the region (Qian *et al.*, 2023; Minamikawa, 2025). In contrast, upland cereal systems such as wheat and maize are major sources of N₂O emissions due to intensive nitrogen fertilization and associated microbial processes, including nitrification and denitrification (Shcherbak *et al.*, 2021; Tian *et al.*, 2022). The rice–wheat cropping system, which occupies approximately 13–14 million hectares in the IGP, exemplifies the dual challenge of sustaining high productivity while minimizing environmental impacts. Continuous flooding in rice fields, coupled with excessive nitrogen use in wheat, results in high emissions of both CH₄ and N₂O. These emissions are further influenced by region-specific factors such as high temperatures, monsoonal rainfall patterns, soil characteristics, and residue management practices (Malyan *et al.*, 2021; Jat *et al.*, 2022).

At the same time, South Asian agriculture is highly vulnerable to climate change. Rising temperatures, increasing frequency of extreme weather events, erratic monsoon patterns and declining groundwater resources are already affecting crop productivity and system stability (Kumar *et al.*, 2022). These challenges are particularly acute for smallholder farmers, who operate under constraints of limited resources, fragmented landholdings, and high exposure to climatic risks (Aggarwal *et al.*, 2018; Aryal *et al.*, 2022).

Given this context, there is an urgent need to transition toward agricultural systems that can simultaneously enhance productivity, improve resilience and reduce greenhouse gas emissions. Climate-smart agriculture (CSA) provides a useful framework for achieving these goals by integrating improved water, nutrient, and crop management practices tailored to local conditions (Aggarwal *et al.*, 2018; Lipper *et al.*, 2020; Rosenstock *et al.*, 2022). This chapter provides insights into current knowledge on greenhouse gas emissions from major cereal crops in South Asia, with a particular focus on the rice–wheat system. It examines the biophysical processes driving emissions, evaluates mitigation strategies and discusses trade-offs, adoption barriers, and policy opportunities. By linking scientific understanding with practical interventions, this study aims to provide a comprehensive foundation for developing low-emission, climate-resilient cereal production systems in South Asia.

A critical limitation in current approaches is that mitigation strategies are often developed and evaluated in isolation, without adequately accounting for system-level interactions between crops, soils, and management practices. This limits their effectiveness when scaled across diverse smallholder systems

2. Cereal Systems and Emission Dynamics in South Asia

Cereal-based production systems in South Asia are shaped by strong seasonal cycles, intensive input use and long-standing agronomic practices that have evolved under conditions of high population pressure and resource constraints. Rice, wheat, and maize dominate these systems, but they differ fundamentally in their management, ecological conditions and greenhouse gas (GHG) emission profiles. Understanding these differences is essential for identifying targeted mitigation strategies.

2.1 Rice Systems

Rice is the most important cereal crop in South Asia, cultivated on approximately 60 million hectares and contributing nearly one-third of global rice production (FAOSTAT, 2023). It is primarily grown during the kharif (monsoon) season under irrigated or rainfed lowland conditions. The prevailing method of establishment is puddled transplanting, where seedlings are transplanted into water-saturated soils that have been tilled under flooded conditions.

This management practice creates anaerobic soil environments that are conducive to methane (CH_4) production. Under oxygen-limited conditions, methanogenic archaea decompose organic substrates and release methane, which is subsequently transported to the atmosphere through diffusion, ebullition, and plant-mediated pathways (Conrad, 2020; Qian *et al.*, 2023). The magnitude of CH_4 emissions is strongly influenced by water management, soil temperature and the availability of labile carbon.

Continuous flooding, which is widely practiced in irrigated rice systems across northwestern India and Pakistan, sustains anaerobic conditions throughout most of the growing season, resulting in high methane emission rates. In contrast, rainfed systems in eastern India and Bangladesh experience intermittent flooding, leading to more variable emission patterns (Yan *et al.*, 2022).

Organic matter inputs, including farmyard manure and crop residues, further influence methane dynamics. While these inputs improve soil fertility and structure, they also provide substrates for methanogenesis, often leading to increased CH_4 emissions when incorporated under flooded conditions (Sander *et al.*, 2020). Residue management practices, particularly the incorporation or burning of rice straw, therefore play a critical role in shaping emission outcomes. A key research gap remains in understanding how short-term reductions in methane emissions translate into long-term carbon stabilization, particularly under varying residue and water management regimes.

2.2 Wheat Systems

Wheat is the second most important cereal crop in the region, grown on approximately 30 million hectares, primarily during the rabi (winter) season following rice. The rice–wheat rotation system, which spans much of the Indo-Gangetic Plain, has been instrumental in ensuring regional food security but is increasingly associated with environmental challenges. Wheat cultivation typically involves conventional tillage practices, including multiple passes of ploughing to prepare a fine seedbed after rice harvest. These operations disturb soil structure, accelerate the decomposition of soil organic matter, and contribute to carbon dioxide (CO_2) emissions (Ladha *et al.*, 2021). In addition, fuel consumption during tillage further increases the carbon footprint of wheat production. Nitrogen fertilization is a major driver of emissions in wheat systems. Application rates often range between 150 and 200 kg N ha⁻¹, and inefficiencies in nitrogen use can result in substantial losses to the environment. Nitrous oxide (N_2O) emissions arise primarily from microbial nitrification and denitrification processes, which are influenced by soil moisture, temperature, and nitrogen availability (Shcherbak *et al.*, 2021; Tian *et al.*, 2022). Despite extensive research on nitrogen use efficiency, practical implementation remains constrained by the mismatch between recommended practices and farmer decision-making under risk and uncertainty.

In irrigated wheat systems, N_2O emissions often occur in pulses following irrigation or rainfall events, when soil moisture levels approach conditions favorable for denitrification. Residual nitrogen from the preceding rice crop can further contribute to emissions, particularly when soils remain moist during early wheat growth stages.

2.3 Maize Systems

Maize cultivation in South Asia has expanded significantly in recent years and now occupies approximately 10 million hectares. It is grown across diverse agroecological zones, including both rainfed and irrigated systems, and in both kharif and rabi seasons depending on regional conditions (Pingali *et al.*, 2022). Unlike rice, maize is typically grown under aerobic soil conditions and methane emissions are therefore negligible. However, maize systems are increasingly associated with high nitrous oxide emissions due to intensive nitrogen fertilization and high yield targets. In many cases, nitrogen application rates exceed crop demand, leading to increased losses through nitrification and denitrification pathways (Ussiri *et al.*, 2021).

Soil moisture dynamics play a critical role in regulating N₂O emissions in maize systems. Fluctuations in moisture, particularly in irrigated fields, create alternating aerobic and anaerobic conditions that enhance microbial activity and promote N₂O production. Additionally, the trend toward continuous maize cultivation in some regions raises concerns about soil degradation, nutrient imbalances and long-term sustainability. Despite these challenges, maize offers certain advantages from a GHG perspective. Its cultivation under non-flooded conditions avoids methane emissions, making it a relatively lower-emission crop in water-limited environments. However, achieving this potential requires improved nitrogen management to minimize N₂O losses.

Overall, cereal systems in South Asia exhibit distinct emission pathways linked to their management and environmental conditions. Rice systems are dominated by methane emissions driven by anaerobic soil conditions, whereas wheat and maize systems are primarily sources of nitrous oxide due to nitrogen fertilization. These differences highlight the need for crop-specific and context-sensitive mitigation strategies that address the underlying biophysical processes governing greenhouse gas emissions.

3. Greenhouse Gas Emission Profiles in South Asian Cereal Systems

Greenhouse gas (GHG) emissions from cereal-based systems in South Asia are governed by complex interactions among soil properties, climate, crop management, and microbial processes. The dominant gases methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) originate from distinct biogeochemical pathways and are influenced by crop-specific practices. Understanding these emission profiles is essential for designing effective mitigation strategies.

3.1 Methane (CH₄) Emissions from Rice Systems

Methane emissions from rice paddies represent the largest share of agricultural CH₄ emissions in South Asia. These emissions are primarily driven by anaerobic decomposition of organic matter under flooded soil conditions. In the absence of oxygen, methanogenic archaea utilize carbon substrates to produce methane, which is then transported to the atmosphere through diffusion, ebullition, and plant-mediated pathways (Conrad, 2020; Qian *et al.*, 2023).

Water management is the most critical factor controlling methane emissions. Continuous flooding, which is widely practiced in irrigated rice systems, maintains anaerobic conditions throughout the growing season and leads to sustained methane production. In contrast, intermittent drainage introduces oxygen into the soil, suppressing methanogenesis and promoting methane oxidation by methanotrophic bacteria (Minamikawa, 2025). Temperature also plays a significant role. The warm tropical and subtropical climates of South Asia enhance microbial activity, resulting in higher methane emission rates compared to temperate regions. Seasonal variations in

temperature and water availability further influence emission dynamics (Yan *et al.*, 2022). Organic inputs, including farmyard manure, green manure, and crop residues, provide additional substrates for methanogenesis. While these inputs improve soil fertility and long-term productivity, they can significantly increase methane emissions when incorporated into flooded soils. In particular, the incorporation of rice straw in rice–wheat system introduces large amounts of labile carbon, further stimulating CH₄ production (Sander *et al.*, 2020).

3.2 Nitrous Oxide (N₂O) Emissions from Wheat and Maize Systems

Nitrous oxide emissions are the dominant GHG flux from upland cereal systems such as wheat and maize. These emissions arise primarily from microbial nitrification and denitrification processes, which transform nitrogen (N) in the soil under varying oxygen conditions (Shcherbak *et al.*, 2021; Tian *et al.*, 2022). The application of nitrogen fertilizers is the principal driver of N₂O emissions. In South Asia, nitrogen is often applied in excess of crop demand due to subsidies, risk-averse farming strategies and limited access to site-specific recommendations. The surplus nitrogen remains in the soil and becomes susceptible to microbial transformations, leading to N₂O release. Soil moisture is a key regulator of these processes. Nitrous oxide emissions typically occur in pulses following irrigation or rainfall events, when soil water-filled pore space reaches levels conducive to denitrification (approximately 60-80%). Under these conditions, oxygen availability declines, and denitrifying microorganisms convert nitrate into gaseous forms, including N₂O (Ussiri *et al.*, 2021).

In rice–wheat systems, residual nitrogen from the rice phase can contribute to N₂O emissions during the subsequent wheat season. This carryover effect is particularly significant when soils remain moist and temperatures are favorable for microbial activity. Similarly, in maize systems, high nitrogen application rates combined with irrigation create conditions that enhance both nitrification and denitrification, leading to substantial N₂O losses.

3.3 Carbon Dioxide (CO₂) Emissions from Land Use and Energy Inputs

Carbon dioxide emissions in South Asian cereal systems are primarily associated with land-use change, soil disturbance and energy use. Although often less emphasized than CH₄ and N₂O, CO₂ plays a critical role in the overall carbon balance of agricultural systems. Land-use change, including the conversion of forests and grasslands to cropland, has historically released large amounts of carbon stored in vegetation and soils. This process continues in certain regions, particularly in the Himalayan foothills and central India, contributing to long-term increases in atmospheric CO₂ concentrations (Tubiello *et al.*, 2021).

Within existing agricultural systems, tillage practices are a major source of CO₂ emissions. Repeated ploughing disrupts soil aggregates, accelerates the decomposition of soil organic matter, and leads to carbon loss. Conventional rice–wheat systems, which rely on intensive tillage, are therefore associated with higher CO₂ emissions compared to conservation-based systems (Lal, 2020; Ladha *et al.*, 2021). Energy use for irrigation is another important contributor. A significant proportion of irrigation in South Asia depends on groundwater extraction using diesel or electric pumps. As groundwater levels decline, energy requirements increase, leading to higher indirect CO₂ emissions associated with fuel consumption and electricity use.

Overall, the emission profiles of South Asian cereal systems are characterized by methane dominance in rice and nitrous oxide dominance in wheat and maize, with carbon dioxide emissions arising from land-use and energy-related processes. These distinct pathways underscore the importance of integrated, system-specific mitigation strategies that address the underlying drivers

of each greenhouse gas. An important implication is that mitigation strategies targeting a single greenhouse gas may inadvertently increase emissions of another, highlighting the need for system-level assessment based on overall global warming potential rather than individual gases.

4. The Rice–Wheat System: Interactions, Intensification, and Emission Dynamics

The rice–wheat cropping system is the most important agricultural production system in South Asia, covering approximately 13–14 million hectares across the Indo-Gangetic Plain. It has played a central role in achieving regional food security since the Green Revolution. However, the long-term sustainability of this system is increasingly challenged by declining soil health, groundwater depletion, and rising greenhouse gas (GHG) emissions.

A defining feature of the rice–wheat system is the alternation between contrasting soil conditions. Rice is cultivated under flooded, anaerobic environments that promote methane (CH₄) production, whereas wheat is grown under aerobic conditions where nitrous oxide (N₂O) emissions dominate. This cyclical transition between anaerobic and aerobic phases creates complex interactions in soil carbon and nitrogen cycling, influencing both the magnitude and timing of GHG emissions (Ladha *et al.*, 2021; Jat *et al.*, 2022; Zhao *et al.*, 2022).

During the rice phase, prolonged flooding leads to the accumulation of reduced compounds and stimulates methanogenic activity. When fields are subsequently drained for wheat cultivation, the reintroduction of oxygen alters microbial processes, enhancing nitrification and creating conditions conducive to N₂O emissions. This temporal coupling of CH₄ and N₂O fluxes makes the rice–wheat system particularly important from a global warming perspective, as both gases have high radiative forcing (Zhao *et al.*, 2022).

Another critical characteristic of the system is the short turnaround time between crops. Farmers typically have only 10–20 days between rice harvest and wheat sowing. This narrow window limits options for residue management and often leads to the widespread practice of rice straw burning, particularly in northwestern India. Burning residues provides a rapid and low-cost solution for field preparation but releases significant amounts of CO₂, CH₄, N₂O, and black carbon, contributing to both climate change and severe air pollution (Jat *et al.*, 2022).

Residue management decisions also influence subsequent emission pathways. Incorporation of rice straw into flooded soils can increase methane emissions by providing labile carbon substrates for methanogens, whereas retaining residues on the soil surface in conservation agriculture systems may enhance soil organic carbon and reduce the need for intensive tillage. These contrasting outcomes highlight the importance of management context in determining environmental impacts.

Water use is another critical concern in the rice–wheat system (Kumar *et al.*, 2022). Puddled rice cultivation requires large volumes of water, leading to excessive groundwater extraction in many parts of the Indo-Gangetic Plain. Declining groundwater levels have increased the energy required for irrigation, thereby raising indirect carbon dioxide (CO₂) emissions. In addition, water scarcity is increasingly constraining the viability of traditional rice cultivation practices, prompting interest in alternative establishment methods and water-saving technologies (Malyan *et al.*, 2021).

Intensification of the rice–wheat system has also led to imbalances in nutrient cycling. High rates of nitrogen fertilization in both rice and wheat contribute to nitrogen losses through volatilization, leaching, and gaseous emissions. Residual nitrogen from the rice phase can carry

over into the wheat season, increasing the risk of N₂O emissions, particularly under conditions of high soil moisture. Despite these challenges, the rice–wheat system also offers significant opportunities for mitigation. Its widespread adoption and relatively uniform structure make it an ideal target for scaling climate-smart interventions. Practices such as zero-tillage wheat, improved residue management, optimized nitrogen application, and alternative water management in rice have demonstrated the potential to reduce emissions while maintaining or enhancing productivity. This dynamic interaction suggests that mitigation efforts must be evaluated across entire crop rotations rather than individual crop phases, as interventions in one season can have cascading effects on emissions in the next.

In summary, the rice–wheat system encapsulates the broader challenge of sustainable intensification in South Asia. Strong interactions between management practices, biophysical processes, and environmental outcomes characterize it. Addressing its limitations requires integrated approaches that consider the full system rather than individual components (Sapkota *et al.*, 2021), ensuring that productivity gains are not achieved at the expense of long-term sustainability. The complexity of emission processes and mitigation options necessitates an integrated systems perspective (Fig. 1).

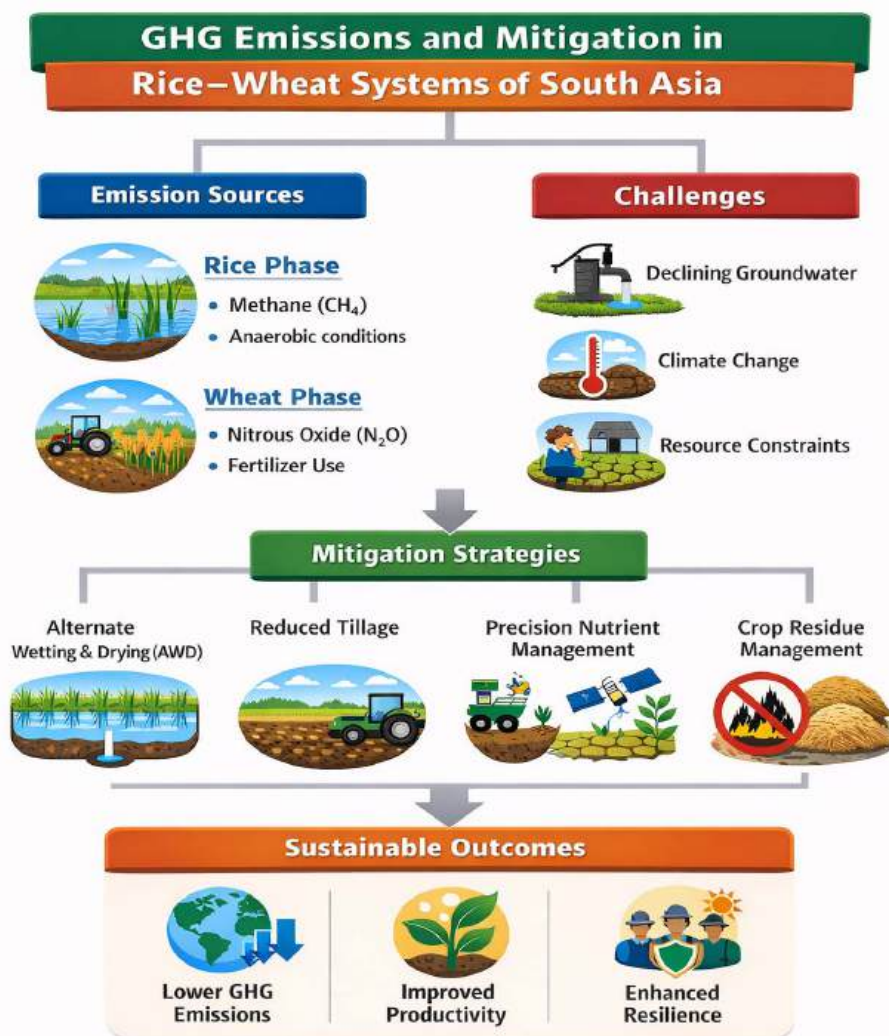


Figure 1. GHG emissions and mitigation in rice–wheat systems of South Asia.

5. Mitigation Strategies for South Asian Cereal Systems

Reducing greenhouse gas (GHG) emissions from cereal systems in South Asia requires approaches that are both scientifically robust and practical in smallholder-dominated farming systems. The majority of farmers operate on fragmented landholdings, often with limited access to capital, mechanization, and decision-support tools. As a result, mitigation strategies must be cost-effective, low-risk, and compatible with existing agronomic practices. In this context, a combination of water, nutrient, residue, and tillage management interventions offers significant potential to reduce emissions while sustaining productivity. A recurring challenge in mitigation research is the gap between experimental effectiveness and field-level adoption, where socio-economic constraints often override biophysical potential, particularly under smallholder conditions with limited access to resources and institutional support, as well as risk aversion, market uncertainties, and inadequate policy alignment.

5.1 Water Management in Rice Systems

Water management is a key determinant of methane emissions in rice cultivation. Alternate wetting and drying (AWD) has emerged as one of the most effective mitigation strategies. This approach involves periodic drainage of rice fields, allowing the soil to dry to a specified threshold before re-irrigation. By introducing oxygen into the soil, AWD suppresses methanogenic activity and promotes methane oxidation, leading to substantial reductions in CH₄ emissions (Minamikawa, 2025).

In addition to lowering methane emissions, AWD reduces water use and can improve root development and nutrient uptake when properly managed. While intermittent drying may create conditions favorable for nitrous oxide formation, studies indicate that the overall global warming potential (GWP) is reduced compared to continuous flooding (Qian *et al.*, 2023). Despite these benefits, adoption remains uneven due to challenges related to water control, particularly in canal-irrigated systems, and concerns about potential yield variability.

Direct-seeded rice (DSR) represents another important shift in water and crop establishment practices. By eliminating puddling and continuous flooding, DSR reduces methane emissions significantly and lowers water and labor requirements. However, the transition to aerobic soil conditions can increase N₂O emissions if nitrogen management is not optimized. Weed pressure is also a major constraint in DSR systems, requiring effective integrated weed management strategies (Jat *et al.*, 2022).

5.2 Nitrogen Management

Nitrogen use efficiency is central to mitigating nitrous oxide emissions in wheat and maize systems. Site-specific nutrient management (SSNM) aims to match nitrogen application with crop demand in both time and quantity, thereby reducing excess nitrogen in the soil. Tools such as leaf color charts, decision-support systems, and soil testing enable more precise fertilizer application, resulting in lower N₂O emissions and improved productivity (Shcherbak *et al.*, 2021).

Enhanced-efficiency fertilizers, including nitrification inhibitors and controlled-release formulations, provide another pathway for reducing nitrogen losses. In South Asia, neem-coated urea has been widely adopted, particularly in India, where it is supported by policy measures. By slowing the conversion of ammonium to nitrate, these fertilizers reduce the substrate available for denitrification, thereby lowering N₂O emissions while improving nitrogen use efficiency (Tian *et al.*, 2022). The effectiveness of improved nitrogen management is therefore not solely a technical

issue but also a behavioral and institutional one, requiring alignment between agronomic recommendations and farmer incentives.

5.3 Residue Management

Crop residue management is a critical component of emission mitigation, particularly in rice–wheat systems where straw burning is prevalent. Burning residues releases multiple greenhouse gases and contributes to severe air pollution. Alternatives such as in-situ residue retention and mechanized solutions have shown considerable promise. The use of specialized machinery, such as zero-till seeders capable of operating in residue-covered fields, allows wheat to be sown without removing or burning rice straw. This approach not only eliminates emissions associated with burning but also enhances soil organic carbon and moisture retention. Biological approaches, including the application of microbial decomposers, can accelerate residue breakdown and improve soil health. However, the effectiveness of these methods depends on timely application and favorable environmental conditions.

5.4 Tillage and Crop Establishment

Conservation agriculture (CA) practices, including reduced or zero tillage, residue retention, and crop diversification, offer significant mitigation potential. By minimizing soil disturbance, CA reduces carbon dioxide emissions associated with soil organic matter decomposition and fuel use. Over time, these practices can enhance soil carbon sequestration (Lal, 2020; Paustian *et al.*, 2016) and improve soil structure and resilience (Ladha *et al.*, 2021). Zero-tillage wheat, in particular, has gained traction in parts of the Indo-Gangetic Plain, where it reduces turnaround time between crops and lowers production costs. While the effects of CA on nitrous oxide emissions can vary depending on soil conditions and management, overall system-level benefits are generally positive when practices are implemented consistently.

5.5 Integrated Approaches and Scaling Pathways

Given the interconnected nature of agricultural systems, single interventions are often insufficient to achieve substantial emission reductions. Integrated approaches that combine multiple practices—such as improved water management, optimized nutrient use, and conservation tillage, are more effective in addressing the full range of emission sources (Sapkota *et al.*, 2021). The concept of climate-smart agricultural systems emphasizes the need to simultaneously enhance productivity, increase resilience, and reduce emissions. Implementation at scale requires strong institutional support, including extension services, access to technology, and enabling policy frameworks. Approaches that bundle technologies with advisory services and financial incentives have shown promise in pilot initiatives across South Asia (Rosenstock *et al.*, 2022). Overall, mitigation strategies in South Asian cereal systems must balance environmental benefits with economic and practical considerations. The most successful approaches are those that align emission reductions with improved resource use efficiency and farm profitability, thereby increasing the likelihood of sustained adoption. This highlights the importance of designing bundled interventions that address multiple constraints simultaneously rather than promoting single technologies in isolation.

6. Trade-offs, Barriers and Enabling Environment

While a range of mitigation strategies is available for reducing greenhouse gas (GHG) emissions from South Asian cereal systems, their effectiveness and adoption are shaped by a series

of biophysical trade-offs, socio-economic constraints, and institutional factors. Understanding these dimensions is essential for designing interventions that are both environmentally effective and practically scalable. These trade-offs underscore the need for decision frameworks that prioritize net climate benefits while maintaining productivity, rather than optimizing for individual emission pathways.

6.1 Trade-offs Among Greenhouse Gases and Productivity

Mitigation strategies in cereal systems often involve trade-offs between different greenhouse gases. For example, water-saving practices such as alternate wetting and drying (AWD) and direct seeded rice (DSR) effectively reduce methane (CH₄) emissions by introducing aerobic conditions into rice soils. However, these same conditions can enhance nitrification and denitrification processes, potentially increasing nitrous oxide (N₂O) emissions. Despite this trade-off, most studies indicate that the overall global warming potential (GWP) is reduced when evaluated on a carbon dioxide equivalent basis (Qian *et al.*, 2023).

Similarly, residue management practices present competing outcomes. Incorporating crop residues into soil can increase soil organic carbon and improve long-term soil health, but under flooded rice conditions, it may also enhance methane production by providing additional carbon substrates. In contrast, removing residues or using them for alternative purposes such as bioenergy can reduce methane emissions but may lead to long-term declines in soil fertility if not managed carefully.

Another important consideration is yield-scaled emissions. In South Asia, where food security remains a priority, mitigation strategies must not compromise crop yields. Practices such as site-specific nutrient management and conservation agriculture are more likely to be adopted because they maintain or increase productivity while reducing emissions per unit of output. In contrast, practices that involve perceived yield risks are less likely to be accepted by farmers.

6.2 Socio-economic and Institutional Barriers

Adoption of climate-smart practices in South Asia is constrained by several socio-economic factors. Small and fragmented landholdings limit farmers' ability to invest in new technologies or machinery. Many mitigation practices, such as zero tillage or mechanized residue management, require access to equipment that may not be economically viable for individual farmers.

Water management interventions such as AWD also face practical challenges. In canal-irrigated systems, farmers often lack control over irrigation timing and quantity, making it difficult to implement precise water management strategies. Similarly, variability in rainfall patterns adds uncertainty to the adoption of water-saving practices.

Policy distortions further complicate the adoption landscape. Subsidies on electricity and nitrogen fertilizers, particularly urea, can incentivize excessive resource use, leading to higher emissions. While these subsidies aim to support farmers, they often undermine efforts to promote efficient input use and sustainable practices. Knowledge gaps and limited access to extension services also hinder adoption. Many farmers lack access to timely and location-specific information on improved management practices. In addition, risk aversion plays a significant role, as farmers are often reluctant to adopt unfamiliar technologies that may affect yields or require changes in labor allocation.

Gender dynamics represent another important but often overlooked dimension. Women play a significant role in agricultural labor, particularly in activities such as transplanting and weeding.

Changes in crop establishment methods, such as the shift from transplanting to direct seeding, can alter labor demand and have implications for gender roles and livelihoods.

6.3 Opportunities and Policy Levers

Despite these challenges, several opportunities exist to accelerate the adoption of mitigation strategies. One promising approach is the development of carbon financing mechanisms that reward farmers for reducing emissions. Carbon credit methodologies for rice systems, including those based on alternate wetting and drying, are being implemented in parts of South Asia and offer potential additional income streams. Reforming subsidy structures represents another critical policy lever. Shifting support from conventional fertilizers to enhanced-efficiency fertilizers, such as neem-coated urea, can improve nitrogen use efficiency and reduce emissions. Similarly, promoting renewable energy solutions, such as solar-powered irrigation systems, can reduce reliance on fossil fuels and lower indirect CO₂ emissions. Institutional innovations such as custom hiring centers can help overcome barriers related to machinery access. By enabling farmers to share equipment such as zero-till seeders and residue management machinery, these centers reduce capital constraints and facilitate the adoption of conservation agriculture practices. Digital agriculture and decision-support tools also offer new opportunities for scaling climate-smart practices. Mobile-based advisory services, remote sensing and precision agriculture technologies can provide farmers with real-time information on weather, soil conditions, and input management, improving decision-making and reducing inefficiencies.

Overall, the successful implementation of mitigation strategies in South Asia requires a holistic approach that addresses not only technical feasibility but also socio-economic realities and institutional frameworks. Aligning incentives, improving access to knowledge and technology, and strengthening policy support will be essential for achieving large-scale reductions in agricultural greenhouse gas emissions.

7. Conclusion and Future Directions

Cereal-based agricultural systems in South Asia, particularly the rice–wheat rotation, are at a critical transition point. These systems have historically delivered substantial gains in food production and played a central role in ensuring regional food security. However, their long-term sustainability is increasingly constrained by rising greenhouse gas (GHG) emissions, declining soil health, groundwater depletion and growing climate variability. Addressing these challenges requires a fundamental shift toward production systems that are both resource-efficient and environmentally sustainable.

This chapter highlights that the major sources of GHG emissions in South Asian cereal systems are well understood. Methane emissions are predominantly associated with flooded rice cultivation, while nitrous oxide emissions arise mainly from nitrogen fertilization in wheat and maize systems. Carbon dioxide emissions, though often less emphasized, are linked to land-use change, soil disturbance and energy-intensive irrigation practices. Importantly, the processes driving these emissions are strongly influenced by management decisions, creating clear opportunities for mitigation.

A range of proven mitigation strategies is already available. Water management practices such as alternate wetting and drying and direct-seeded rice can substantially reduce methane emissions while conserving water. Improved nitrogen management, including site-specific nutrient management and the use of enhanced-efficiency fertilizers, offers significant potential to reduce

nitrous oxide emissions. Conservation agriculture practices, residue management alternatives and reduced tillage can enhance soil carbon sequestration and lower carbon dioxide emissions. When implemented in combination, these strategies can deliver meaningful reductions in overall global warming potential without compromising crop productivity. Despite the availability of these solutions, their adoption remains limited. The primary challenge is not the lack of technologies but the difficulty of scaling them across diverse and resource-constrained farming systems. Small landholdings, limited access to capital and machinery, policy distortions and knowledge gaps all contribute to slow adoption rates. In addition, mitigation strategies must be aligned with farmers' priorities, particularly the need to maintain yields and reduce production risks. Future efforts should therefore focus on scaling climate-smart practices through integrated and context-specific approaches. Strengthening agricultural extension systems will be critical to delivering tailored advisories that combine multiple interventions rather than promoting isolated practices. Policy reforms are needed to realign incentives toward efficient resource use, including rationalizing subsidies for water and fertilizers and promoting technologies that enhance input-use efficiency.

Investment in infrastructure and supply chains will also play a key role. Expanding access to enhanced-efficiency fertilizers, precision agriculture tools and mechanized residue management technologies can facilitate wider adoption. At the same time, innovative financial mechanisms, such as carbon credit programs and payments for ecosystem services, offer opportunities to incentivize farmers to adopt low-emission practices. Ensuring that these mechanisms are accessible to smallholders will be essential for achieving inclusive and equitable outcomes. Advances in digital agriculture, remote sensing and modeling provide new opportunities for monitoring, reporting, and verifying emission reductions at scale (Smith *et al.*, 2020). These tools can support the development of robust, low-cost methodologies for tracking progress and informing policy decisions. Ultimately, the transition toward low-emission cereal systems will depend less on the availability of technologies and more on the ability to integrate scientific knowledge with local socio-economic realities.

Looking ahead, the transformation of South Asian cereal systems will depend on coordinated efforts across research, policy and practice. Interdisciplinary approaches that integrate biophysical science with socio-economic considerations will be essential for designing effective solutions. By successfully transitioning toward low-emission, climate-resilient production systems, South Asia has the potential to serve as a global model for sustainable intensification in smallholder-dominated agricultural landscapes. Ultimately, achieving this transition is not only critical for mitigating climate change but also for securing the long-term sustainability of food systems and rural livelihoods in one of the most vulnerable regions of the world. The challenge is therefore not conceptual but operational, translating well-established mitigation principles into scalable, context-specific solutions.

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Chapter-3

Climate-Smart Agriculture: Drivers of Adoption, Constraints, and Potential Solutions

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ABSTRACT

Indian agriculture is highly vulnerable to climate change due to its heavy dependence on small and marginal farmers and the predominance of rain-fed farming systems. Increasing climate variability, rising temperatures and frequent extreme weather events such as droughts, floods and cyclones pose serious threats to agricultural productivity and rural livelihoods. In this context, Climate-Smart Agriculture (CSA) has emerged as a sustainable approach that integrates climate change adaptation and mitigation while ensuring food security. Despite its potential, the adoption of CSA remains limited due to multiple barriers, including high initial investment costs, lack of awareness, inadequate policy support, weak institutional frameworks and socio-cultural resistance. Resource constraints, digital divide and infrastructural deficiencies further restrict large-scale implementation. The various factors influencing the adoption of CSA practices includes: technological attributes, socio-economic conditions, institutional support and farmers' perceptions. Among these, some are external factors such as access to credit, extension services, subsidies and infrastructure and others are internal factors such as landholding size, income, education and farming experience. Thus, it emphasized that there is need for targeted strategies such as strengthening extension systems, enhancing digital literacy, improving access to finance and promoting inclusive and region-specific approaches. Overall, it is concluded that a coordinated policy framework, improved institutional support and farmer-centric interventions are essential to scale up CSA adoption and ensure resilient and sustainable agricultural systems.

Keywords: Climate Change; Agricultural Sustainability; Adaptation and Mitigation; Socio-economic Factors; Extension Services; Climate Resilience

1. Introduction

Indian agriculture is dominated by small and marginal farmers, with a large proportion of cultivated area being rain-fed. This makes the sector highly sensitive to climate variability and extreme weather events such as droughts, floods, heat waves and cyclones (ICAR 2023). It is expected that climate change is likely to reduce yields of major crops such as rice and wheat unless adaptive measures are adopted (Government of India 2025). According to the Intergovernmental Panel on Climate Change (IPCC) 2019 report, the mean temperatures may increase by 1.5°C between 2030 and 2050. The frequent climatic shocks, such as droughts, floods, and cyclones, are expected to affect crop productivity both directly and indirectly and continue to threaten rural livelihoods. Changes in atmospheric CO₂ concentration, temperature and rainfall patterns directly influence crop yields and land suitability, while indirectly affecting water availability and irrigation requirements (Anwar *et al.*, 2013). Additionally, emerging pests and diseases pose serious risks to crop production (Gregory *et al.* 2009). To address these challenges, several policy initiatives have been undertaken. The Indian Council of Agricultural Research (ICAR) launched the National Innovations on Climate Resilient Agriculture (NICRA) in 2011 to enhance the resilience of agricultural systems to climate variability and climate change (ICAR 2011). NICRA focuses on strategic research, technology demonstration and capacity building across crops, livestock, fisheries and natural resource management. The programme has been implemented in more than

150 climate-vulnerable districts, demonstrating climate-resilient technologies and improving farmers' adaptive capacity (ICAR 2011; ICAR 2023). In addition, Government of India initiatives such as the National Mission for Sustainable Agriculture (NMSA) (Government of India 2018), Pradhan Mantri Krishi Sinchai Yojana (PMKSY) (Government of India 2015) and Soil Health Card Scheme (Government of India 2015) aim to promote sustainable resource use and climate-resilient agricultural practices. These programmes emphasize efficient water management, soil health improvement and adoption of improved technologies to enhance agricultural productivity under changing climatic conditions. Other approaches, such as Climate-Smart Agriculture (CSA), supported by advancements in information and communication technologies (ICTs), decision support systems and early warning mechanisms, offer significant potential to enhance productivity, resilience and resource-use efficiency. By promoting CSA, India can simultaneously advance multiple Sustainable Development Goals (SDGs), including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action) (Okolie *et al.* 2022; Patra & Babu 2023). Despite the availability of CSA technologies and interventions, their adoption among smallholder farmers remains limited due to a range of socio-economic, institutional, and informational constraints. These barriers restrict farmers' capacity to effectively utilize climate-resilient practices, resulting in uneven adoption across regions and cropping systems (Raihan 2024). Therefore, it is essential to identify and analyze the key factors influencing farmers' adoption decisions. A comprehensive understanding of these determinants is crucial for designing targeted policies and strengthening extension strategies that enhance climate resilience, improve agricultural productivity, and ensure long-term food security and sustainable rural development. In this context, it is important to critically examine the current status of CSA in India, highlighting major challenges, evaluating future prospects, and providing strategic insights to promote the wider adoption of sustainable agricultural practices under changing climatic conditions.

2. Climate-Smart Agriculture (CSA): Concept, Scope and Adoption Dynamics

CSA has emerged as a promising solution (Rao, 2017; Rao *et al.*, 2024) in the form of participatory and bottom-up approach that explicitly addresses the challenges posed by climate change (Lipper & Zilberman 2018), particularly for developing nations (Long *et al.*, 2016; Ahmad *et al.*, 2020; Jamil *et al.*, 2021). Introduced by the FAO in 2010, CSA is an innovative and cleaner production alternative to conventional farming. It aims to transform agriculture towards climate-resilient practices, thereby strengthening food systems. CSA's objectives are threefold: (i) increasing agricultural productivity and farmer income, (ii) enhancing resilience and adaptation to climate change, and (iii) reducing greenhouse gas (GHG) emissions to mitigate climate change (Anuga & Gordon 2016; Joshi *et al.*, 2019; Nongmaithem *et al.*, 2019; Raihan, 2024). While sharing the fundamental principles of enhancing productivity and sustainability with conventional sustainable agriculture, CSA distinguishes itself through the deliberate integration of climate change adaptation and mitigation strategies, with a strong emphasis on ensuring food security (CSA Guide; Rosenstock *et al.*, 2015). Rather than introducing entirely new principles, CSA represents a strategic adaptation of existing agricultural development policies, programs and investments by incorporating climate-specific considerations (Lipper and Zilberman 2018). Thus, it can be viewed as an evolution of sustainable agriculture, maintaining its foundational goals while advancing a more focused agenda on climate resilience and reduction of greenhouse gas (GHG) emissions (CSA Guide). The scope of CSA is broad and encompasses a variety of innovative and resource-efficient practices such as water-smart, energy-smart, carbon-smart, nutrient-smart, weather-smart and knowledge-smart strategies (Mrabet 2023; Raihan *et al.* 2024). This adaptive framework

emphasizes locally tailored solutions, enabling farmers to effectively manage agricultural systems under increasing climate variability. At the same time, it seeks to reduce GHG emissions and enhance food security outcomes (Kumari *et al.*, 2019; Joshi *et al.*, 2019; Nongmaithem *et al.*, 2019).

3. Factors Influencing the Adoption of CSA

Adaptation to climate change in agriculture needs a comprehensive strategy, at the centre of which remains a shift towards climate-resilient agricultural practices. Theoretically, both external and internal factors may enable farmers to adopt climate-resilient agricultural practices. The adoption of CSA technologies is increasingly recognised as crucial for enhancing resilience, productivity and sustainability in global agricultural systems, particularly in light of the growing impacts of climate change (Abegunde and Obi 2022). These technologies provide pathways to mitigate climate-related risks, improve crop yields and promote sustainable farming practices, making them indispensable for smallholder farmers, who are often the most vulnerable to climate impacts (Hansen *et al.*, 2018). Numerous studies have emphasised the complex dynamics, including barriers and enablers that influence CSA adoption across diverse regions and agricultural systems (Silva *et al.*, 2024).

3.1 External factors influencing CSA adoption

External factors help to rebuild farmers' capacity to enhance their adaptive skills. Access to extension services, such as training (Tanti & Jena 2023; Zakaria *et al.*, 2020), farm field schools (Osumba *et al.*, 2021) and demonstrations, make farmers aware and knowledgeable about the Climate-Smart Agricultural (CSA) practices (Mgendi *et al.*, 2022; Makate *et al.*, 2019). Farmers who receive credit from public banks, private banks and cooperative societies are better equipped to adopt climate-resilient practices (Kangogo *et al.*, 2021). The provision of subsidies in the form of machinery and seeds also encourages farmers to adopt CSA practices. Such subsidies can be particularly beneficial for marginal farmers who may struggle to finance the transition from conventional to improved agricultural practices (Ou'edraogo *et al.* 2019). The availability of affordable energy sources and proximity to energy supplies near farm fields can facilitate the use of farm power-oriented machinery, including micro-irrigation, sprinkler irrigation, drip irrigation, and other small and large agricultural machinery (Das *et al.*, 2022). Access to clean energy sources enables farmers to tap irrigation sources and helps them to adopt sustainable agricultural practices, such as crop diversification and crop rotation. Subsidies and government credit programmes are likely to enhance the adaptive capacity to adopt CSA practices. Agricultural input subsidies significantly affect the adoption techniques used by farmers (Truong *et al.*, 2022). Jena *et al.*, (2023) identify the determinants that jointly influenced farmers to adopt these practices as access to extension services, access to credit, and subsidies for seed and electricity use in agriculture. The insufficient technical capacity of extension services has also been found to hinder knowledge transfer (Islam & Farjana 2024). In this context, digital tools like DAS could complement traditional extension by providing timely information directly to farmers (Asante *et al.*, 2024).

3.2 Internal factors influencing CSA adoption

The internal factors, including the size of landholding, asset ownership, savings and income from secondary occupations, influence farmers' decisions on adopting CSA practices (Deressa *et al.* 2011). These economic factors are critical determinants of farmers' capacity to invest in more sustainable agricultural practices, as they provide the financial resources needed to cover the costs of inputs and equipment required for CSA adoption. However, other household characteristics,

such as age, gender, experience in farming, the number of family members, and level of education, also play a significant role in farmers' adoption decisions. Farmers who are educated and have more diversified income sources tend to have greater awareness of CSA strategies (Mashi *et al.*, 2022). Demographic and socio-economic factors, including gender, age, land size and financial resources, consistently emerge as influential determinants in CSA adoption. Studies from Ethiopia and Ghana emphasized the importance of tailored strategies that account for these variables (Asante *et al.*, 2024; Chuang *et al.* 2020). Farmers in Taiwan, possessing greater knowledge and a stronger perception of the value of smart agricultural technologies are more inclined to adopt CSA, stressing the need for targeted educational strategies (Glover 2022). Younger farmers, for instance, are more receptive to new practices, while older farmers often prefer to adhere to traditional methods (Mwikamba *et al.* 2024). Gender disparities are prominent in rural communities, where women often lack access to essential resources like land, credit and extension services. Enhancing women's accesses to financial and institutional support could significantly enhance CSA adoption rates, given their essential roles in farm management and food production (Mbanasor *et al.* 2024).

3.3 Environmental and context-specific factors

Although theoretically a wide array of factors can influence farmers' decisions about CSA adoption, field-based research is needed to identify specific factors that are key determinants in specific regions. Given the geographical terrain of a particular region, the soil texture and local indigenous farming practices, recommendations for CSA practices need to be prepared. Further, the socio-economic composition and cultural beliefs vary widely. Hence, there is a need for conducting an investigation in climatically vulnerable regions to identify key policy parameters which can be controlled to widen the adoption of climate-resilient farming. Environmental factors such as soil type, rainfall and temperature also play a role in the adoption of climate-resilient crops. Environmental and climate-specific factors also impact CSA feasibility. Climate variability, extreme weather events and resource scarcity pose significant challenges to implementing practices like rain-fed irrigation and soil conservation. In drought-prone areas, limited water resources hinder irrigation, which is essential for climate resilience (Meshesha *et al.*, 2022). Adaptive strategies that incorporate CSA with traditional agricultural knowledge can enhance resilience by aligning practices with local farming systems and cultural contexts (Pedersen *et al.*, 2024). Additionally, environmental challenges such as land degradation and water shortages in remote regions further complicate CSA adoption (Autio *et al.*, 2021). Restrictive market conditions and the emergence of new pests create additional barriers to uptake (Rodriguez-Barillas *et al.*, 2024).

4. Challenges in the Implementation of Climate-Smart Agriculture

Despite the significant potential of Climate-Smart Agriculture (CSA) to mitigate the adverse impacts of climate change, its global implementation faces numerous challenges, particularly in developing countries (Mizik 2021). These challenges are multidimensional, encompassing economic, institutional, socio-cultural, technological and infrastructural constraints that limit widespread adoption.

Table 1: Studies on implementation challenges and determinants of CSA adoption

Key Determinants / Challenges	Country	Source
Gender and farm income significantly affect adoption decisions	Kenya	Raj and Garlapati (2020)
Limited access to credit, extension services, and subsidies	India	Muriithi <i>et al.</i> , (2021)
Knowledge and perception influence willingness to adopt CSA	Taiwan	Glover (2022)
Policy inconsistency, traditional practices, and limited state resources	India	Tanka <i>et al.</i> , (2019)
Input scarcity, labour shortages, and land access constraints	Mali	Jena <i>et al.</i> , (2023)
Unclear program guidelines and inconsistent institutional support	USA	Kamau <i>et al.</i> , (2023)
Limited access to land and water restricts CSA adoption	India	Mallappa & Pathak (2023)
Lack of appropriate policies, political support, the small shareholder farmer's lack of knowledge, and institutional and financial constraints	Sub-Saharan Africa	Wakweya (2023)
Gender disparities and large household size hinder CSA adoption	Ethiopia	Zelege <i>et al.</i> (2024)
Financial and procedural barriers due to weak institutional support	Pakistan	Mahmood <i>et al.</i> , (2024)
Gender equity, education, and credit access influence adoption	Nigeria / Kenya	Agbenyo <i>et al.</i> , (2022); Mbanasor <i>et al.</i> , (2024)
Stakeholder collaboration, policy incentives, and technology drive adoption	Europe	Perdersen <i>et al.</i> , (2024)
High implementation cost and limited institutional support	Malaysia	Aziz <i>et al.</i> (2024)
Lack of awareness, lack of participation in training programmes, lack of access to irrigation facilities and other resource constraints	India	Chanchal (2025)

4.1 Economic constraints: The most critical barriers to CSA implementation. High initial investment costs, recurring financial requirements and limited access to institutional credit significantly restrict farmers' ability to adopt CSA practices. In non-climate-smart villages, technical challenges such as lack of awareness persist, whereas in climate-smart villages, economic concerns such as elevated production costs and substantial upfront investments are more prevalent (Mishra *et al.*, 2024). Furthermore, socio-economic characteristics, including age, education level, access to credit, and off-farm income, significantly influence farmers' capacity to invest in CSA technologies (Ma & Rahut, 2024).

4.2 Policy and governance challenges: These challenges further complicate the implementation of CSA. Although supportive policies—such as subsidies, financial incentives and improved access to resources—can enhance adoption, fragmented institutional frameworks and weak enforcement mechanisms often undermine their effectiveness. Therefore, coherent and consistent policy frameworks, including subsidies for CSA inputs, tax incentives, and crop insurance schemes, are essential for reducing risks and promoting adoption (Guynn *et al.*, 2024).

4.3 Socio-cultural factors: These factors also play a crucial role in shaping farmers' decisions. Deep-rooted cultural norms and traditional practices often limit openness to new technologies, especially when conventional methods have historically been reliable (Pangapanga-Phiri *et*

al., 2024). In many regions, farmers exhibit reluctance to shift from familiar practices due to risk aversion and uncertainty. Promoting participatory approaches that actively involve farmers in decision-making processes and integrate indigenous knowledge systems can help build trust and enhance acceptance of CSA practices (Khumalo *et al.*, 2024). Additionally, fostering an entrepreneurial mindset among farmers can encourage them to perceive CSA as a long-term investment rather than a short-term risk (Truong *et al.*, 2022).

4.4 Farm-level and institutional barriers (draggers) to adoption: CSA practices are often perceived as more complex than conventional farming methods, making them difficult to implement without adequate support (Peshin, 2013). Insufficient training and lack of continuous technical guidance hinder farmers' ability to effectively adopt and sustain these practices (van de Fliert, 1993). Additionally, weak or absent enabling policy frameworks, inadequate financial resources for climate-smart interventions, and limited access to critical inputs such as climate-resilient crop varieties act as major deterrents (Peshin, 2013; Deguine *et al.*, 2021). Socio-economic limitations, the absence of follow-up after training programs, and inconsistencies between theoretical recommendations and field-level realities further reduce the effectiveness and adoption of CSA practices (Peshin *et al.*, 2022).

4.5 Resource and infrastructure constraints: Resource scarcity further complicates adoption, particularly in areas with limited access to essential agricultural inputs such as seeds, fertilisers, and water (Rodriguez-Barillas *et al.* 2023). Water shortages, in particular, severely restrict CSA practices that depend on irrigation (Kifle *et al.*, 2022). Infrastructure deficiencies, combined with inconsistent climate awareness among farmers, pose major barriers to CSA adoption (Konfo *et al.*, 2024). Addressing these challenges requires substantial investment in rural infrastructure, including irrigation systems and storage facilities, along with the promotion of sustainable resource management practices that ensure efficient resource utilisation (Autio *et al.*, 2021).

4.6 Technological constraints: Digital technologies can significantly enhance CSA adoption by improving farmers' access to real-time information on climate conditions, market trends and best agricultural practices (Waaswa *et al.* 2021). Tools such as Decision Support Systems (DSS), mobile applications and online platforms have proven effective in reaching farmers in remote areas (Jellason *et al.* 2020). However, limited digital literacy, poor internet connectivity and lack of access to digital devices remain major barriers. These constraints prevent many farmers from fully utilizing digital tools for climate-smart decision-making. Therefore, expanding rural digital infrastructure and promoting digital literacy programs are essential to empowering farmers and facilitating the effective implementation of CSA practices (Prashanthi *et al.*, 2022).

5. Strategies to Overcome Barriers

To address the challenges hindering the adoption of CSA technologies, several targeted interventions are essential. Financial constraints are among the primary challenges, with high costs of inputs, infrastructure, and labour requirements, and labour deterring many farmers from implementing CSA practices (Raj & Garlapati, 2020). Expanding access to credit and providing affordable financing options, such as low-interest loans, subsidies, and tax incentives, can empower farmers to make the necessary investments for CSA adoption (Guynn *et al.*, 2024). Strengthening extension services and enhancing farmer education are also critical, as they provide the knowledge

and technical support farmers need to implement CSA practices effectively (Tanti *et al.*, 2024). Improved farmer-to-extension agent ratios, coupled with digital tools like DAS, can extend the reach of extension services, especially in remote areas, thus enhancing farmers' decision-making and adaptability to climate risks (Makate *et al.*, 2018). Digital solutions also enable real-time information sharing, giving farmers access to updates on climate conditions, pest control and market trends that are vital for CSA's success (Kifle *et al.*, 2022). Moreover, it is essential to tailor CSA strategies to socio-demographic factors such as age, education, gender and household income, which significantly influence adoption rates (Ting, 2022). Programs targeting younger farmers who may be more receptive to new practices should also account for the needs of older farmers who adhere to traditional methods (Desai & Zhang, 2021). Gender-sensitive interventions are essential in rural communities where women often lack access to resources such as land and credit, despite their critical role in farm management and food production (Thottadi and Singh 2024). Empowering women through targeted financial support and access to extension services could increase CSA participation (Agbenyo *et al.*, 2022).

Enhanced institutional support and improved infrastructure are also crucial for creating an enabling environment for CSA adoption. Investments in infrastructure, such as roads and market facilities, can improve market access for farmers, stabilize their incomes and increase their capacity to invest in CSA technologies. Farmer cooperatives and associations can further strengthen collective bargaining power, reduce input costs and improve market access, thus facilitating CSA implementation (Jena *et al.*, 2023). Region-specific and environmentally adaptive approaches are essential for CSA sustainability, given environmental variability and the need for practices tailored to local conditions (Gemtou *et al.*, 2024). For instance, water-efficient irrigation practices are particularly critical in drought-prone areas, where water scarcity limits adoption. Combining CSA with traditional agricultural knowledge can enhance resilience by aligning CSA practices with local farming methods and cultural contexts, fostering acceptance and sustainability (Meshesha *et al.*, 2022). Consistent policy frameworks and supportive incentives, such as subsidies, tax breaks and insurance schemes are vital for promoting CSA adoption by reducing associated costs and providing a safety net for farmers (Van Asseldonk *et al.*, 2023). Coherent policies that prioritize CSA adoption can help farmers overcome financial and institutional barriers, allowing them to invest confidently in CSA practices (Guynn *et al.*, 2024). Addressing these complex barriers through integrated financial assistance, policy support, extension services and tailored educational strategies can enable widespread CSA adoption and foster resilient, sustainable farming systems globally.

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Chapter-4

Recent Developments and Technological Innovations in Weed Management for Climate-Resilient Agriculture

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ABSTRACT

Weed management is a crucial component of sustainable crop production systems. Globally, weeds account for an estimated 37–45% yield losses when left unmanaged, severely constraining food security and economic stability (Gharde et al., 2018; Rao and Nagamani, 2010). In India, where more than 55% of agriculture is rainfed, the challenge is intensified due to climate change, limited mechanization, and labor shortages. Furthermore, the climate change fundamentally altering the weed-crop dynamics. Elevated CO₂ levels, fluctuating temperature regimes, and erratic rainfall patterns have shifted weed phenology, weed seed dormancy, expanded the geographical range of invasive species, and reduced the efficacy of conventional herbicides through physiological adaptations. In this context, achieving climate-resilient agriculture requires a paradigm shift from reactive chemical control to proactive, technology-driven Integrated Weed Management. Recent innovations spanning nano-formulations, automation, artificial intelligence, robotics, and biological suppression have redefined global and Indian weed science. Nanotechnology has become a cornerstone of next-generation herbicide delivery, offering controlled release, enhanced selectivity, and reduced ecological footprint. Encapsulated and nano-enabled formulations of diclosulam, metolachlor, sulfentrazone, and pendimethalin demonstrate prolonged weed suppression with minimal residue. Emergence of "Smart Weeding" technologies that leverages the Artificial Intelligence and Machine Learning. Deep learning algorithms, trained on vast libraries of spectral images, now enable real-time, species-specific identification. This precision allows for the deployment of Site-Specific Weed Management via autonomous ground vehicles and Unmanned Aerial Vehicles. These platforms reduce herbicide use by up to 90% through targeted micro-dosing or "see-and-spray" systems, mitigating the environmental footprint and slowing the evolution of herbicide resistance. Parallel developments in automation and robotics through UAVs, AI-based sensors, and laser or electrothermal weeders enable site-specific mechanical and chemical interventions. Biological and allelopathic strategies utilizing fungal pathogens, microbial bioherbicides, and allelochemical-rich crops such as sorghum and sunflower are gaining momentum as chemical-free alternatives. Integrated Weed Management frameworks now merge chemical, biological, mechanical, and digital methods to sustain efficacy and prevent herbicide resistance. Climate-smart and conservation agriculture practices mulching, residue retention, and competitive cultivars further enhance resilience in agroecosystems.

Keywords: Climate Resilience, Controlled Release Herbicide Efficacy, Integrated Weed Management, Nano-herbicides, Nanotechnology, Precision Agriculture, Smart Weeding

1. Introduction

Weeds impose substantial yield losses across major cropping systems, accounting for up to 37–45% reduction in productivity when unmanaged (Gharde et al., 2018; Rao & Nagamani, 2010). Traditional control methods such as hand weeding and broad-spectrum herbicide use are increasingly constrained by labor shortages, rising costs, herbicide resistance, and environmental concerns (Chhokar et al., 2012; Jat et al., 2021). In India, where 55% of agriculture is rainfed, the problem is intensified by erratic rainfall and limited mechanization (Yaduraju, 2013; Das, 2019). Consequently, researchers and policymakers advocate for technological advancements that integrate precision tools, eco-friendly formulations, digital surveillance, and climate-adaptive strategies.

Over the past decade, weed science has witnessed paradigm shifts toward nano-enabled herbicide delivery (Kumar *et al.*, 2021; Saharan *et al.*, 2015), AI-guided robotics (Slaughter *et al.*, 2008), UAV-based herbicide application (Martin *et al.*, 2019), allelopathic interventions (Verma *et al.*, 2020), and machine learning-based weed recognition (Ahmad *et al.*, 2021). Indian institutions such as the ICAR-Directorate of Weed Research (DWR), JNKVV, TNAU, and PAU have contributed significantly to integrated strategies suitable for rice, wheat, pulses, cotton, and horticultural crops (Balyan and Malik, 2017; Mahajan and Chauhan, 2013).

Emerging concerns around herbicide resistance in species like *Phalaris minor*, *Echinochloa crus-galli*, *Amaranthus viridis*, and *Cyperus rotundus* are further accelerating research into advanced delivery systems, multi-mechanism herbicides, and biological suppression methods (Chhokar *et al.*, 2012; Singh *et al.*, 2020). Additionally, climate-smart weed management approaches are being tailored for dryland and conservation agriculture systems (Kumar and Yadav, 2017; Sah *et al.*, 2022). This review provides a detailed synthesis of the latest trends and technologies, emphasizing innovation, field applicability, and regional relevance to Indian and global contexts.

2. Advances in Chemical Weed Management

The evolution of chemical control remains a backbone of modern weed management, but recent innovations have focused on improving selectivity, reducing doses, enhancing delivery mechanisms, and mitigating resistance. Low-dose, high-efficiency herbicides like pyroxsulam, halauxifen-methyl, and penoxsulam have gained prominence due to better crop safety and environmental compatibility (Matloob *et al.*, 2019; Beffa *et al.*, 2019). Indian researchers have extensively evaluated herbicide combinations and sequential applications in rice-wheat, soybean, maize, cotton, and groundnut systems (Yaduraju, 2013; Choudhary *et al.*, 2016; Ghosh *et al.*, 2020).

Tank mixes and ready-mix formulations combining different modes of action, such as atrazine + pendimethalin, metsulfuron + carfentrazone, and glyphosate + 2,4-D, have improved resistance management and broadened weed spectrum control (Kaur *et al.*, 2018; Singh *et al.*, 2020). Safener technologies, like isoxadifen-ethyl and mefenpyr-diethyl, have enhanced crop tolerance (Grossmann *et al.*, 2011), while Indian trials reported improved selectivity in maize, sorghum, and wheat (Kumar and Rana, 2017; Mishra *et al.*, 2020). Drift-reducing adjuvants such as organosilicone surfactants, plant oils, and polymers have further optimized field performance (Ebert *et al.*, 2019; Verma *et al.*, 2021).

Controlled droplet application (CDA) nozzles, electrostatic sprayers, and variable-rate sprayers have increased deposition accuracy and lowered spray volumes in Indian orchards and row crops (Sharma *et al.*, 2020; Gupta and Jain, 2019). Herbicide stewardship programs led by ICAR and SAUs have promoted resistance mapping and region-wise recommendations (Balyan and Malik, 2017; Rao, 2014). However, rising cases of resistance in *Lolium rigidum*, *Conyza bonariensis*, and *Phalaris minor* demand newer chemistries and adaptive rotations (Heap, 2023; Bhullar *et al.*, 2017). Minimization of environmental contamination through targeted formulations and dose optimization has also been emphasized (Das, 2019; Jain *et al.*, 2020). Overall, chemical weed control continues to evolve with increased precision, rotational planning, and integration with non-chemical methods.

3. Nanoherbicides and Encapsulation Technologies

The emergence of nanotechnology has revolutionized modern weed management through the

development of nanoformulations that enhance herbicide delivery, improve target specificity, and minimize environmental contamination. Nanoherbicides represent a sustainable approach to achieving effective weed control with reduced doses and extended field persistence. Chinnamuthu and Kokiladevi (2007) first proposed the concept of target-specific nanoherbicides, wherein the active ingredient is encapsulated within nanoparticles designed to recognize specific receptors in the roots of target weeds. Modern nanotechnological strategies emphasize receptor-based nanoherbicides aimed at disrupting weed seed or tuber dormancy, thereby exhausting the soil weed seed bank and reduced amount of herbicide residue left in the soil (Chinnamuthu and Boopathi, 2009). Research at TNAU has shown that combining growth regulators (e.g., cytokinins) with herbicides such as metolachlor or glyphosate effectively breaks dormancy and kills *Cyperus rotundus* tubers (Ravisankar and Chinnamuthu, 2013). Metallic nanoparticles particularly zinc oxide (ZnO) and iron oxide (Fe₃O₄) degrade phenolic dormancy inhibitors, enhancing germination and enabling subsequent weed suppression (Brindha and Chinnamuthu, 2012).

Enzymatic treatments such as α -amylase, alone or in combination with silver nanoparticles, accelerate starch degradation in tubers, depleting energy reserves and causing pre-emergent death (Brindha and Chinnamuthu, 2015). Nanoparticles have been shown to stimulate dormancy release and germination in *C. rotundus* tubers by degrading phenolic compounds such as caffeic, ferulic, chlorogenic, vanillic, and hydroxybenzoic acids (Viji and Chinnamuthu, 2015a). Iron oxide nanoparticles at 3.0 g kg⁻¹ of tubers enhanced phenol degradation by 89%, indicating their catalytic role in hydroxyl radical generation through advanced oxidation processes (AOPs). Similarly, ZnO nanoparticles at 1500 mg kg⁻¹ reduced starch and phenol content while improving germination by 80% over control treatments (Viji and Chinnamuthu, 2015b). Silver nanoparticles bio-conjugated with α -amylase further facilitated starch hydrolysis in *C. rotundus* tubers, depleting stored energy reserves essential for weed persistence (Viji *et al.*, 2016). Further studies at TNAU demonstrated that integrating hydrogen peroxide (H₂O₂) with pendimethalin and ZnO nanoparticles effectively reduced weed emergence and soil seed bank size in black gram. Application of H₂O₂ (300 ml m⁻²) followed by pendimethalin (0.75 kg ha⁻¹) and ZnO NPs (500 ppm) significantly decreased weed density and enhanced crop yield (Vimalrajiv *et al.*, 2018).

Nanoencapsulation involves enclosing herbicidal molecules within a continuous polymeric shell at the nanoscale to achieve controlled and targeted release. Encapsulation can be accomplished through several techniques direct and indirect methods, solvent evaporation, spray drying, and ionotropic gelation each offering distinct advantages (Kumar *et al.*, 2015). Encapsulation enhances environmental safety by minimizing volatilization, leaching, and photodegradation (Saharan *et al.*, 2015; Grillo *et al.*, 2016). The solvent evaporation method, optimized at Tamil Nadu Agricultural University (TNAU), effectively encapsulated the pre-emergence herbicide pendimethalin, providing sustained release for up to 40 days (Pradeesh Kumar and Chinnamuthu, 2014). Such formulations suppress weed seed bank enlargement, conserve soil moisture and nutrients, and improve harvest quality compared to conventional herbicide applications.

At TNAU, pendimethalin nanoformulations were developed using a direct encapsulation technique wherein herbicide molecules were loaded onto a MnCO₃ nanocore template via layer-by-layer (LBL) adsorption of oppositely charged polyelectrolytes (Pradeesh Kumar and Chinnamuthu, 2014). The encapsulated pendimethalin herbicide in starch using solvent evaporation technique, which delivered herbicide sustainably during the period of forty days to achieve the season-long weed control (Kumar and Chinnamuthu, 2017). Similarly, encapsulated

sulfentrazone @ 0.30 kg a.i. ha⁻¹ with at 1 DBS proved effective for for season long weed management in blackgram without affecting the soil and ground water, while simultaneously increasing crop productivity (Kannamreddy *et al.*, 2020). Further, Bommayasamy *et al.*, (2018) observed that oxadiargyl entrapped within zeolite, biochar, or starch polymers significantly reduced total weed dry weight and extended the duration of weed suppression in transplanted rice. Likewise, Bommayasamy and Chinnamuthu (2020) reported that zeolite loaded oxadiargyl resulted in lower weed density compared to commercial formulation due to its slow, sustained release throughout the season, which depleted the food reserves of weed seeds and minimized their regeneration.

Building upon these findings, the solvent evaporation technique has been further applied to pre-emergence herbicides such as Sulfentrazone, diclosulam, metolachlor, and Oxyflourfen, among that encapsulated diclosulam demonstrated prolonged weed suppression under rainfed groundnut (Swetha *et al.*, 2023). More recently, encapsulation of diclosulam and metolachlor using sodium alginate with various cross linkers has been engineered at TNAU (Chinnamuthu and Srimathi, 2024). The resultant controlled release formulations provided effective and extended weed control in rainfed groundnut and pulse crops, marking a significant step toward sustainable herbicide delivery systems.

Green synthesis of nanocarriers using plant extracts (e.g., neem, moringa, and eucalyptus) offers an eco-friendly route to reduce chemical load (Sridhar *et al.*, 2021; Ramesh *et al.*, 2022). Novel delivery systems, including spray-dried and electrospun nanofibers, have potential in high-value horticultural crops (Verma *et al.*, 2020; Pradhan *et al.*, 2021). Biodegradable bio-nanocomposites based on starch, lignin, and cellulose enable controlled degradation in soil environments (Chatterjee *et al.*, 2019). Surface-modified nanoparticles, such as silver, zinc oxide, and titanium dioxide, enhance herbicide solubility and uptake through cuticular diffusion and stomatal penetration (Kah *et al.*, 2018; Singh *et al.*, 2020). Layered double hydroxides, mesoporous silica nanoparticles, and metallic nanocarriers have shown synergistic effects in weed suppression (Gajbhiye *et al.*, 2019; Mohanty *et al.*, 2022). Smart carriers responsive to pH, moisture, or enzymatic triggers are being developed for precision herbicide release (Raliya *et al.*, 2017).

Susha and Chinnamuthu (2012) demonstrated that silver-modified ferric oxide (Fe₃O₄ CMC) nanoparticles degraded 82–88% of atrazine within 24 hours, underscoring their potential in herbicide residue remediation. Toxicological studies indicate that nanoherbicides, when applied at optimized levels, are generally safer for non-target organisms and soil microbiota than conventional formulations (Kah and Hofmann, 2014). However, challenges such as regulatory standardization, field-scale validation, cost efficiency, and farmer awareness persist (FICCI, 2020; ICAR-DWR, 2021).

4. Precision Weed Management and Smart Agriculture

Precision weed management represents an advanced approach that combines geospatial tools, variable-rate technologies (VRTs), decision support systems (DSSs), and data-driven models to optimize herbicide application while reducing environmental impacts. The adoption of GPS-enabled sprayers, digital weed maps, and prescription-based spraying systems has substantially improved herbicide targeting accuracy, achieving 25–60% enhancement in application precision across several field trials (Christensen *et al.*, 2009; Shanmugam *et al.*, 2020). Recent advances in multispectral and hyperspectral imaging have transformed weed detection and mapping. Satellite based platforms such as Sentinel-2 and Landsat-8, together with drone-mounted RGB and near-

infrared (NIR) sensors, enable spatial monitoring of weed infestations at high resolution (Huang *et al.*, 2016; Thanki *et al.*, 2020). Field studies using unmanned aerial vehicles (UAVs) for detecting *Echinochloa* and *Cyperus rotundus* in paddy and groundnut fields have reported detection accuracies exceeding 80% (Kumar *et al.*, 2022; Desai *et al.*, 2021).

The concept of site-specific weed management (SSWM) has gained traction with the deployment of optical sensing systems such as WeedSeeker®, GreenSeeker®, and Crop Circle™, which detect chlorophyll fluorescence differences between crops and weeds. These systems have demonstrated up to 50% herbicide savings in fallow lands, sugarcane plantations, and dryland cropping systems (Khot *et al.*, 2021; Mahajan *et al.*, 2017). Likewise, variable-rate application (VRA) technologies use geotagged field data to modulate herbicide dosages according to weed intensity zones, thereby enhancing precision and minimizing input wastage (Timmermann *et al.*, 2003; Sharma and Yadav, 2020).

Geographic Information System (GIS)-based weed mapping, coupled with remote advisory platforms, has been successfully piloted in regions such as Maharashtra, Tamil Nadu, and Karnataka, providing spatial recommendations for weed control (Patel *et al.*, 2020; ICAR-DACNET, 2021). Decision support systems (DSS) such as WeedCast, HERBIS, and FASAL further facilitate predictive modeling of weed population dynamics and herbicide scheduling, enabling data-informed management strategies (Rao, 2014; Singh *et al.*, 2019).

The integration of machine learning (ML) and artificial intelligence (AI) tools has accelerated the development of automated weed classification systems. Algorithms such as Convolutional Neural Networks (CNNs), Support vector Machine (SVMs), and deep learning frameworks have achieved 85–95% accuracy in identifying both pre and post emergent weeds (Ahmad *et al.*, 2021; Hasan *et al.*, 2020). Smartphone-based applications like “Pest Manager” and “AgriApp” are now enabling farmers to perform real-time weed identification and receive recommendations at the field level.

The Internet of Things (IoT) further enhances precision weed management through sensor networks that integrate weed detectors, soil moisture probes, micro-weather stations, and crop growth models. These systems enable adaptive timing of weed control operations based on real-time field data (Chakraborty *et al.*, 2021). Additionally, autonomous vehicles equipped with RTK-GPS, machine vision, and boom controllers are being tested for selective herbicide spraying in plantation and row crops (Torretta *et al.*, 2020; Deshmukh *et al.*, 2022).

Despite its immense potential, the widespread adoption of precision weed management in India faces challenges including high implementation costs, limited digital literacy, and fragmented landholdings. To overcome these barriers, custom hiring centers and cooperative-based models are being promoted, enabling collective access to precision technologies and fostering sustainable weed management under Indian farming conditions.

5. Robotics, Drones, and AI-Based Weed Control

The integration of automation, robotics and artificial intelligence (AI) is transforming weed management by enhancing precision, reducing labour requirements and minimizing chemical dependence. These technologies collectively enable both mechanical and targeted chemical control, providing sustainable alternatives for modern agriculture.

Ground-based robotic weeders such as *Robocrop*, *FarmDroid*, *EcoRobotix*, and *TerraSentia* employ computer vision, GPS guidance and real-time decision algorithms to identify, uproot or spot-spray weeds with remarkable precision (Slaughter *et al.*, 2008; Fennimore *et al.*, 2016). In India, indigenous prototypes developed at IITs, CIAE-Bhopal, and PAU have shown promising potential for row crops such as cotton, groundnut, and vegetables, offering localized solutions suited to smallholder systems (Patel *et al.*, 2021; Gupta *et al.*, 2020).

Drones and UAVs have emerged as versatile platforms for herbicide application, weed scouting, and crop surveillance across diverse systems, including rice, tea, orchards, and sugarcane (Martin *et al.*, 2019; Singh *et al.*, 2022). The advent of swarm-based drones equipped with precision nozzles has enabled patch-specific herbicide spraying in inaccessible or waterlogged fields (Wan *et al.*, 2020). Field evaluations by ICAR and CAU demonstrated that quadcopter-based application of glyphosate and 2,4-D achieved 30–40% reductions in input use, with uniform coverage and minimal drift (Raj *et al.*, 2021; John *et al.*, 2020).

The use of AI and machine learning algorithms enables real-time image recognition and selective herbicide application. Deep learning architectures such as CNNs and You Only Look Once (YOLO) models have been successfully trained to distinguish weed species in crops like cotton, chilli, paddy, and soybean, enabling precise and automated control decisions (Hasan *et al.*, 2020; Dhruw *et al.*, 2022).

Advances in non-chemical weeding technologies include laser-guided and electrothermal systems, which physically destroy weeds without leaving residues. Lased-based weeders target the photosynthetic tissues of broadleaf and grassy weeds with sub-centimeter accuracy (<1 cm), effectively minimizing crop injury (Mathiassen *et al.*, 2006; Rakhmatov *et al.*, 2020). Similarly, autonomous intra-row cultivators equipped with RTK-GPS and LiDAR sensors have enhanced weed removal efficiency in crops like maize, carrot, and soybean (Bakker *et al.*, 2011; Khosla *et al.*, 2019). Electrothermal weeding, which employs high-voltage electrical pulses to disrupt weed meristems, is gaining attention as an eco-friendly and residue-free alternative (Diprose *et al.*, 2015; Verma *et al.*, 2022).

Lightweight robotic systems such as *Tertill* and *Naïo Oz* are being customized for polyhouse and horticultural environments, enhancing automation in confined cropping systems (Pedersen *et al.*, 2020). Collaborative research among ICAR, IIT Kharagpur, and TNAU is actively piloting low-cost robotic weeders tailored to smallholder and rainfed Indian conditions, aiming to improve field adaptability and affordability (Jain *et al.*, 2021; Maheshwari *et al.*, 2022).

Despite the clear benefits, several challenges including high initial investment, limited battery endurance, system ruggedness, and weed recognition accuracy continue to constrain large-scale deployment in fragmented Indian farmlands. To facilitate adoption, co-ownership models, FPO based services, and targeted government subsidies are being encouraged. These collaborative and inclusive frameworks are expected to accelerate the transition toward AI-enabled, precision-driven weed management across diverse cropping systems.

6. Biological and Allelopathic Weed Suppression

Biological and allelopathic strategies represent sustainable, eco-friendly alternatives to conventional chemical weed control. These approaches harness natural antagonism, allelochemical interactions, and ecological competition to suppress weed populations, offering long-term resilience and reduced environmental risks. Biological control involves the use of living organisms

such as fungi, bacteria, insects, and nematodes to manage weed species selectively, minimizing harm to non-target flora and fauna. Globally, several fungal pathogens including *Colletotrichum gloeosporioides*, *Alternaria alternata*, and *Sclerotinia sclerotiorum* have been tested for their efficacy against invasive weeds such as *Parthenium hysterophorus*, *Eichhornia crassipes*, and *Cyperus rotundus* (Patel *et al.*, 2019; McFadyen, 2000).

In India, research institutions like ICAR-DWR, IARI, and various SAUs have evaluated bioherbicides and microbial formulations targeting major weeds such as *Parthenium*, *Echinochloa*, and *Ageratum* species (Rana *et al.*, 2018; Kumar *et al.*, 2017; Singh *et al.*, 2020). Among bacterial bioherbicides, strains of *Pseudomonas fluorescens* and *Bacillus subtilis* produceare known to secrete phytotoxic metabolites that inhibit weed seed germination and root elongation (Choudhary *et al.*, 2016; Yaduraju and Seetharama, 2008). Similarly, mycoherbicides formulations based on fungal pathogens have shown promising results in suppressing *Cuscuta* spp., *Ageratum conyzoides*, and *Parthenium hysterophorus* under both controlled and field conditions (Sharma *et al.*, 2018; Mahajan and Chauhan, 2013).

Allelopathy refers to the chemical inhibition of one plant species by another through the release of allelochemicals – biologically active compounds present in root exudates, crop residues or mulches. These natural compounds suppress weed seed germination, which inhibit weed germination and growth. Crops such as sorghum (*Sorghum bicolor*), sunflower (*Helianthus annuus*), black gram (*Vigna mungo*) and certain rice cultivars are known for their strong allelopathic potential (Verma *et al.*, 2020; Bhadoria and Singh, 2019; Chhokar *et al.*, 2012).

In India's rice-wheat systems, the incorporation of rice straw residues has been reported to markedly reduce the emergence of *Echinochloa colona* and *Cyperus rotundus*, offering a sustainable residue-based weed management strategy (Rao *et al.*, 2014; Prasad *et al.*, 2017). Cover crops such as legumes and brassicas not only suppress weeds through competition and allelopathy but also improve soil fertility and microbial health (Mahajan *et al.*, 2017; Yaduraju, 2013).

Recent innovations aim to integrate allelopathic mechanisms with modern technologies to improve efficiency and stability. The combination of allelopathic plant extracts with nanoherbicide formulations has shown enhanced selectivity and reduced chemical loading (Sridhar *et al.*, 2021). Additionally, biochar incorporation with allelopathic crop residues has demonstrated synergistic weed suppression while stimulating soil microbial activity and nutrient recycling (Chatterjee *et al.*, 2019; Pradhan *et al.*, 2021). These hybrid approaches align with the goals of sustainable intensification and low-input agriculture.

Despite their potential, biological and allelopathic approaches face constraints, including variability in field performance, host-pathogen specificity, limited shelf life and regulatory hurdles for bioherbicide approval and commercialization. Environmental factors such as temperature, moisture and soil microbiota also influence their effectiveness.

Nevertheless, these eco-compatible methods hold strong promise as complementary components of integrated weed management (IWM). By reducing reliance on synthetic herbicides, they contribute to agroecological balance, biodiversity conservation, and soil health restoration paving the way toward a sustainable and climate-resilient weed management paradigm.

7. Integrated Weed Management (IWM) Approaches

Integrated Weed Management (IWM) represents a holistic strategy that combines chemical, cultural, mechanical, biological, and precision-based approaches to achieve sustainable, long-term

weed control. The objective of IWM is to maintain weed populations below economic thresholds while minimizing environmental impact and preventing herbicide resistance. Globally, IWM frameworks emphasize crop rotation, cover cropping, mechanical weeding, selective herbicide use, and continuous monitoring for informed decision-making (Oerke, 2006; Heap, 2023).

In India, IWM has been actively promoted across rice-wheat, maize, pulses, cotton, sugarcane, and horticultural systems through coordinated research and extension initiatives (Mahajan and Chauhan, 2013; Chhokar *et al.*, 2012). Cultural methods form the foundation of IWM and include practices such as stale seedbed preparation, delayed sowing, competitive cultivars, high-density planting, intercropping, mulching, and residue retention (Yaduraju, 2013; Verma *et al.*, 2020; Ghosh *et al.*, 2020). These approaches enhance crop competitiveness and suppress weed germination.

Mechanical interventions including rotary hoeing, inter-row cultivation, and mechanical uprooting are often combined with selective herbicide applications to achieve effective and economical weed control (Rao *et al.*, 2014; Sharma *et al.*, 2020). Sequential and combination herbicide programs, integrating pre- and post-emergence applications, have been shown to minimize weed resistance risks and improve yield outcomes (Kaur *et al.*, 2018; Singh *et al.*, 2020).

Sustainability within IWM systems is further strengthened by incorporating bioherbicides, allelopathic crops, organic mulches and cover crops, which help restore soil health and reduce dependency on synthetic chemicals (Prasad *et al.*, 2017; Verma *et al.*, 2020). Recent advancements have integrated drone-assisted weed scouting, variable-rate spraying, and AI-driven decision support systems, optimizing input use and improving precision in field management (Kumar *et al.*, 2022; Ahmad *et al.*, 2021). The benefits of IWM are multifaceted reducing herbicide consumption, preserving biodiversity, improving soil fertility, enhancing economic returns, and mitigating resistance evolution (Mahajan *et al.*, 2017; Das, 2019). However, challenges such as limited farmer awareness, high initial costs for precision technologies, and the need for location-specific recommendations hinder widespread adoption. Government initiatives, including ICAR-DWR programs and participatory extension through Farmer Producer Organizations (FPOs), have significantly improved IWM adoption and adaptation across diverse Indian agroecosystems (ICAR-DWR, 2021; Yaduraju, 2013).

8. Herbicide Resistance Management Strategies

Herbicide resistance has emerged as a major challenge in modern weed management, primarily resulting from the repeated and indiscriminate use of herbicides with similar modes of action. Globally and in India, resistant populations of *Phalaris minor*, *Echinochloa crus-galli*, *Conyza bonariensis*, *Amaranthus spp.*, and *Cyperus rotundus* have been widely reported (Heap, 2023; Bhullar *et al.*, 2017; Singh *et al.*, 2020).

Effective resistance management strategies rely on diversifying weed control methods. This includes rotating herbicide modes of action, using herbicide mixtures, and integrating non-chemical methods such as cultural and mechanical practices (Powles and Yu, 2010; Chhokar *et al.*, 2012). Indian research demonstrates successful management of *Phalaris minor* in wheat through rotation of sulfonylurea, ACCase, and pendimethalin herbicides, effectively delaying resistance buildup (Balyan and Malik, 2017; Kumar *et al.*, 2018). Complementary practices such as crop rotation, residue retention, and competitive cultivars further reduce selection pressure (Mahajan and Chauhan, 2013; Rao *et al.*, 2014).

Recent advancements emphasize early detection and proactive management, employing molecular diagnostics, bioassays, and GIS-based mapping for timely interventions (Heap, 2023; Singh *et al.*, 2020; Raj *et al.*, 2021). Moreover, AI-integrated weed identification systems and targeted herbicide applications are emerging as cutting-edge technologies to reduce chemical load and mitigate resistance evolution (Ahmad *et al.*, 2021; Deshmukh *et al.*, 2022).

In essence, herbicide resistance management must be embedded within an IWM framework, promoting diversification, early surveillance and technology-assisted precision interventions to ensure long-term sustainability of herbicide efficacy and cropping system resilience.

9. Digital Tools, Sensors, and Remote Sensing

The advent of digital technologies has transformed weed monitoring, mapping, and management by providing precise, real-time insights into weed distribution and dynamics. Remote sensing using multispectral, hyperspectral, and thermal sensors enables early detection of weed patches, species discrimination, and biomass estimation with high accuracy (Huang *et al.*, 2016; Thanki *et al.*, 2020). In India, research initiatives utilizing UAV-based imaging for weeds in rice, maize, and sugarcane cropping systems have reported detection accuracies exceeding 80% (Kumar *et al.*, 2022; Desai *et al.*, 2021; Singh *et al.*, 2022).

The integration of IoT-enabled weed sensors with cloud computing platforms facilitates automated field monitoring, variable-rate herbicide applications, and predictive modeling for proactive weed control (Chakraborty *et al.*, 2021; Khot *et al.*, 2021). Farmer-centric smartphone applications such as *Weed Manager*, *AgriApp*, and *Plantix* have enhanced accessibility to weed identification and management recommendations (Yadav *et al.*, 2019; ICAR-DACNET, 2021).

By coupling GIS and GPS technologies, precision weed management enables site-specific herbicide spraying, patch-level treatment, and mapping of herbicide resistance hotspots (Sharma and Yadav, 2020; Patel *et al.*, 2020). Meanwhile, machine learning approaches, including convolutional neural networks (CNNs), support vector machines (SVMs), and deep learning algorithms, are achieving remarkable success in automated weed classification and detection (Ahmad *et al.*, 2021; Hasan *et al.*, 2020; Dhruw *et al.*, 2022).

Digital tools not only support field-level decisions but also aid in long-term documentation of weed population dynamics, offering valuable datasets for research and policy planning. However, challenges persist particularly in terms of high capital investment, limited technical expertise, rural connectivity gaps and farmer training needs (Deshmukh *et al.*, 2022; Raj *et al.*, 2021). Strengthening digital literacy and extension is vital for scaling these technologies across diverse farming systems.

10. Climate-Smart Weed Management under Rainfed and Dryland Systems

Climate variability and increasing water scarcity significantly influence weed ecology, growth patterns and herbicide performance, calling for climate-resilient weed management approaches. In rainfed ecosystems, practices such as drought-tolerant crop selection, soil moisture-conservation, mulching, and residue retention have proven effective in minimizing weed competition and enhancing resource use efficiency (Kumar and Yadav, 2017; Sah *et al.*, 2022).

Field studies in rainfed pulses, sorghum, and groundnut systems indicate that mulching with crop residues can substantially reduce soil moisture loss while suppressing weed emergence

(Verma *et al.*, 2020; Prasad *et al.*, 2017). Adaptation measures also involve adjusting sowing dates, selecting competitive cultivars, and employing precision herbicide applications guided by soil moisture and microclimatic monitoring (Mahajan *et al.*, 2017; Chhokar *et al.*, 2012). Conservation agriculture practices such as zero-tillage, residue retention, and intercropping, have been widely demonstrated to lower weed density and biomass while improving soil structure and microbial diversity (Yaduraju, 2013; Kumar *et al.*, 2021). Emerging climate-smart frameworks integrate decision support systems (DSS), weather forecasting models, and remote sensing data to predict weed emergence and optimize herbicide timing (Rao, 2014; Thanki *et al.*, 2020).

Overall, climate-smart weed management emphasizes adaptation, resilience and resource efficiency, aligning agronomic practices with changing climatic realities to ensure sustainable productivity under rainfed and dryland conditions.

11. Weed Seedbank Management and Soil Health Innovations

Long-term and sustainable weed control fundamentally depends on management of the soil weed seedbank, which acts as the primary source of weed infestation across cropping cycles. Effective strategies include stale seedbed preparation, pre-emergence herbicides, allelopathic cover cropping, and promotion of natural seed predation by soil fauna, birds and insects (Oerke, 2006; Mahajan & Chauhan, 2013).

Experiments in rice, wheat and pulse systems have shown that stale seedbeds, shallow tillage, and flaming techniques significantly reduce weed seed germination and seedbank persistence (Chhokar *et al.*, 2012; Rao *et al.*, 2014). Parallel efforts to improve soil health through organic amendments, biochar addition, and residue recycling enhance microbial competition and biological suppression of weeds (Chatterjee *et al.*, 2019; Pradhan *et al.*, 2021).

Integrating soil health interventions with IWM practices, nanoherbicides, and allelopathic residues provides synergistic benefits reducing weed seed viability, promoting beneficial microbes, and improving nutrient cycling and overall crop productivity (Sridhar *et al.*, 2021). Thus, managing the weed seedbank is not merely a weed control measure but an essential component of ecological intensification and soil system sustainability.

12. Policy, Economics, and Adoption Constraints (India & Global Context)

The large-scale adoption of innovative weed management practices is governed by policy support, economic feasibility, and socio-cultural acceptance. In India, government led initiatives such as FPO-based mechanization programs, custom hiring centers, and subsidy schemes are instrumental in promoting precision, robotic and mechanized weed management (ICAR-DWR, 2021; FICCI, 2020).

Economic analyses suggest that adoption of UAV-assisted spraying, precision applicators and nanoherbicides can reduce input costs by 20–50%, while enhancing yield and resource efficiency (Mahajan *et al.*, 2017; Gupta and Jain, 2019). Despite these advantages, barriers persist such as high initial investment, lack of skilled manpower, limited access of equipment, small landholdings, and stringent regulatory processes for bioherbicides and nanoformulations (Yadav *et al.*, 2019; Das, 2019).

To overcome these challenges, awareness programs, on-farm demonstrations, cooperative models, and policy frameworks are vital for scaling up innovation and bridging the gap between research and adoption (Raj *et al.*, 2021; Sharma *et al.*, 2020). Globally, policy emphasis is shifting

toward regulatory harmonization and environmental safety evaluation of emerging technologies, including nanoherbicides, autonomous robotic weeders, and gene-edited biocontrol tools (Heap, 2023; Kah *et al.*, 2018).

Ultimately, sustained success in weed management requires a multi-dimensional policy approach that integrates science, and governance to foster innovation, ensure farmer inclusivity and maintain environmental integrity.

13. Future Prospects and Research Gaps

Future research in weed management emphasizes sustainability, climate resilience, and technology integration. Key areas include:

Development of multi-functional nanoherbicides with target-specific delivery and minimal ecological impact (Kumar *et al.*, 2021; Sridhar *et al.*, 2021).

AI-enabled, autonomous robotic systems for selective mechanical and chemical weeding in smallholder fields (Patel *et al.*, 2021; Maheshwari *et al.*, 2022).

Integration of remote sensing, IoT, and decision support systems for predictive weed management (Ahmad *et al.*, 2021; Chakraborty *et al.*, 2021).

Expansion of biological control agents and allelopathic crops tailored to local agroecosystems (Verma *et al.*, 2020; Rana *et al.*, 2018).

Addressing herbicide resistance through molecular tools, crop rotations, and integrated strategies (Heap, 2023; Singh *et al.*, 2020).

Indian studies highlight the need for large-scale field validation, farmer-centric adoption models, regulatory clarity for nano- and bio-based products, and cost-effective deployment (ICAR-DWR, 2021; FICCI, 2020). Future directions should also explore synergistic approaches combining precision, biological, chemical, and cultural methods for resilient agroecosystems.

14. Conclusion

Weed management in modern agriculture is evolving from conventional, herbicide-dependent practices to integrated, precision-driven, and environmentally sustainable approaches. Emerging technologies such as nanoherbicides, robotics, AI, UAVs, and allelopathic strategies are redefining the landscape of weed control by enhancing selectivity, reducing chemical load, and improving field conditions. Indian research has significantly contributed to adaptation and validation of these technologies in diverse cropping systems, including rice, wheat, pulses, cotton, and groundnut.

Integrated Weed Management (IWM) a holistic framework that synergizes cultural, biological, mechanical, and chemical methods to ensure long-term sustainability. However, the success of IWM and emerging innovations depends largely on policy support, farmer capacity building, and equitable access to technologies. Looking ahead, future research should prioritize the development of climate-resilient, cost-effective, and environmentally safe weed control strategies. Strengthening interdisciplinary collaborations, digital decision-support tools and participatory extension models will be vital to enhancing productivity, ensuring food security and safeguarding agroecosystem health in an era of changing climate and resource constraints.

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Chapter-5

Climate-Resilient Agricultural Practices for Enhancing Productivity, Profitability, and Sustainability in Smallholder Cropping Systems

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ABSTRACT

Climate change poses a serious threat to agricultural sustainability, particularly in smallholder farming systems characterized by limited resources and high climate vulnerability. Increasing temperature, erratic rainfall, frequent extreme weather events, and declining natural resource quality are adversely affecting crop productivity, profitability, and food security. Climate-resilient agriculture (CRA) integrates adaptive and mitigation strategies to enhance system resilience while ensuring efficient resource utilization and environmental sustainability. The Climate Resilient Agriculture Programme implemented in Bihar promotes a participatory approach through Krishi Vigyan Kendras to demonstrate climate-smart technologies at village level. Key interventions include precision seed sowing, direct seeded rice, zero tillage, conservation agriculture practices, site-specific nutrient management, nano and biofertilizers, laser land levelling, efficient irrigation methods such as alternate wetting and drying, and water harvesting techniques. Adoption of smart tools like Leaf Colour Chart, SPAD meter, Nutrient Expert decision support system, and drone-based crop management improved input-use efficiency and reduced production costs. Resource conservation practices enhanced soil health, water productivity, and reduced greenhouse gas emissions. Climate-resilient crop varieties, diversified cropping systems, and crop intensification significantly improved farm productivity and profitability compared to conventional practices. The programme demonstrated that integrated climate-smart interventions not only strengthen farmers' adaptive capacity but also promote sustainable intensification and long-term agricultural resilience. These approaches provide a scalable pathway for transforming smallholder agriculture under changing climatic conditions while safeguarding natural resources and ensuring livelihood security.

Keywords: Climate-resilient agriculture; Smallholder farming systems; Conservation agriculture; Resource-use efficiency; Precision nutrient management; Sustainable crop productivity.

Introduction

Climate change is not a theoretical discussion anymore but one that most farmers have experiences to share. The uncertainty brought in by this development is threatening the agriculture system, making farmers ever so vulnerable; and posing a challenge to policy makers. World's population is expecting a one third increase from now to 2050 and most of these additional two billion people will live in developing countries. At the same time, more people will be living in cities. If current income and consumption growth rate continue, food and agriculture organization (FAO) estimated that agriculture production will have to increase by 60 per cent by 2050 to satisfy the expected demand for food and feed (Conforti, 2011). This is more challenging for smallholder farmers who constitute more than 50% population of our country as well as Bihar. These resource poor farmers have to bear the brunt of such events that eventually falls on the shoulders of the government. The sheer scale of involvement of the poor in agriculture calls for an effort to meet the challenge of climate change head-on through resilience building measures that

work through a system of adaptive and mitigation strategies. Climate change affects agriculture and food production in complex ways; directly affecting food production through increase in frequency of extreme weather events that are inhospitable for normal development of crops, and indirectly by affecting their growth and distribution. Other possible impact of climate change on agriculture are Changes in soil microflora, low production, attack of disease and insect pest more, complex weeds, emergence of new weeds etc. A number of studies have shown conclusively that climate change has become a major threat to food availability by adversely affecting agricultural productivity and increasing inter-annual variations in yields (Jat *et al.*, 2016; IPCC, 2015). New diseases of major cereals like wheat, rice and maize are other potential threats (Joshi *et al.*, 2011; Chowdhury *et al.*, 2017). Yield of major cereals like wheat and rice is predicted to decline from 10 to 40% by 2050. With each degree Celsius rise in temperature, the demand for irrigation water is also expected to rise by at least 10% (UN-Water, 2013). So, agriculture system must therefore transform itself if it to feed a burgeoning global population and provide the basis for economic growth and poverty reduction. Climate change will continue to make this task more difficult due to adverse impacts on agriculture, requiring new technologies, which seems very promising to move to the next level of farm productivity and profitability. To achieve for security and agriculture and development goals. Adaptation to climate change and lower emission of greenhouse gases (GHGs) are necessity of changing scenario. However, this transformation must be accomplishing without depletion of the natural resources base. Transformation of Indian agriculture needs to be more productive through efficient use of inputs, sustainability in production, and needs more resilience towards risks, shocks and long term climate variability we need some sustainable and climate resilient agriculture technologies.

Climate resilient agriculture is the incorporation of adoption, mitigation and other practices in agriculture with increase the capacity of the system to respond to various climate related disturbance by resisting damage and recovering quickly or in shorts can say that the it is the ability of agriculture system to bounce back. Climate resilient agriculture will essentially involve judicious and improved management of natural resource, viz. land, water, soil, and genetic resources, through adoption of best bet practices. Climate resilient agriculture have two main approaches to bring resilience to the climate change /variability impact in agriculture. (i) Adoption: It is adjustment of ecological, social or economic system in response to actual or expected stimuli and their effects or impacts. This term refers to change in process, practices and structure to moderate potential damage or to benefit from opportunity associated with climate change (IPCC 2001) and (ii) Mitigation: It refers to efforts to reduce or prevent emission of greenhouse gases. Climate change mitigation generally involves reductions in human (anthropogenic) emissions of greenhouse gases. Mitigation can be achieved through (i) reducing greenhouse gases emissions (ii) enhancing removals and (iii) avoiding greenhouse gases emission.

Keeping all these points of view in mind Government of Bihar have launched a project namely Climate resilient agriculture (CRA) programme in November, 2019. This project is a flagship programme of Govt. of Bihar aimed at promoting climate resilient technologies in Bihar. Under this project Krishi Vigyan Kendra of each district (38) are directed to select five villages and implement all CRA interventions on farmer's field in participatory approach. This project proposes sustainable and climate resilient agriculture practices such as: deployment of climate resilient crop varieties, cropping system/crop cycle/diversification of crop as per the local climatic conditions, conservation agriculture (CA) and resource conservation technologies based management practices like zero tillage, direct seeded rice, raise bed sowing of crops, residue management, smart nutrient

management practices like nutrient expert (NE), green-seeker based site-specific nutrient management; precision water management i.e. laser leveling, micro-irrigation, alternate wetting and drying irrigation system and deficit irrigation, and capacity building of farmers. Three year after the project, we found that these practices are not only playing important role in conserving natural resources and building farmers' capability but helping in changing the mind-set as well. Here, we will discuss about effect of these technologies in adopted villages and farmers and its benefits which is not only improving productivity, but just as importantly, safeguarding the environment.

Innovative practices for higher resources use efficiency

Precision in seed sowing and sowing time

Intensive farming of cereal crops in order to produce more food often forces the late sowing of wheat due to late harvesting of rice crop under the rice based cropping systems Bihar. Late-sown wheat is usually exposed to high temperature called as "heat stress" during flowering to grain-filling stages consequently reduces green area duration that affects the production of photosynthates and thereby results in shriveled and smaller grains resulting loss in yield of wheat. To counter this problem under CRA Programme sites direct seeded rice (DSR) and zero tillage (ZT) sowing technologies are being promoted. Due to sowing of rice by direct seeded (DSR) method reduces 7-10 days in total crop duration consequently farmers are able to complete sowing of wheat by zero tillage technique in November month sad protecting his crops by the adverse effect of heat stress. Another major problem of farmers is low crop establishment in conventional tillage system which may be due to deep placement of seed due to deep ploughing and high seed rate. Seed sowing at right place and right quantity is very tedious in fields. Effective seeding requires control over two variable: planting seeds at the correct depth, and spacing plants at the appropriate distance apart to allow for optimal growth. Precision seeding equipment have been provided to the farmers under CRA programme to maximize these variables every time. Seed have the best chance to germinate and grow and the overall crop will have a greater harvest. In future, existing precision seeder will come together with autonomous tractor and ICT-enabled system that feed information back to the farmers.

Adoption of Precision nutrient management

The approach of site specific nutrient management (SSNM), a systematic approach to provide sound knowledge on "feeding crops" with nutrients as and when needed to make synergy between nutrient demand and supply under different field crops production system, is the solution to manage especial variability of nutrient and better nutrient use efficiency.

3.1 Promotion of Smart/Nano fertilizers:

As we know very well agricultural decreasing day by day due to water erosion and unconscious irrigation and fertilizer. On the other hand, it is necessary to increase agriculture production in order to full fill the food demand of increasing population. To achieve the national goal, we need to find out efficient use of all agricultural resources especially fertilizer. In this order, some new fertilizer is invented by scientists called as smart fertilizer. These are the new type of fertilizers which are formulated based on micro-organisms and nano-materials. These fertilizers have developed with an emphasis on controlled-released and/or carrier/delivery system will synchronies nutrient availability with the plant demands thereby reducing nutrient losses resulting increased nutrient use efficiency and reduced amount of fertilizers application without negative effect on yield, soil health, and environment. Nano fertilizers are important in agriculture to

increase crop yield and nutrient use efficiency and to excessive use of chemical fertilizers and reduction of dose was up to 90 per cent. Due to less investment farmers' income can be raised by 15-20 per cent. Bio stimulants have direct hormonal effect on plants that positively affect root growth, root efficiency, nutrient uptake and characters that are beneficial in shifting from chemical to organic fertilization regime. Bio fertilizer on the other hand have an indirect effect on nutrient availability without itself supplying nutrients. They are live microbial formulations that aid in nutrient availability and uptake. So, under CRA Programme farmers are benefiting with these scientific innovations and helping in minimizing the climate change.

Use of Leaf colour chart (LCC):

Leaf colour is a fairly good indicator of the nitrogen status of plant. To easy identify the nitrogen status a simple and eco-friendly tool called as leaf colour chart (LCC) is provided to the farmers of CRA programme sites of Bihar. LCC occurs with 4 coloured called as four panel LCC and six coloured called six panel. Nitrogen optimized by matching its supply to the crop demand as observed through change in the leaf chlorophyll content of leaf colour. It is an ideal tool to optimize nitrogen use in crops like rice at high yield levels irrespective of the source of nitrogen applied *viz.* organic matter, biological fixed nitrogen or chemical fertilizers. Thus, LCC is helping to the farmers in saving the fertilizer especially urea because leaf colour intensity relates to leaf nitrogen status of rice plant. The monitoring of leaf colour helps in the determination of right time of nitrogen application. During the matching of leaf with LCC, farmers select the top most fully expanded and healthy leaf placed in the middle part on top of the LCC colour strips for comparison and take the readings at the same time of the day (8-10 AM). Do not exposed the LCC to direct sun light during readings and every time same person must take the readings. Use of LCC is simple, easy and cheap under all situations. The studies indicated that nitrogen can be saved from 10-15 per cent using the LCC. According to the farmer's statement number of splits of urea application increased but they saved about 20-25 kg/ha urea without any yield penalty in rice crop.

Use of Soil-Plant Analysis Development (SPAD) Value:

SPAD is simple, quick and portable diagnostic tool of monitoring leaf nitrogen status and improving the timing of nitrogen topdressing in rice. SPAD is a low-cost chlorophyll meter and affordable by farmers. It is possible to monitor nitrogen leaf nitrogen status using SPAD thresholds and guide fertilizer nitrogen timing on irrigated rice. Measuring SPAD readings of the uppermost fully expanded leaf to reveal plant nitrogen status has been accepted as a common practice, although it was found that leaves in lower positions could be more suitable to serve as testing sample for nitrogen status diagnosis as the lower leaves in separating nitrogen level, in case the total nitrogen was used as indicator. SPAD meter-based N management appeared to be more efficient and smarter nitrogen management.

Use of Nutrient Expert (NE):

NE is the recently developed precision nutrient management technology guided by decision support system software for improving crop yields, environmental-quality and over-all agricultural sustainability. International Plant Nutrition Institute (IPNI) in collaboration in collaboration with CIMMYT has developed in NE, a nutrient decision support system, based on site-specific nutrient management principles. NE provides fertilizer recommendations by considering yield responses and targeted agronomic efficiencies along with contribution of nutrient from indigenous sources. This system follows systematic approach of capturing site specific information that is important for developing a location specific recommendation. NE has been successfully in major maize growing agro-ecologies of country and also increased yield and farm-profitability over existing fertilizer recommendations.



Use of Leaf Colour Chart in direct seeded rice

Use of green seeker in wheat crop

Innovative Practice for efficient water management

Water is the most critical natural resources for human survival and sustainable development as its availability is decreasing day by day. The total projected demand of water for irrigation sector more than the present level so, there will be three major challenges i.e. (i) “more crop per drop of water” by efficient and productive use of available water resources in irrigated areas, (ii) increased productivity of sub-productive challenged ecosystem, i.e., rainfed and water logged areas, and (iii) making waste of gray water (waste water) for agriculture production. It is possible only through efficient irrigation management when and how required by the crop.

Adoption of Water harvesting and Field Bunding:

Rainfall in the state is under good condition but its efficient use, management and conservation is not in proper way. So, to control, conservation and management of water in paddy field under this project we adopted in-situ water harvesting and saving technology or renovate existing water saving technology i.e. water harvesting and field bunding technique around field especially in paddy field. Rainwater harvesting, and efficient water use are inevitable options to sustain rainfed agriculture in future. In CRA Programme sites to solve the irrigation water scarcity in upland as well as low land area in-situ rain water collection is being promoted. To collect the rain water construct 50 cm wide and 30 cm height of bunds around the field (Pic. 4.1a). To stop/minimize water loss through seepage bunds are prepared well compacted and properly sealed with no cracks, holes etc. The collection of for future lifesaving irrigation in corner of the field a small pond has prepared which was economically assisted by government under CRA Programme. With the help of this technique farmers are saving lots of money by saving number of irrigation, irrigation water and fuel burning required for irrigation (pic 4.1b).

Pic: Water harvesting and field bunding in CRA Sites on farmer's field



Pic 4.1a. Water harvesting in corner in field



Pic 4.1b. Field Bunding Around in Rice field

Intermittent wetting and drying (AWD) irrigation system:

Under limited water availability condition, irrigation strategies based on meeting the partial crop water requirements should be adopted for more effective and rational use of water. The adoption of alternate wetting and drying (AWD) irrigation system are becoming an accepted strategy for water conservation and to reduce the amount of water used for crop production with increased water use efficiency and water productivity. AWD irrigation system is an innovative irrigation system in which on project sites a PVC Pipes or Pani pipe (4a & 4b) are being established on farmer's rice field that allows the lowland rice growers to save water by intermittent irrigation by alternatively flooding and drying the field at certain days' interval which may vary from 1-10 or more days depending on the soil type. AWD irrigation system requires 23–33% less water as compared to continuous flood irrigation thereby improving the water use efficiency (WUE), it reduces the anthropogenic GHGs emission by 45–90% while maintaining the grain yield. This system has shown to improve the grain quality by reducing total Arsenic (by 50%) and has been effective in decreasing insect pests (92%) and disease infestation. AWD irrigation system is an efficient strategy for saving irrigation water as well as enhancing rice yields in the future. AWD has various advantages over continuous flooding as it enhances the rice production as well as environmental and human health, in addition to the fundamental advantages. Climate, soil type, pests, rotation type, and irrigation availability will all have to be considered while using AWD strategy for reaping its maximum benefits.



Pic 4a. Establishment of Pani Pipe for AWD Irrigation system in Rice field



Pic 4b. Established Pani Pipe in Rice field

Popularization of Automation Irrigation System:

Pressurized irrigation system like sprinkler, drip and subsurface irrigation are already prevalent irrigation methods that allow farmers to control when and how much water their crops receive. These irrigation methods are being promote and popularize among the farmers of on project sites and using irrigation water efficiently with more water use efficiency. By pairing these irrigation systems with increasingly sophisticated internet of things (IoT)-enabled sensors to continuously monitor moisture levels and plant health, farmers will be able to intervene only when necessary, otherwise allowing the system to separate autonomously. While pressurised systems are not exactly robotic, they could operate completely autonomously in a smart farm context, relying on data from sensors deployed around the fields to perform irrigation as needed.



Irrigation of Crop by Sprinkler irrigation system

Innovative Practices for weed and Pest Management:

New generation herbicides:

An Appropriate technology towards controlling increasingly more difficult perennial weeds will be important paradigm in future weed research. Recently some post emergence new generation herbicides are available in the market with the assurance of selective effective control of weeds in field crops. These herbicides are required in very low doses and these are very easy in handling and transportation. The post emergence herbicides like imazethapyr, fenoxaprop-p-ethyl, cyhalofop butyl, quizalofop ethyl and clodinafop-propargyl in pulse and oilseeds; tembotrion in maize, Pyrazosulfuron ethyl, chlorimuron ethyl + metsulfuron methyl in rice, clodinafop + metsulfuron methyl in wheat are found very affective to control both broad leaved and grassy weeds. Under this project, the climate smart weed management practices like summer ploughing, soil solarization, stale seed bed, brown manuring etc. with aim at better control of weeds while environment friendly are being promoted.

Herbicide Resistant Crops (HRCs):

Herbicide resistance crops are genetically modified (GM) crops engineered to resist specific broad spectrum herbicides, which kill the surrounding weeds, but leave the cultivated crop intact. These HRCs comprised 83 per cent of the total crop area, equating to just fewer than eight percent of the arable land worldwide. Most herbicide resistance GM crops i.e., cotton, soybean and maize) have been engineered for glyphosate tolerance but now GM crops are evolved resistance against Glyphosate, Glufosinate, 2,4 D, Sulfonylurea, oxynil, etc. If government of India allows growing herbicide resistant GM crops, then weed management will be more efficient.

Use of drones:

Under this project drones have been used on farmers' field for application of fertilizer, spray of pesticides, access the crop damage etc. offering the chance to automate yet another labour intensive work. Based on the size and configuration of the drone, and agriculture drone can cost between Rs.1 lakh to 10 lakhs. To promote the use of drones in Bihar, government providing subsidies to various agricultural organizations upto 80-90%. The main advantages of drones are saving of farmer's time and money, because with the use of drones pesticides, and fertilizer can be easily sprayed over a large area in a very short time. Under this project used drone has a 10-liter tank for filling pesticides which sprayed 1-acre field in 10-15 minutes which if sprayed by hand will take a whole day. When tank is empty the drone came back automatically for refill the tank from where it was first filled. After filling the tank drone started spraying from the same place where the tank was empty and it stopped spraying. So, using a combination of GPS, laser measurement and ultrasonic positioning; a crop spraying drones can adopt to altitude and location easily, adjusting for variables such as wind speed, topography, and geography. The enables the drone to perform crop spraying herbicide, fertilizers and pesticides more efficiently, and with greater accuracy and less waste.



Use of Drone for application of Fungicides in rice field

Innovative Resource Conservation Practice

Laser land levelling (LLL) of field:

Levelling of land/field done with the help of laser/sensors guided system to get perfectly leveled field, so called laser land levelling which is another resource conservation technology. In India, for the first time LLL was introduced in western Uttar Pradesh in 2001. In Bihar, generally farmers leveled their fields by using locally available scraper resulting fields have 5-15 cm uneven and undulation condition consequently water stagnation, fertilizer application and germination of field crops found uneven. But under CRA Programme now farmers of these areas are well aware about laser land leveler provided by government and using to leveled their field. Farmers are experienced that there is yield advantage in zero tillage sown crops, direct seeded rice and transplanted rice and having of 20-25 per cent of irrigation water apart from several other benefits like better crop establishment, nutrient use efficiency, uniform irrigation etc. have been reported with laser land leveling. Farmers also stated that as a consequence of LLL, it has increased water application efficiency by about half when they compared with leveling by scraper, improved weed control efficiency and nutrient use efficiency.



Laser land leveling at CRA site on farmer's field

Sowing of crop on permanent raised bed:

Sowing of crop like wheat, maize, pigeon pea etc. in row geometry on newly prepared or already made ridges or beds. Ridges or beds are prepared by using multi crop raised bed planter and beds get old in next season again reshape it and sow the crop. Irrigation done with the furrow irrigation system which helps in saving about 18- 50% irrigation water (Hobbs and Gupta, 2003; Jat *et al.*, 2005). Same experience shared by the farmers of the site of this project. According to him the in raised bed sowing technique two extra irrigation are required by crop but total quantity of irrigation water and timing is reduced by half and also stated that furrow act as drainage channel in case of heavy rains and hence save crops from excess moisture if stayed for longer period. One more benefit is that due to presence of previous crops' residue in the furrow soil became soft, light and friable consequently population of earthworm increased very fast and crop shows healthier. This provides excellent opportunity for intercultural operations and crop diversification.



Raised bed Sowing of wheat



Raised bed sown 55 days old wheat crop

Adoption of Direct Seeded Rice (DSR)

Direct seeded rice (DSR) is a sustainable and climate resilient approach of rice production. In traditional rice cultivation practice about 40% of the world's irrigation water is applied for paddy cultivation. In changing climate production of rice with to less irrigation water use, reduced emission of GHGs, shortage of labour, and decreasing arable land is very challenging. So, in this scenario DSR is seen to be one of the most efficient, sustainable and economically viable rice production system so, direct seeding is another complement to conservation agriculture. DSR avoids water required for land preparation/puddling and reduces overall water demand compared to puddled transplanted rice. It is labour, fuel, time and water saving technology and gives similar yield to transplanted rice, if weeds are controlled with judicious use of herbicides on time. By using DSR technique, improve the soil health, and fertilizer and water use efficiency which saves irrigation water. Therefore, DSR is technically and economically a feasible alternative to PTR. CRA Programme helping in growing one more crop i.e. summer mung bean (*Vigna radiate*) can be adopted without delay is sowing of rice crop which gives 8-10 q/ha and adds 40-60 kg N/ha in soil, reducing requirement of N of subsequent crop.

Major advantages of DSR as compare to transplanted rice explained by farmers of CRA Programme sites;

Major advantage is exclusion labour intensive works like seedling uprooting and its transplanting resulting reduced the labour, drudgery, cultivation time, energy and cost of cultivation thus increase total income.

Saving of irrigation water by 15-35% especially during puddling and transplanting operations under efficient water management practices.

If all management practices are adopted on time and optimal condition no significant grain yield reduction is reported by farmers.

Crop matures about 7-10 days than the PTR, so next crop of wheat can sow on time.



Direct seeded rice (DSR)



Direct seeded rice (DSR) in project sites

Conservation tillage (CT):

Conservation tillage (CT) means any tillage and planting system that leaves sufficient crop residue to cover the soil surface at least 30 per cent or more or the soil surface with crop residue, after planting to reduce erosion of soil by water. These CT practices range from zero tillage, reduces tillage, strip tillage, mulch tillage, ridge tillage and use of happy seeder. CT farming is a way of

growing crops without disturbing the soil through using zero tillage machine. It increases the amount of water that infiltrate into the soil and increases organic matter, retention and cycling of nutrient in the soil. Conservation tillage improves soil properties, making it more resilient. It helps in timely planting, reduce cost, improve soil health, increase profit, help in adapting to terminal heat stress and reduced environmental foot prints.



Use of Happy seeder for Zero tillage sowing of wheat in Paddy harvested field

Innovation Practices for higher productivity and profitability

Use of climate resilient crops and varieties: Identification of crops and varieties that fits well into changed climatic condition is common denominator for sustainable crop production in all land use and climatic conditions. An ideal variety must be tolerant/resistance to biotic and abiotic stresses, high yielding, ability to withstand against adverse weather conditions and fits well to farming situations. Sowing right variety of right crops at right time under right land and weathers conditions makes as significant difference towards attaining higher yield. Some short duration varieties have also been released to escape the vagaries of weather conditions. In CRA project government providing only that crops and varieties to the farmers which are resilient and suitable for Bihar. The choice of crops for an eco-system could further be narrowed down by matching crop requirements with prevailing location specific climatic and soil information. During the selection of any crop depends several factors like soil depth, texture, soil water holding capacity, heat, cold, drought, flood and local climatic condition etc. are of great use for micro and macro level crop planning. So, under CRA Programme pulses, oilseeds and millets with zero tillage technology is being provide to the farmers with respect to water requirement and for delayed kharif sowing. For cultivation of conserved soil moisture during rabi season, chickpea and lentil sowing with zero tillage technology are being provided to the farmers.

Table 1. Name of resilient crops and varieties adopting under CRA programme

S.N.	Crop/Variety	Characteristics
1.	Rice	
a.	Sabour Deep, and Turanta	Short duration varieties 110 days ¹ , and 75-80 days ²
b.	Sabour Sampann	Able to grow in both water scare condition and water flooding conditions
c.	Samba Mahsuri	Resistant to bacterial leaf blight disease
d.	Sahabhazi Dhan, Shusk Samrat, Sabour harshit	Drought tolerance
e.	Sabour Ardhjal	For upland and low rainfall area
2.	Wheat	
a.	Sabour Nirjal	Required very low irrigation (1-2)
b.	Sabour Shrestha	Short duration (105-115 days) and late sown variety
c.	HD 2967	Rust Resistance

d. HD 2987	Drought tolerant
e. Raj 3765	High temperature stress tolerant
3. Millets (Pearl millet, finger millet, foxtail millet etc.)	In water scarcity areas
4. Sorghum	In water scarcity areas
5. Barley	In water scarcity areas
6. Pulse crops (Chick pea, Lentil, Summer green gram etc.)	In water scarcity areas

Adoption of climate resilient cropping systems:

Under changing climate scenario, many conventional practices and cropping systems are becoming redundant and ineffective and may no longer be relevant, and thus there is urgent need of revalidation and modification in accordance to changing climate and soil-site conditions. This necessitates need of technologies responding to climate change effects and giving more resilience against different bad effects on crop production. Growing of early maturing, photo insensitive, high tillering crops' varieties, tolerant to biotic and abiotic stresses, mulching with crop residue for soil moisture conservation etc. can be implement for best cropping system mode. Under this CRA Programme farmers different cropping systems are being adopted which are suitable for Bihar viz. Rice-Wheat-Mung, Rice-Lentil-Mung bean, Rice- Chick pea- Mung bean, Rice- Mustard- Mung bean, Pearl millet- Wheat- Mung bean, Soybean-Wheat- Mung bean, Rice- Winter maize, Maize-Wheat-Mung bean and Potato + Maize intercropping etc. with zero tillage and raised bed sowing of crops and saving lots of inputs. The maximum cropping system productivity was recorded in Rice- Winter maize (129 q/ha), Maize -Wheat-Mung (106 q/ha) and Rice-Wheat-Mung (102 q/ha) of have increased significantly as compare to conventionally sown Rice-wheat cropping system (78 q/ha) (fig.1). According to highest cropping system profitability, Rice- Winter maize (Rs. 1,67,005/ha), Rice- Mustard- Mung bean (Rs. 1,62,785/ha), Rive-Wheat- Mung bean (Rs. 1,58,318/ha) while in conventionally grown Rice-Wheat cropping gained (Rs. 96,219/ha) (fig.2). So, here we can see with the adoption of proper cropping system according to local condition farmers can be benefited even in changing climate.

Fig. 1. Average Productivity of different cropping System of CRA Sites

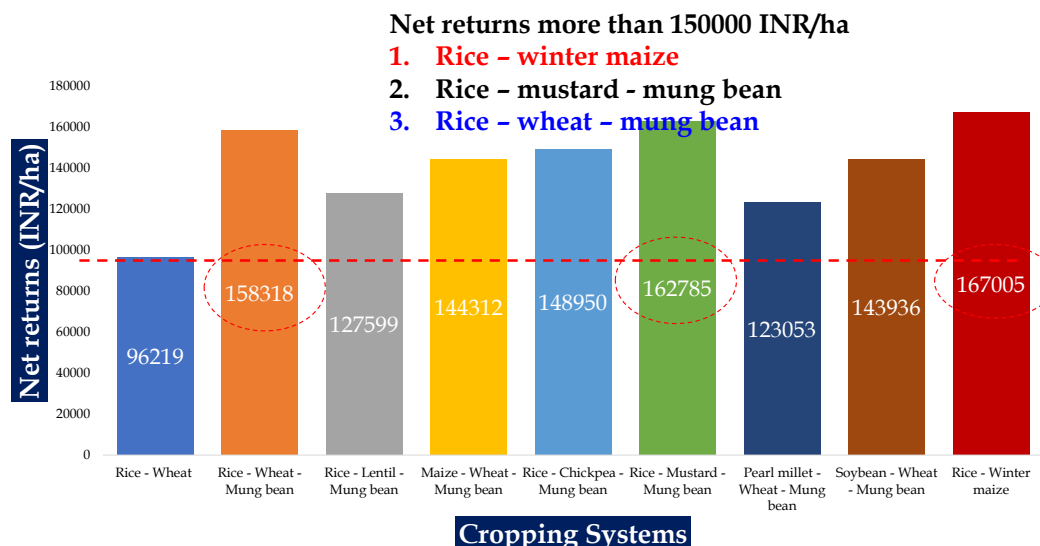
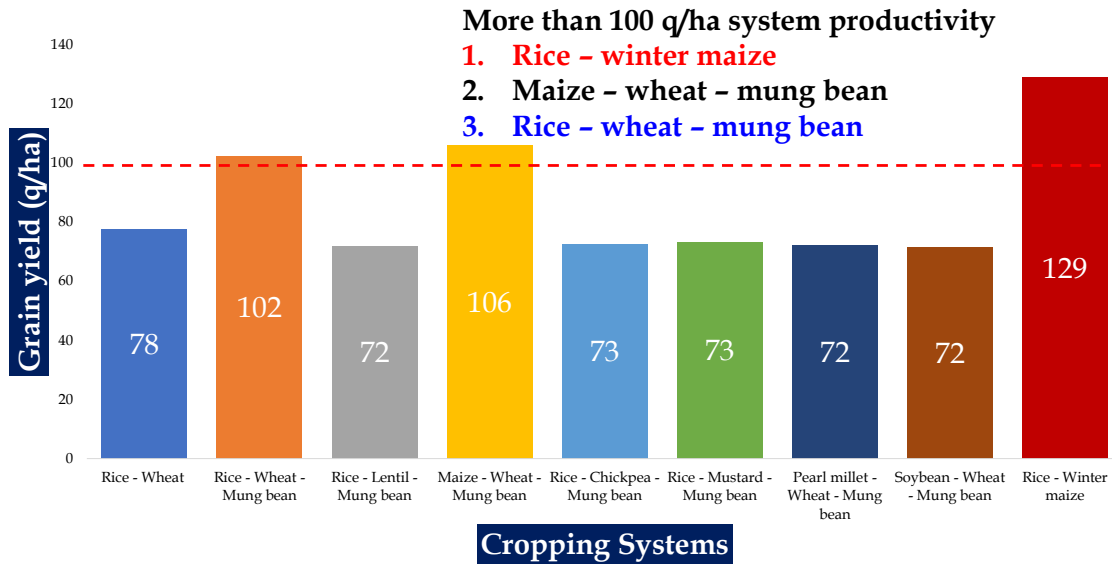


Fig.2 Average Profitability of different Cropping system of CRA Sites



Crop diversification/Intensification

Crop diversification and intensification/intercropping with high value crops have potential to help the thousand producing basic staples and surplus for modest incomes and it is the most important agriculture activity providing employment and food security to millions of people in the country. Crop diversification can be practiced in two ways i.e., temporal/horizontal/crop rotational diversification and spatial/vertical diversification. The component crops which are less productive or need more inputs is substituted with more remunerative, less inputs requiring and which sustain the soil fertility. The intercropping of Potato+ Maize intercropping is introduced through this project and farmers are taking benefits of both the crops with same inputs like field preparation expenditures, irrigation water, and fertilizer application. Rice-wheat cropping system is most dominating cropping system and nearly contributes 42 per cent to the total food grain production. The growth in crop productivity of component crop is either stagnating (wheat) or declining (rice) despite the use of higher yielding cultivars. Thus, substitution of rice which requires more water with maize or cash crops like sugarcane and cotton will not only reduce water requirement but also enhance the system productivity which leads to increase in farmers' income.



Intercropping of Potato + Maize crop at Project sites

Conservation agriculture (CA):

CA is a management system that maintains a soil cover through surface retention of crop residue with zero or minimum soil disturbance. It is important for optimizing crop yield economic and environmental benefits.

The CA have three are 3 basic principles which is interlinked with each other. These principles are; (i) Minimum Soil disturbance (ii) soil cover (iii) Crop rotation/diversification)

Minimum soil disturbance: by adopting zero or minimum tillage technology and machines and seed sowing must be practiced in the line made by zero tillage machine. For sowing of seed the disturbed area must be less than 15 cm wide or 25% of the cropped area.

Maximum soil covers by leaving and managing the crop residue on the soil surface. The purpose behind the soil cover to protect the soil moisture, erosion, enhance organic matter, and to improve physical, chemical and biological properties of soil.

Crop rotation/diversification must involve two to three different crop having different habitation. The main objective is to employ economically viable, diversified crop rotation to help moderate/mitigate possible weed, disease and pest problems. The main advantages of CA are reduction in cost of cultivation, reduced incidence of weeds, saving in water and nutrients, increased yield, environmental benefits, crop diversification opportunities, improvement in resource use efficiency, etc. By the following all these principles and conditions CRA programme providing all machineries and technologies to the farmers of project site and they are adopting technologies making soil and environment healthy and saving lots of inputs

Crop Residue management:

In Bihar, quantity of crop residue burning is very less but, in some area due to lack labour farmers harvest their crop by the use of combine harvester which left residue behind which would be needed to remove for sowing of next crop. So, they chose burning option as the cheapest and easiest way of removing large amount of residue. The burning of agricultural field residue, such as stalk and stubbles after during the harvesting of rice and wheat crop in open field which have an adverse impact on the soil fertility and produce several harmful greenhouse gases like Carbon dioxide (CO₂) Carbon monoxide (CO), Methane (CH₄), and aerosols in the environment and create the pollution. Actually, crop residue is not a waste but rather a useful natural resource which can be use as source of nutrient in field by the way retention, incorporation, composting, and subsequent application after appropriate decomposition. Besides, some other alternative crop residue management options that are being adopted for climate resilient agriculture under this project. These options are retention and mulching, bail making for animal feed by using bailer machine, bio char production, mushroom production. In this project 200-250 tonns crop residue of rice is being sell every season to the COMFED for animal feed by making bail and about 150-180 tonns of Rs. 1,60,872.00, rice crop residue is being used for the production of bio char which produced about 53.6 tonns bio char which are used in field application to increase sustainable soil health by enhancing soil organic carbon and biological activity. By the use crop residue about 196.03 q mushroom of Rs. 20,510,00.0 monetary value have produced and training on mushroom production have provided in CRA selected villages.



Bio char Production Unit



Use of Bailer in Paddy straw for bail to make Bail

7.6 Preparation of Soil Fertility Map

Soil fertility is the ability of soil to sustain plant growth and optimize crop yield. It is very important for agricultural productivity and therefore for food security which can be maintained or improved by management practices. An integrated soil fertility management aims at maximizing the efficiency of agronomic use of nutrients and improving crop productivity and provision of food. But now a days fertility management have great challenges because of various intrinsic and extrinsic factors. The soil fertility evaluation is the most basic decision making tool in order to efficient plan for a particular land use system. For easy understandable, informative and precision management of soil of project sites a soil fertility map has been prepared. It is a data-driven farming by collecting, analyzing and correlating information about the soil nutrient status, soil nutrient supplying capacity, fertilizer rate and potential yield in the respective location, will make farmers more informed decisions. An all this information has presented on map for the purpose of visual display and analyzing spatial distribution of the available data. So, farmers of the villages of project sites can easy know about their soil status and take precision soil management steps.

Benefits of soil fertility map Judicious use of fertilizers

Based on soil test-based recommendations, farmers may be advised to use balance use of fertilizers thus can save money

Farmers may start using the Site specific nutrient recommendations in CRA villages

This display may be helpful in diverting the fertilizer demand based on its regional referencing.

Help in choosing suitable cropping pattern and agronomic procedure.

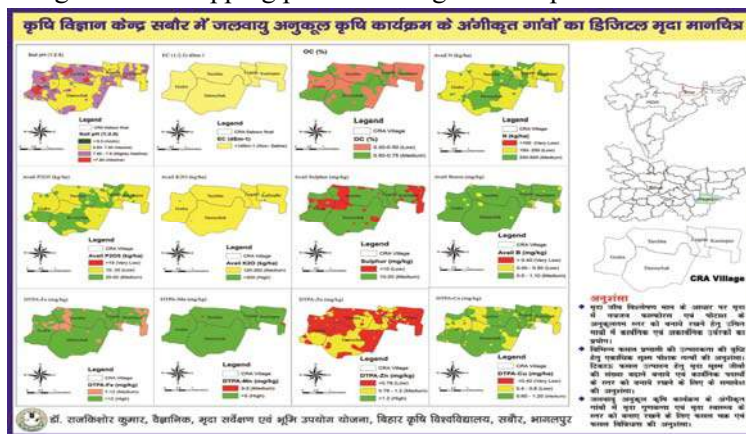


Fig. Soil fertility map

Conclusion

Climate change is now a reality and has already shown its impact on crop productivity in all the agro-ecosystem, and impact may more serious if timely corrective measures are not adopted. Locally as well globally agricultural production is stagnating even in resources rich regions and crop requiring ever increasing inputs to maintain good production. So, a well-planned complementary cropping systems and intercropping have great potential to reduce the risk and uncertainties in production through effectively exploiting differential performance of crop in even changing climate in different agro-climatic and agro-ecological conditions. But, the CRA programme assisting to farmers of Bihar in coping in changing climate to get maximum possible crop production by providing regular input with their maximum use efficiency by adopting climate resilient agriculture practices. Farmers are adopting all technologies hand to hand. All innovative approaches will find their due for smart agricultural practices, increased productivity, resource use efficiency, and profit to the farmers and environment safety. So, it can be said the government approach toward minimizing the negative effects of climate change on crop production is successful and very effective.

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Chapter-6

Climate-Smart Breeding for Resilient Agriculture

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ABSTRACT

Climate change poses significant challenges to global agriculture through rising temperatures, erratic rainfall, and increased frequency of abiotic and biotic stresses, threatening crop productivity and food security. Climate-smart breeding has emerged as an innovative strategy to develop resilient crop varieties capable of sustaining yield stability under changing environmental conditions. This approach integrates conventional breeding with modern genomic, phenomic, and computational tools to enhance tolerance to drought, heat, salinity, flooding, and emerging pests and diseases. Climate-smart breeding focuses on improving resource-use efficiency, maintaining yield stability across environments, and reducing agriculture's environmental footprint. Key adaptive traits include improved root architecture, water-use efficiency, radiation-use efficiency, carbon assimilation, and stress-responsive physiological mechanisms. Traditional breeding methods such as selection, hybridization, backcrossing, and participatory plant breeding continue to provide the genetic foundation for crop improvement, while molecular tools like marker-assisted selection, genomic selection, genome sequencing, and CRISPR-Cas genome editing accelerate genetic gain. High-throughput phenotyping technologies, including drone imaging, thermal sensing, hyperspectral analysis, and automated platforms, enable precise evaluation of stress tolerance traits. Furthermore, artificial intelligence and machine learning facilitate predictive breeding by integrating genomic, phenotypic, and environmental datasets. Despite challenges related to genetic diversity, technological costs, and regulatory frameworks, climate-smart breeding offers a transformative pathway toward resilient agricultural systems. The integration of advanced breeding technologies with sustainable agricultural practices will be essential for ensuring climate adaptation, enhancing productivity, and securing global food systems under future climate scenarios.

Keywords: Climate-smart breeding; Climate change adaptation; Genomic selection; Stress tolerance; High-throughput phenotyping; AI in breeding; Sustainable agriculture.

1. Introduction

Extreme weather events and climatic variability pose a serious threat to agriculture. Global warming, altered precipitation patterns, and an increase in abiotic stresses like drought, heat, salinity, and flooding are all consequences of rising atmospheric greenhouse gas concentrations. These factors have a substantial impact on crop stability and productivity (Intergovernmental Panel on Climate Change, 2022; Food and Agriculture Organization, 2013). By changing physiological processes including photosynthesis, transpiration, and nutrient uptake, these climate variations impede crop growth and development and ultimately result in yield losses (Lobell *et al.*, 2011; Porter *et al.*, 2014). By combining agricultural development with climate adaptation and mitigation techniques, climate-smart agriculture (CSA) has evolved as a strategic approach to solve these issues (Food and Agriculture Organization, 2013). Increasing agricultural output, strengthening climate change resilience, and minimizing greenhouse gas emissions whenever feasible are the three main goals of CSA (Lipper *et al.*, 2014). These goals seek to minimize farming systems' environmental impact while ensuring sustainable agricultural production. Increasing agricultural

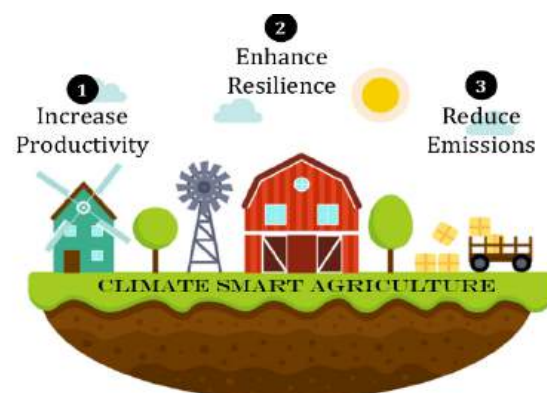
productivity is needed to meet the growing global food demand driven by fast population increase and changing dietary choices (Food and Agriculture Organization, 2017). Crop and farming system resilience is improved by enhancing their ability to tolerate climatic shocks such as drought, heat waves, and unpredictable rainfall (Wheeler and von Braun, 2013). Reducing greenhouse gas emissions from agriculture is especially critical because the agricultural sector is responsible for a major portion of world emissions through activities such as fertilizer use, livestock production, and land use modification.

Crop improvement through plant breeding is one of the key tactics employed to accomplish these goals. Farmers can sustain steady yields even under challenging environmental circumstances by developing climate-resilient crop types (Reynolds *et al.*, 2016). Plant breeding is still a primary force behind agricultural innovation and has historically led to significant increases in crop output, especially during the Green Revolution (Tester and Langridge., 2010).

The goal of climate-smart breeding is to create crop types that can sustain yield stability in a variety of erratic environmental circumstances. This strategy aims to increase resistance to new pests and diseases as well as tolerance to various abiotic stresses as heat, salinity, drought, and flooding (Varshney *et al.*, 2021). Crops can function better in stressful situations by incorporating adaptive features like better root architecture, increased water-use efficiency, and heat-tolerant reproductive structures (Borrell *et al.*, 2014). The speed at which climate change is occurring frequently makes traditional breeding methods inadequate. According to Hickey *et al.*, (2019), conventional breeding relies significantly on phenotypic selection and takes multiple generations to produce superior varieties, which might not be able to keep up with quickly changing environmental conditions. In order to speed up crop improvement, it is now crucial to incorporate contemporary techniques like molecular breeding, genomics, gene editing, and predictive breeding. Molecular breeding approaches, particularly marker-assisted selection, enable breeders to identify and select desirable genes linked with stress tolerance early in plant development (Collard and Mackill, 2008). Advances in genomics have enabled the discovery of quantitative trait loci and candidate genes relevant for complex climate resilience traits (Varshney *et al.*, 2021). Furthermore, genome editing technologies such as CRISPR-based systems allow for precise change of genes implicated in stress responses, resulting in the quick production of superior crop varieties (Jaganathan *et al.*, 2018). In contemporary crop development initiatives, predictive breeding techniques that integrate genetic data with environmental and phenotypic information are also becoming more significant. Breeders can forecast crop performance under various climatic conditions and expedite the selection of superior genotypes by utilizing machine learning, artificial intelligence, and climate modeling (Crossa *et al.*, 2017). In order to create climate-resilient agricultural systems that can maintain global food security in the face of climate change, these integrated techniques are anticipated to be crucial.

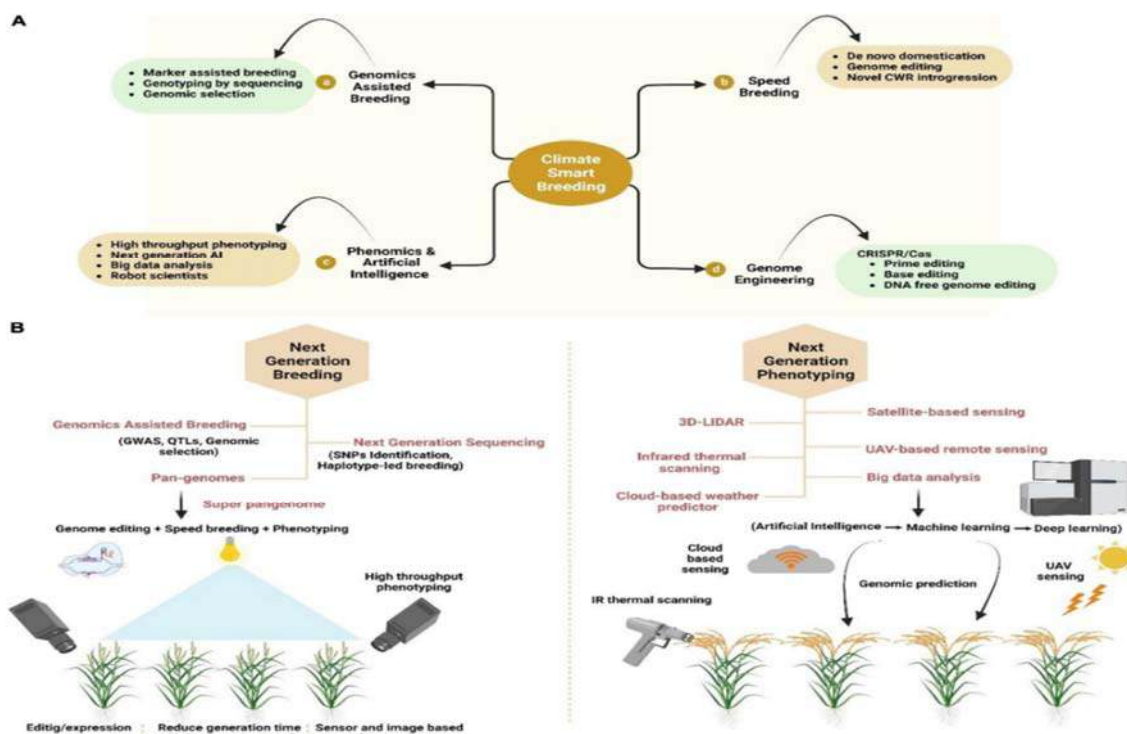
2. Concept of Climate-Smart Breeding

The creation of crop varieties that can withstand climatic shocks while maintaining production and enhancing resource-use efficiency in the face of shifting environmental conditions is known



as "climate-smart breeding." It is an integrated breeding technique that creates crop varieties that can respond to climatic variability and extreme weather events by combining traditional plant breeding with contemporary genomic, phenomic, and computational tools. The idea is in line with the more general framework of climate-smart agriculture, which seeks to promote sustainable agricultural systems and guarantee food security. The goal of climate-smart breeding is to create crop genotypes that can withstand a variety of stresses, including heat, salinity, drought, flooding, and new pests and diseases, while still producing consistent yields in a range of agro-ecological settings (Lipper *et al.*, 2014; Hickey *et al.*, 2019).

As climate change continues to modify environmental variables that impact crop growth and yield, the need for climate-smart breeding has grown. Abiotic and biotic stressors are more common in agricultural systems due to rising temperatures, erratic rainfall patterns, and an increase in the frequency of extreme weather events. Under these increasing environmental constraints, traditional crop types that were bred under relatively stable climatic circumstances frequently do not perform at their best. Breeding strategies must therefore prioritize increasing crop resilience and adaptability to changing climate circumstances in addition to optimizing yield potential (Tester and Langridge, 2010; Varshney *et al.*, 2021).



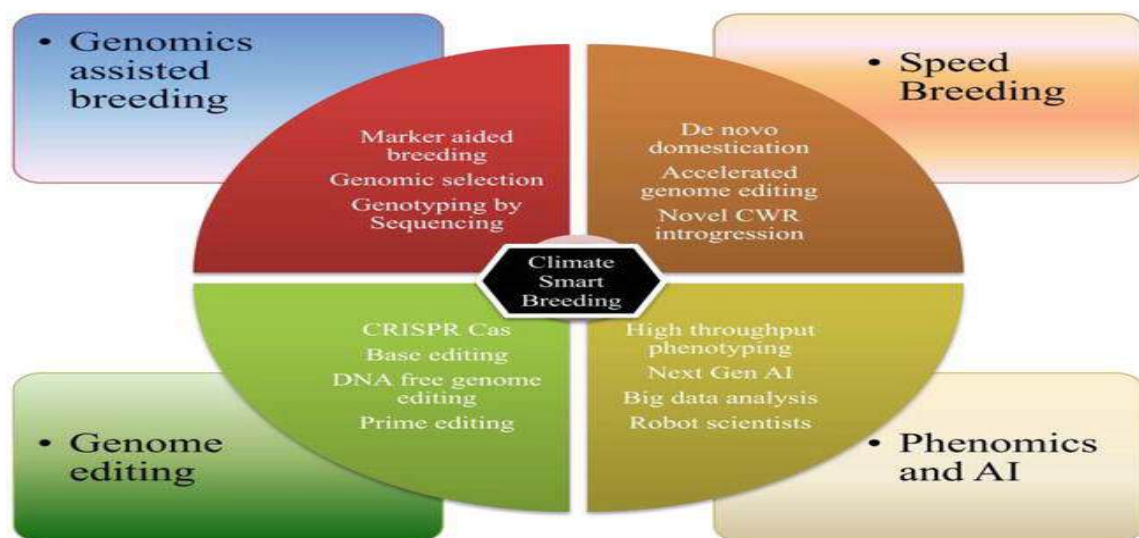
Strategies for climate-smart breeding

2.1 Key Objectives of Climate-Smart Breeding

One of the main goals of climate-smart breeding is to increase resistance to abiotic challenges like drought, heat, salinity, and flooding. These stresses significantly affect plant physiological processes including photosynthesis, transpiration, nutrient uptake, and reproductive development. Creating crop varieties that are more resistant to such shocks can help stabilize agricultural production in adverse environmental situations (Reynolds *et al.*, 2016).

Another major goal is to improve resistance to new pests and diseases. Climate change can

alter the distribution and life cycles of illnesses and insect pests, frequently resulting in new outbreaks in previously uninfested areas. Breeding crops with increased genetic tolerance to these biotic stresses reduces production losses and reduces reliance on chemical pesticides (Bebber *et al.*, 2013). Another important objective of climate-smart breeding is to maintain yield stability in a variety of conditions. Climate-smart breeding places more emphasis on steady performance in a variety of climatic situations than traditional breeding programs, which prioritize maximal production under ideal circumstances. This guarantees consistent food production even in times of environmental stress (Hickey *et al.*, 2019). Improving resource-use efficiency, particularly for water and nutrients such as nitrogen, is another important objective. Crops that can effectively use few resources are more resilient to drought and nutrient scarcity. Crop performance under stressful conditions can be greatly increased by breeding for characteristics such as deeper root systems, increased nitrogen uptake, and greater water-use efficiency (Lynch, 2013). Another crucial goal is to lessen agriculture's environmental impact. By increasing nitrogen-use efficiency and lowering the demand for fertilizers and irrigation inputs, climate-smart crop types can help reduce greenhouse gas emissions. These advancements lessen the effects of climate change while promoting sustainable farming methods (Smith *et al.*, 2014).



Modern breeding approached for resilient agriculture

2.2. Key Components of Climate-Smart Breeding

The efficient use of genetic diversity is a key element of climate-smart breeding. Important genes for stress tolerance and environmental adaptation can be found in crop germplasm collections, including landraces and wild relatives. An essential source of features for enhancing agricultural climate resilience is the exploration and integration of this genetic diversity into breeding programs.

Another crucial element is sophisticated phenotyping technology. To find genotypes with better stress tolerance, precise measurements of plant characteristics under various environmental situations are required. Researchers can gather a lot of information on plant growth, canopy temperature, biomass, and water status utilizing high-throughput phenotyping platforms that use drones, thermal imaging, remote sensing technologies, and hyperspectral sensors. These

innovations greatly improve breeding operations' accuracy and efficiency (Araus and Cairns 2014). Genomic selection has emerged as an effective strategy for expediting crop improvement. This method predicts plant breeding value using genome-wide molecular markers and selects superior genotypes early in the breeding cycle. By combining genomic data with phenotypic and environmental information, genomic selection enables breeders to make faster and more accurate selection decisions, boosting the rate of genetic gain (Crossa *et al.*, 2017). Gene editing technologies have further advanced climate-smart breeding. Modern genome editing methods, such as CRISPR-based systems, allow for precise change of genes related to stress tolerance, plant architecture, and resource efficiency. These tools enable breeders to rapidly add favorable genetic alterations while preserving the general genetic background of elite cultivars (Jaganathan *et al.*, 2018). Another essential component of climate-smart breeding is predictive breeding models. Crop performance under different climatic conditions can be predicted by integrating genetic, phenotypic, and environmental datasets thanks to developments in artificial intelligence, machine learning, and big data analytics. By helping breeders identify the most promising genotypes for upcoming climate conditions, predictive models improve breeding operations' efficiency. In general, climate-smart breeding is a multidisciplinary approach that develops robust crop variants using plant genetics, biotechnology, computational biology, and climate research. By combining these strategies and technologies, climate-smart breeding has the potential to significantly increase agricultural productivity, bolster climate change resilience, and promote sustainable food supply systems worldwide.

3. Key Adaptive Traits for Climate-Resilient Breeding

Finding adaptive features that allow plants to sustain growth, reproduction, and yield in the face of abiotic challenges including drought, heat, salinity, and flooding is essential for breeding crops for climate resilience. Together, these characteristics—which can be morphological, physiological, biochemical, or molecular—determine a plant's ability to tolerate environmental changes brought on by climate change. In stress-prone situations, adaptive characteristics increase crop output by improving resource acquisition, stress avoidance, and stress tolerance.

The goal of climate-resilient breeding is to create crop ideotypes that can maintain productivity in a variety of climatic circumstances by integrating several adaptive features.

3.1 Abiotic Stress Tolerance Traits

Plant growth, photosynthesis, reproductive development, and yield formation are all directly impacted by abiotic stressors. Therefore, the development of climate-resilient cultivars depends on the identification of stress-specific adaptation characteristics.

Stress	Key Adaptive Traits
Drought	Deep root system, osmotic adjustment, stomatal regulation, stay-green phenotype
Heat	Heat shock proteins, membrane thermostability, pollen viability
Salinity	Na ⁺ exclusion, K ⁺ /Na ⁺ homeostasis, osmotic adjustment
Flooding/Submergence	Aerenchyma formation, anaerobic respiration, stem elongation

3.1.1 Drought Tolerance Traits

Drought is one of the most important limitations on agricultural productivity worldwide. It

lowers water availability, resulting in diminished photosynthesis, biomass accumulation, and yield loss. Plants respond with morphological and physiological changes that promote water uptake and decrease water loss. One of the most essential drought-adaptive characteristics is root system architecture. Plants with deeper and more widespread root systems can draw water from deeper soil levels and remain physiologically active throughout lengthy droughts. Root plasticity enables plants to change root development direction, length, and density in response to soil moisture availability.

Other important drought tolerance traits include:

Osmotic adjustment through accumulation of compatible solutes such as proline and glycine betaine

Reduced stomatal conductance to limit water loss through transpiration

Leaf rolling and reduced leaf area to minimize evaporative loss

Stay-green trait, allowing sustained photosynthesis during water deficit

These traits collectively improve water acquisition and utilization efficiency in drought-prone environments.

3.1.2 Heat Tolerance Traits

Heat stress impairs plant metabolism, photosynthesis, and reproductive development. High temperatures can lower pollen viability, limit fertilization efficiency, and shorten grain filling time. Plants deal with heat stress using a variety of adaptive processes, including the creation of heat shock proteins (HSPs), which operate as molecular chaperones, protecting cellular proteins from denaturation. Furthermore, membrane thermostability aids in membrane integrity under high-temperature situations.

Important heat tolerance traits include:

- Heat shock protein expression
- Membrane stability
- Maintenance of pollen viability
- Canopy temperature depression
- Early flowering for heat escape

These traits help maintain metabolic activity and reproductive success during heat stress.

3.1.3 Salinity Tolerance Traits

Salinity stress generates ionic toxicity and osmotic imbalance, which interfere with cellular metabolism and nutrient intake. Plants have evolved a variety of physiological systems to deal with high salt concentrations.

Key salinity tolerance traits include:

- Ion exclusion, particularly the restriction of sodium ions (Na^+) from entering shoots

Ion compartmentalization, where excess Na^+ is stored in vacuoles

Maintenance of high K^+/Na^+ ratio, which is critical for enzymatic activities

Osmotic adjustment, allowing cells to maintain turgor pressure

These mechanisms help plants maintain ionic homeostasis and protect metabolic processes under saline conditions.

3.1.4 Flooding and Submergence Tolerance

Flooding leads to oxygen deficiency in the root zone and disrupts aerobic respiration. Flood-tolerant plants develop specialized anatomical and metabolic adaptations that facilitate survival under low-oxygen conditions. Important flooding tolerance traits include:

- Aerenchyma formation for oxygen transport from shoots to roots
- Stem elongation to escape submergence
- Switch to anaerobic metabolism during oxygen deficiency

These adaptations enable plants to maintain energy production and survive temporary flooding events.

4. Physiological Traits Associated with Climate Resilience

4.1 Water-Use Efficiency (WUE)

Water-use efficiency is defined as the quantity of biomass or carbon assimilated per unit of water consumed. High WUE is a critical goal feature for drought-prone settings. Plants with a high WUE typically exhibit:

- Decreased stomatal conductivity.
- Effective root water uptake.
- Optimized photosynthesis and transpiration.
- Increased root-to-shoot ratio.

Genes regulating stomatal growth, aquaporin function, and water transport have a considerable impact on WUE and are important targets in climate-resilient breeding efforts.

4.2 Radiation-Use Efficiency (RUE)

The ability of plants to transform collected solar radiation into biomass is known as radiation-use efficiency. Enhancements in leaf orientation, chlorophyll content, and canopy design can improve photosynthetic efficiency and radiation interception.

The following characteristics are linked to high RUE:

- The ideal arrangement of leaf angles
- A higher concentration of chlorophyll
- Effective canopy design
- The trait of staying green

A viable tactic to boost agricultural productivity under climate stress is to improve RUE.

4.3 Carbon Assimilation Efficiency

Efficient carbon assimilation ensures that photosynthesis continues even under stressful conditions. Plants maintain carbon fixation via

- Stable Rubisco enzyme activity.
- Efficient electron transport systems.
- Protect photosynthetic apparatus from heat and oxidative damage.

Wild crop cousins frequently have superior carbon absorption properties and thus provide useful genetic resources for producing climate-resilient crops.

4.4 Root Architecture

Root architecture is an important factor in influencing plant tolerance to drought and nutritional stress. Important root characteristics include:

- Deeper rooting depth.
- Increased lateral root branching.
- Increased root length density.
- Proliferation of root hairs

Such characteristics enable plants to explore bigger soil volumes and increase water and nutrient acquisition in difficult conditions.

5. Traditional Breeding Approaches for Climate-Resilient Crops

Traditional plant breeding methods have long been important in generating crop types that can survive environmental conditions. Prior to the development of molecular breeding and genome editing tools, breeders relied heavily on phenotypic selection, hybridization, and backcrossing to increase crop performance in adverse environmental conditions. These traditional tactics are still very relevant today because they enable breeders to integrate desired qualities like stress tolerance, yield potential, and quality features into superior cultivars. Traditional breeding methods also provide the genetic foundation for current breeding techniques like as marker-assisted selection and genomic selection (Allard, 1999; Acquaah, 2012).

5.1 Selection Breeding

Selection of superior individuals from variable populations for stress tolerance (drought, heat, salinity). Includes mass, pure-line, and recurrent selection (Allard, 1999; Acquaah, 2012).

5.2 Hybridization

Crossing diverse parents to combine yield and stress tolerance; exploits genetic recombination and heterosis (Singh, 2005; Acquaah, 2012).

5.3 Backcross Breeding

Transfer of specific genes into elite cultivars via repeated backcrossing; e.g., Sub1 gene in rice (Singh, 2005; Collard & Mackill, 2008).

5.4 Participatory Plant Breeding

Farmer involvement in selection under local conditions; improves adaptation, diversity, and adoption (Ceccarelli and Grando, 2007; FAO, 2019).

6. Modern Molecular Tools for Climate-Resilient Crop Improvement

Plant breeding techniques have been drastically changed by the quick development of molecular genetics and genomics. Phenotypic selection, which can be sluggish and impacted by environmental conditions, is a major component of traditional breeding techniques. On the other hand, breeders can choose plants directly based on their genetic composition using molecular breeding technologies, which speeds up the creation of better varieties. Climate-smart breeding initiatives now depend heavily on contemporary molecular techniques including genomic selection (GS), marker-assisted selection (MAS), and marker-assisted backcrossing (MABC). These

methods make use of DNA markers linked to significant agronomic characteristics as heat tolerance, salinity resistance, and drought tolerance. Breeders can increase the effectiveness, accuracy, and speed of crop improvement programs by combining genomic data with traditional breeding techniques (Collard and Mackill, 2008; Xu and Crouch, 2008).

6.1 Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) is a molecular breeding technique that uses DNA markers (SSR, SNP, AFLP) linked to genes/QTLs to select plants with desired traits at early stages. It enables faster and more precise selection than phenotype-based methods. MAS is especially useful for traits that are hard to measure, expressed late, environmentally influenced, or controlled by major genes/QTLs. A key example is the introgression of the SUB1 gene for submergence tolerance in rice, improving survival in varieties like Swarna-Sub1 and IR64-Sub1 (Xu *et al.*, 2006; Collard and Mackill, 2008). Thus, MAS accelerates breeding and enhances stress tolerance in crops.

6.2 Marker-Assisted Backcrossing (MABC)

Marker-assisted backcrossing (MABC) combines backcross breeding with molecular markers to transfer desired genes into elite cultivars while retaining their genetic background. It uses three types of selection: foreground (target gene), recombinant (minimum donor DNA), and background (maximum recurrent parent genome). This reduces breeding time and improves efficiency. MABC has been widely used to introgress stress tolerance traits, such as the Sub1 gene for flood tolerance and Saltol QTL for salinity tolerance in rice (Septiningsih *et al.*, 2009; Singh *et al.*, 2011).

6.3 Genomic Selection (GS)

Genomic selection (GS) is an advanced breeding approach that uses genome-wide markers to predict the breeding value (GEBVs) of individuals. Unlike MAS, it captures both major and minor gene effects across the genome. It involves genotyping and phenotyping a training population, building prediction models, and selecting individuals based on GEBVs without extensive phenotyping. GS is highly effective for complex traits like grain yield, drought and heat tolerance, and nutrient-use efficiency, which are controlled by many small-effect genes.

7. Advanced Genomic Approaches for Climate-Resilient Crop Improvement

Plant breeding has been transformed by recent developments in genomics and genome editing technology. Researchers can decipher crop genomes, find genes governing significant agronomic features, and create accurate genetic improvement plans thanks to high-throughput sequencing technologies. With the use of these technologies, breeders can target certain genes linked to yield stability, abiotic stress tolerance, and climate adaptation. Among these methods, CRISPR-Cas genome editing and genome sequencing have proven to be effective instruments for speeding up crop development and creating climate-resilient cultivars.

7.1 Genome Sequencing

Genome sequencing entails determining the entire DNA sequence of an organism's genome. Advances in next-generation sequencing (NGS) technology have considerably lowered the cost and time necessary to sequence plant genomes. The sequencing of key crop genomes such as rice, wheat, maize, and soybean has enabled the discovery of genes and quantitative trait loci (QTLs) linked to stress tolerance and other agronomic properties.

Genome sequencing provides valuable information for plant breeders by enabling:

- Identification of genes controlling stress tolerance
- Discovery of quantitative trait loci (QTLs)
- Development of molecular markers for breeding
- Understanding of gene regulatory networks

7.2 CRISPR-Cas Genome Editing

An innovative approach called CRISPR-Cas genome editing makes it possible to precisely alter particular DNA regions in the genome. Originally identified as a component of the bacterial immune defense system, the CRISPR-Cas system has been modified for targeted genome editing in plants. The most popular approach is CRISPR-Cas9, which directs the Cas9 nuclease to a particular DNA sequence using a guide RNA (gRNA). Cas9 creates a double-strand break in the DNA after identifying the target sequence. Cellular repair processes including homology-directed repair (HDR) and non-homologous end joining (NHEJ) fix this break and produce targeted gene changes. CRISPR-Cas genome editing offers several advantages for plant breeding:

- High precision in gene modification
- Ability to edit multiple genes simultaneously (multiplex editing)
- Faster development of improved crop varieties
- Reduced linkage drag compared to traditional breeding methods

These features make CRISPR-Cas technology particularly valuable for improving crop adaptation to climate change (Jaganathan *et al.*, 2018; Chen *et al.*, 2019).

8. High-Throughput Phenotyping for Climate-Resilient Crop Breeding

Phenotyping is important in plant breeding because it allows for the measurement and evaluation of observable plant features caused by genotype-environment interactions. While breakthroughs in genomics have significantly increased our ability to detect genetic variation, accurately measuring phenotypic features remains a major problem in crop improvement. In modern plant breeding, the "phenotyping bottleneck" refers to the difference between the quick synthesis of genetic data and the relatively slow acquisition of phenotypic data. High-throughput phenotyping (HTP) technologies have emerged as effective techniques for overcoming this constraint. These technologies use remote sensing, robotics, imaging systems, and data analytics to measure plant features quickly, precisely, and non-destructively. HTP platforms allow breeders to analyze large populations in both field and controlled situations, making it easier to identify genotypes that are more resistant to environmental stresses including drought, heat, and salinity (Furbank and Tester, 2011; Araus and Cairns, 2014). Recent advances in sensor technologies and automation have enabled the development of several high-throughput phenotyping tools that allow precise measurement of plant growth and stress responses.

8.1 Drone-Based Imaging

Unmanned aerial vehicles (UAVs), sometimes known as drones, are rapidly being employed in agricultural research to conduct large-scale crop phenotyping studies. Drones outfitted with high-resolution cameras and sensors may quickly acquire detailed photographs of crop canopies across huge experimental areas. Breeders can use drone-based imagery to monitor plant growth, canopy

development, plant height, and vegetation indices like the Normalized Difference Vegetation Index (NDVI). These measurements aid in the identification of stress-tolerant genotypes capable of maintaining increased photosynthetic activity and biomass in harsh environmental conditions. Drone technology also allows breeders to track temporal changes in plant development and stress responses (Zhang and Kovacs, 2012; Araus and Cairns, 2014).

8.2 Thermal Sensors

Thermal imaging sensors detect the temperature of plant canopies, providing useful information regarding plant water status and transpiration rates. Under drought conditions, plants frequently block their stomata to conserve water, resulting in decreased transpiration and increased canopy temperature. Thermal cameras can detect temperature changes, allowing breeders to find genotypes that are more water efficient and drought tolerant. Crops that maintain lower canopy temperatures in water-limited environments are more effective at regulating transpiration and maintaining physiological activity. Thermal sensing has been widely employed in crops such as wheat and maize to identify drought-tolerant genotypes in the field (Jones *et al.*, 2009).

8.3 Hyperspectral Imaging

Hyperspectral imaging is a sophisticated remote sensing technique that measures reflectance over hundreds of small spectral bands. This technique offers precise information on plant biochemical and physiological features. Hyperspectral sensors can detect small changes in plant health, nutritional status, chlorophyll concentration, and stress reactions before they become visible. Researchers can use spectral fingerprints to estimate qualities like:

- Chlorophyll concentration.
- The nitrogen content of the leaves.
- Photosynthesis efficiency
- Water status.

These data are especially valuable in detecting early reactions to environmental challenges like drought, heat, and salinity (Mahlein, 2016).

8.4 Automated Greenhouse Phenotyping Platforms

Automated phenotyping platforms in controlled greenhouse environments continuously monitor plant growth with robotics, conveyor systems, and imaging technology. Plants are automatically moved through imaging stations, where sensors collect information about plant morphology, growth rate, and physiological characteristics. These systems allow scientists to measure plant responses to controlled stress treatments like drought or salinity while reducing human error and environmental variability. Automated greenhouse systems can assess numerous traits at the same time, such as plant height, leaf area, biomass accumulation, and growth dynamics. These platforms are increasingly being employed in modern breeding efforts to screen huge populations for stress tolerance traits (Fahlgren *et al.*, 2015).

8.4.1 Measurement of Key Traits for Climate Resilience

High-throughput phenotyping tools enable accurate measurement of several plant traits associated with climate resilience.

Canopy Temperature

Canopy temperature is an important indicator of plant water status and transpiration efficiency. Lower canopy temperature under drought conditions generally indicates better water uptake and

transpiration regulation. Thermal imaging technologies allow rapid measurement of canopy temperature across large breeding populations

Water Content of Leaves

The water content of leaves indicates a plant's level of hydration and its capacity to sustain turgor in the face of a water shortage. Breeders can track how plants react to drought stress by using near-infrared sensors and hyperspectral imaging to determine leaf water content non-destructively.

Accumulation of Biomass

One important measure of plant productivity and overall growth performance is biomass generation. By examining canopy structure, plant height, and vegetation indices, imaging systems and remote sensing technologies can estimate biomass buildup. Breeders can find genotypes that sustain growth under stressful environmental circumstances by keeping an eye on biomass accumulation.

9. Artificial Intelligence and Machine Learning in Climate-Smart Breeding

Modern plant breeding now faces both new opportunities and difficulties due to the fast growth of genetic, phenotypic, and environmental datasets. For the analysis of such big and complicated datasets, traditional statistical methods are frequently inadequate. Large biological datasets may now be used to find patterns, correlations, and predictive models thanks to the development of artificial intelligence (AI) and machine learning (ML). AI-driven approaches enable breeders to integrate diverse datasets, including genomic sequences, phenotypic measurements, environmental variables, and management practices, to predict crop performance and accelerate breeding programs. These approaches enhance the efficiency of selection decisions and improve the rate of genetic gain in crop improvement programs. AI-based predictive models are particularly valuable for breeding crops adapted to climate variability and environmental stress conditions (Montesinos-López *et al.*, 2021; Crossa *et al.*, 2017). Machine learning techniques such as random forests, support vector machines, neural networks, and deep learning algorithms are increasingly applied to plant breeding datasets. These algorithms can analyze complex nonlinear relationships between genes and traits, allowing researchers to identify genomic regions associated with stress tolerance, yield stability, and other important agronomic characteristics.

9.1 Applications of AI and Machine Learning in Plant Breeding

By aiding extensive data analysis and predictive modeling, artificial intelligence and machine learning are revolutionizing plant breeding.

- Predicting Trait Performance
- Identifying Gene–Trait Associations
- Optimizing Breeding Strategies
- Predictive Breeding Models.
- Integration of Genomic Data

DNA sequences, molecular markers, and gene variations linked to significant characteristics are all included in genomic data. To forecast the genetic potential of breeding lines, machine learning algorithms can examine genome-wide marker data. Breeders can choose better genotypes early in the breeding cycle by using prediction models that incorporate genomic information to determine an individual's genomic estimated breeding values (GEBVs).

Integration of Environmental Data

Crop performance is significantly influenced by environmental elements such as temperature, rainfall, soil characteristics, and climate variability. In order to account for genotype \times environment (G \times E) interactions, which affect trait expression under various climatic circumstances, predictive breeding models use environmental datasets.

Breeders can create varieties tailored to certain agro-ecological circumstances by using AI models that use environmental data to forecast how various genotypes will perform under future climate scenarios.

Integration of Phenotypic Data

Information about observable plant characteristics including yield, biomass, canopy temperature, and drought tolerance can be found in phenotypic data from field experiments and high-throughput phenotyping platforms. In order to create predictive models that increase selection accuracy, machine learning algorithms combine phenotypic data with genomic and environmental facts. Breeders can more confidently identify superior genotypes thanks to this integrated method, which also speeds up the creation of climate-resilient crops.

10. Challenges in Climate-Smart Breeding

Even though advanced breeding technologies have greatly advanced the development of climate-resilient crops, a number of obstacles still prevent climate-smart breeding programs from being widely adopted and being effective. The creation and uptake of improved crop varieties are influenced by biological, technological, economic, and regulatory variables.

- Limited Genetic Diversity in Breeding Pools
- Complex Inheritance of Stress Tolerance Traits
- High Cost of Phenotyping Technologies
- Regulatory Issues for Gene-Edited Crops
- Need for Interdisciplinary Collaboration

12. Future Perspectives

The goal of future climate-smart breeding techniques is to create crop types that can maintain productivity in the face of shifting environmental factors including heat, salinity, drought, and flooding. Resilient agriculture will require the integration of cutting-edge technologies with traditional breeding methods.

Integration of Genomics, Phenomics, and Bioinformatics

Modern crop improvement increasingly relies on integrating genomics (genetic information), phenomics (large-scale trait measurement), and bioinformatics (data analysis tools).

Exploitation of Wild Germplasm

Crop plants' wild relatives are a significant source of genetic variation, especially when it comes to characteristics linked to stress tolerance. During domestication, several cultivated crops experienced genetic bottlenecks that reduced their genetic variability. Genes for tolerance to pests, diseases, salinity, and drought that are lacking in contemporary cultivars are frequently found in wild germplasm. The genetic foundation of crops is expanded by the introduction of these genes through molecular breeding, hybridization, and backcrossing.

For instance, genes for increased yield and stress tolerance have been introduced into farmed rice from wild rice species like *Oryza rufipogon* and *Oryza nivara*.

Development of Multi-Stress Tolerant Varieties

Climate change frequently exposes crops to several challenges at once, such as heat and drought or salinity and water scarcity. Future breeding must concentrate on multi-stress resistance, yet traditional breeding strategies frequently concentrate on single stress aspects.

Important tactics consist of:

Finding the genes and QTLs that regulate resistance to various stressors.

- Combining physiological characteristics including effective photosynthesis, osmotic adjustment, and deep root systems.
- Accumulating several advantageous alleles through genomic selection.
- Creating cultivars that can withstand many stresses promotes consistent crop yield in the face of variable weather.

Accelerated Breeding Using Speed Breeding Techniques

By shortening the period needed for generation development, speed breeding is a cutting-edge method that speeds up crop progress. Plants can grow more quickly and flower earlier under controlled environmental circumstances including an extended photoperiod (20–22 hours of light) and ideal temperature. Breeding cycles can be significantly shortened by producing multiple generations in a single year. Crops including wheat, barley, canola, and chickpeas have all benefited from speed breeding. This method makes it possible to generate improved varieties more quickly and to incorporate advantageous features into breeding populations more quickly.

Climate-Informed Crop Improvement Programs

Predictive modeling and climatic data must be incorporated into future breeding plans in order to account for environmental changes. Climate-aware breeding consists of:

- Determining future stress situations by using climate projections.
- Examining breeding lines in situations that mimic stress
- Predicting performance across locations by integrating genetic data with crop modeling.

These methods assist breeders in creating cultivars that are adaptable to future climate conditions in addition to being adapted to their existing surroundings.

Conclusion

Future climate-smart breeding will rely on combining advanced genomic tools, high-throughput phenotyping, artificial intelligence, and climate modeling with traditional breeding methods. The integration of these approaches will accelerate the development of high-yielding, climate-resilient crop varieties, ensuring sustainable agricultural productivity in the face of global climate change.

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Chapter-7

Trees Outside Forests: A Potential Nature-Based Solution for Climate Change and Livelihood Security

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ABSTRACT

Trees Outside Forests (TOF) represent a vital yet often underappreciated component of global landscapes, occurring in agricultural fields, urban areas, homesteads, roadsides, and other non-forest environments. Despite not being part of designated forest ecosystems, these trees contribute significantly to ecological stability, rural livelihoods and climate change mitigation. In recent years, growing attention has been directed toward understanding the multifunctional role of TOF in sustaining human-dominated landscapes. TOF provide a wide range of ecosystem services, including carbon sequestration, biodiversity conservation, soil fertility enhancement, microclimate regulation, and improved water retention. In agricultural landscapes, trees integrated within farmlands through agroforestry systems enhance crop productivity, reduce land degradation, and support diversified farm income through timber, fuelwood, fruits, fodder, and non-timber forest products. In many developing countries, particularly in rural regions, these trees act as a critical resource base for household subsistence and economic resilience. The increasing recognition of TOF has also led to advancements in their assessment and monitoring using remote sensing, geographic information systems, and participatory approaches. However, several challenges still limit their full potential, including policy and institutional constraints, lack of reliable data, unclear land and tree tenure, and limited integration of TOF into national forest inventories and climate strategies. Strengthening supportive policies, improving monitoring frameworks, and promoting farmer participation are essential for enhancing the contribution of Trees Outside Forests to sustainable development. Recognizing and integrating TOF into broader landscape management strategies can play a crucial role in achieving climate resilience, biodiversity conservation, and livelihood security in both rural and urban environments. This article highlights the ecological, economic, and social importance of Trees Outside Forests and emphasizes the need to increase area under TOF.

Keywords: *Trees Outside Forests, Livelihood Security, Ecosystem Services, Climate Change Mitigation*

1. Introduction

Trees play a vital role in maintaining ecological balance and supporting human livelihoods by providing a wide range of ecosystem services and goods. While forests are traditionally viewed as the main repositories of tree resources, a substantial number of trees occur outside formally designated forest areas. These resources are collectively referred to as Trees Outside Forests (TOF), encompassing trees growing outside forest lands and other wooded areas. The concept of TOF was introduced in 1995 to characterise tree resources that do not fit into traditional forest categories but are nevertheless important both environmentally and commercially. Attention that had previously been divided across similar fields including agroforestry, silvopastoral systems, urban forestry, rural forestry, and other tree-based land-use systems was brought together by the phrase “trees outside forests” (Yadav *et al.*, 2017). Trees outside forests include a wide range of formations such as scattered trees on agricultural land, agroforestry systems, urban green spaces, and trees along rivers, canals, roads, and other linear infrastructures. The FAO defines TOF as all trees growing on land that does not meet the criteria for forests or other wooded lands. According to FAO definitions, forests are areas larger than 0.5 hectares with a canopy cover greater than 10% and trees capable of reaching a height of 5 meters at maturity. Consequently, TOF includes trees

on agricultural land, urban areas, barren lands, and small patches of tree cover that do not meet these thresholds (Peros *et al.*, 2022).

In India, TOF refers to trees growing outside government-recorded forest areas (RFAs) and includes trees on farms, private lands, community lands, urban spaces, and along infrastructure networks such as roads, canals, and railway lines (Rossi *et al.*, 2016). Despite their widespread presence, TOF historically received limited attention in policy frameworks and resource assessments. However, growing concerns regarding environmental degradation, climate change, and sustainable resource management have gradually highlighted their importance. Trees outside forests contribute significantly to national biomass and carbon stocks while supporting the livelihoods of millions through the provision of timber, fuelwood, fodder, fruits, and other non-timber forest products. Nearly two-thirds of fuelwood demand in many developing nations is satisfied by TOF, highlighting their significance for home energy security. Additionally, nearly 40% of agricultural land worldwide has a tree cover of more than 10%, demonstrating the pervasiveness of trees in managed landscapes. A major step toward recognising these resources in international forest monitoring systems was taken when the Food and Agriculture Organization (FAO) integrated TOF into the Global Forest Resource Assessment (FRA) 2000 (Thomas *et al.*, 2021). Beyond their economic contributions, TOF provide numerous ecological services that enhance environmental sustainability and agricultural productivity. These systems improve soil fertility through nitrogen fixation, enhance soil moisture retention, regulate watershed functions, reduce soil erosion, and moderate microclimatic conditions, thereby supporting crop productivity. In generally human-dominated environments, they also play a crucial role as habitats for biodiversity. By lowering temperatures, reducing air pollutants, managing dust and noise pollution, and improving aesthetic and recreational value, trees in urban and peri-urban regions contribute to better environmental quality (Chakravarty *et al.*, 2019).

In the context of climate change mitigation, TOF represent an important but often underutilized carbon sink. Forests and TOF together form complementary components of tree-based landscapes and contribute significantly to carbon storage and sequestration. Accurate accounting and monitoring of TOF resources can, therefore, provide valuable insights into their contribution to national carbon budgets and climate mitigation strategies. Overall, Trees Outside Forests represent a vast yet underutilized resource with significant potential for biodiversity conservation, climate change mitigation, and sustainable livelihood support. Strengthening their inclusion in national inventories, policy frameworks, and climate initiatives will be essential for harnessing their full ecological and economic potential in the future. Furthermore, integrating TOF initiatives with global climate programmes such as REDD+ may enhance carbon sequestration potential while providing financial incentives to farmers and supporting national climate commitments. Besides, TOF play an important role in climate change adaptations.

2. Distribution of TOFs throughout the tropics and India

Trees Outside Forests (TOF) make up a significant portion of the world's tree resources in tropical climates and occupy a large portion of landscapes that are dominated by humans. In the tropics, TOF is found on around 1.35 billion hectares of land. Their distribution is extremely diverse, influenced by environmental factors including soil properties, water availability and climate as well as human factors like land-use practices, agricultural growth, and settlement patterns. Tropical subregions differ greatly in the incidence of TOF. More than 50% of the land

surface in Western Africa and southern and eastern Asia is covered by trees outside of forests, demonstrating the deep integration of trees into rural and agricultural environments. TOF is supported on more than one-third of the land in southern Africa, Southeast Asia, the Caribbean, and northern and eastern Africa. The growing importance of TOF in managed ecosystems is demonstrated by the fact that by 2020, more than half of all agricultural and urban land in the majority of tropical regions had tree cover above 10%. In the Caribbean, more than 71% of urban land surpasses this criterion, and in Asia and Oceania, more than 66% of cropland has comparable tree cover. These trends highlight the increasing significance of TOF in improving livelihood security, climate regulation, and biodiversity conservation in tropical regions (Brandt *et al.*, 2023; World Resources Institute, 2023). Figure 1 depicts distribution and proportion of land that contains TOF by subregion.

In India, the total extent of TOF at the country level is 8.94 % of the total geographical area of the country. The Union Territory of Lakshadweep is having maximum extent of TOF (91.3 %). Among the States, Kerala (37.17 %) and Goa (36.05 %) have maximum TOF area, as percentage to their geographical area. In absolute terms Maharashtra has the maximum area under TOF, followed by Odisha and Karnataka. Table 1 depicts the classification of TOF as per Indian standards. Figure 2 shows extent of TOF in different states of India.

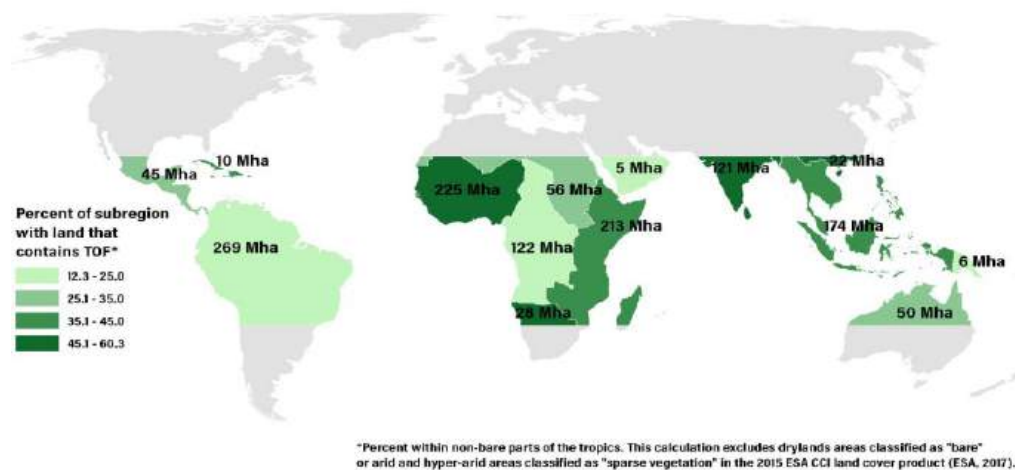


Figure 1. Distribution and proportion of land that contains TOF by subregion

Source : World Resources Institute (2023)

Table 1: Classification of TOF

As per Land Use	As per Geometrical Formation
Trees with settlements	Isolated and scattered trees
Rural	Trees exist in scattered form
Urban	
Trees with Agricultural Lands	Zonal trees
Agroforestry	Trees in blocks Trees in lines
Trees along Manmade or Natural Features	
Beside Roads	Different formations
Beside Canals/ Rivers	
Beside Railways	

Source : FSI (2020)

Extent of Trees Outside Forest w.r.t. Geographical Area

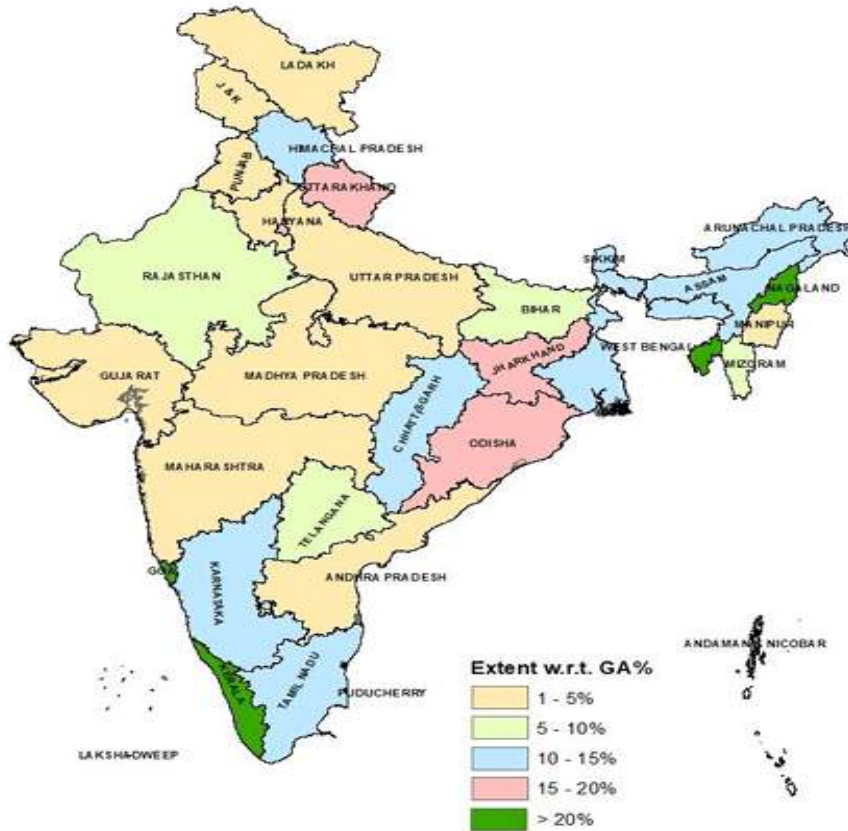


Figure 2. Extent of TOF in India (% of geographical area) (FSI, 2020)

3. Monitoring Trees Outside Forests

Monitoring Trees Outside Forests (TOF) is challenging because unlike continuous forest stands, TOF often appear as isolated trees, small clusters, hedgerows, or linear plantations along roads and waterways, making conventional forest inventory methods less effective. As a result, modern monitoring increasingly relies on advanced technologies such as remote sensing, GIS, LiDAR, UAVs (drones), machine learning, and field inventories to accurately map and assess their distribution, structure, and ecosystem services.

3.1 Remote Sensing Approaches: Remote sensing has become an important tool for monitoring TOF on a regional and global scale. Satellite platforms such as Landsat, Sentinel-1, Sentinel-2, and PlanetScope enable large-scale mapping of tree cover. Vegetation indices such as the Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are commonly used to distinguish tree cover from neighbouring land uses as well as to assess vegetation health and canopy density. Recent research has also demonstrated the use of combining optical and radar images with deep learning algorithms to detect scattered trees with canopy diameters higher than three meters across various environment (Sarti *et al.*, 2021; Brandt and Stolle, 2021).

3.2 Geographic Information Systems (GIS): GIS plays an important role in integrating spatial datasets derived from remote sensing, field inventories, and environmental variables. GIS-based analysis is useful for mapping TOF distribution, evaluating tree density and landscape connectivity, and assessing ecosystem services like carbon sequestration, soil conservation, and biodiversity

support. These geographical studies also help to identify priority sites for agroforestry extension, tree conservation, and ecosystem restoration.

3.3 LiDAR Technology: Light Detection and Ranging (LiDAR) provides detailed three-dimensional information on vegetation structure by emitting laser pulses to measure canopy height and structure. This allows precise estimation of tree height, crown dimensions, and above-ground biomass, making LiDAR particularly useful for detecting scattered trees and small clusters in complex landscapes.

3.4 Unmanned Aerial Vehicles (UAVs): The use of UAVs or drones has grown rapidly in TOF monitoring. UAVs equipped with multispectral or hyperspectral sensors acquire ultra-high-resolution imagery, allowing for the identification of individual trees and canopy characteristics. UAV photography paired with object-based image processing may efficiently map agroforestry systems, urban trees, and orchards and even enables for tree species classification in varied contexts (Sivanandam and Lucieer, 2022).

3.5 Machine Learning and Artificial Intelligence: Advances in machine learning and artificial intelligence (AI) have greatly improved TOF monitoring. Satellite and aerial imagery are increasingly being analysed for automated tree detection and categorisation using algorithms such as Random Forest, Support Vector Machines (SVM) and Convolutional Neural Networks (CNN). These techniques allow for reliable identification of individual tree crowns, canopy cover, and plant types, permitting large-scale tree-cover mapping and ecological modelling (Gominski *et al.*, 2025).

3.6 Field Inventories and Ground-Based Monitoring: Despite technological advancements, field-based surveys remain essential for collecting detailed information on tree species, diameter at breast height (DBH), tree health, and growth characteristics, which are necessary for accurate biomass and carbon stock estimation. Field data also help calibrate remote sensing models. Increasingly, participatory monitoring involving farmers and local communities is being adopted to improve TOF inventories and promote sustainable tree management on private lands.

4. Role of TOF in Carbon Sequestration

Global climate change and the rapid loss of biodiversity are among the most critical environmental challenges threatening the sustainability of future generations. The concentration of atmospheric carbon dioxide (CO₂) has risen to almost 379 parts per million over the previous century and the global mean temperature has risen by 0.74 degrees Celsius, underscoring the pressing need for efficient mitigation measures. Trees in managed landscapes, especially in developing nations, absorb and convert atmospheric CO₂ into biomass, making them excellent carbon sinks. Institutional and academic landscapes are a distinct type of TOF-dominated ecosystem, with many varied tree species and significant biomass. Several such landscapes (TOF) in India and throughout the world have been studied for their biodiversity and carbon storing capacity (Tamang *et al.*, 2021). Trees outside forests serve an important role in both carbon sequestration and long-term carbon storage. In addition to storing carbon in live biomass, TOF helps to increase soil organic carbon, which improves ecosystem productivity and stability (FAO, 2005). In India, TOF plays an important role in national carbon storage. Figure 3 depicts an estimated total carbon stock of India linked with TOF of approximately 2532 million tonnes, comprising 1596 million tonnes from TOF forest cover and 936 million tonnes from tree cover, illustrating their major contribution to the country's carbon balance (FSI, 2020).

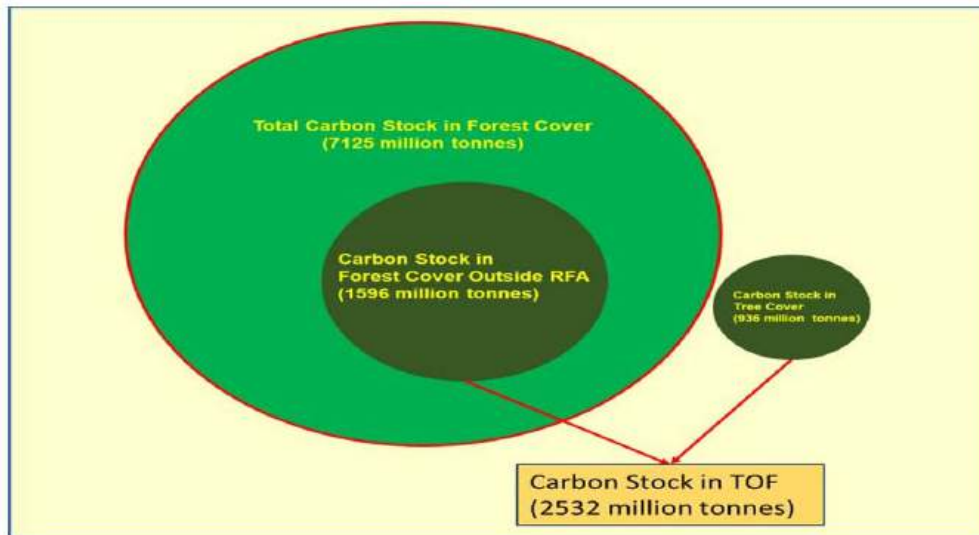


Figure 3. Carbon Stock in TOF in India Source: FSI (2020)

Expanding TOF through urban greening, agroforestry systems, plantations along highways and railways, and afforestation on culturable wastelands holds the potential to increase national carbon stocks. To support India's climate commitments, the Forest Survey of India (FSI) estimated that approximately 43.16 million hectares of land are available for plantation and tree-based interventions aimed at meeting the Nationally Determined Contributions (NDC) target of creating additional carbon sinks by 2030 (Mathur *et al.*, 2021). Therefore, strengthening TOF-based initiatives and evaluating their biomass and carbon sequestration potential are essential steps toward climate change mitigation, sustainable land management and ecological resilience.

5. Socioeconomic and Livelihood Benefits

Trees Outside Forests (TOF) offer several socioeconomic, cultural, and environmental benefits, especially in developing nations where rural communities rely significantly on tree-based resources. One of the most significant contributions of TOF is to meet home energy demands. In many areas, TOF provides a significant amount of the fuelwood needed for cooking and heating. In India, TOF accounts for around 49% of total fuelwood supply, underscoring their importance in rural energy security. Only 1.23 million tonnes of fuelwood are provided through state forests, while around 19.25 million tonnes come from Trees Outside Forests, illustrating rural people's reliance on trees growing on farmlands, homesteads, and other non-forest settings (Manasa *et al.*, 2023). Beyond their economic value, trees outside forests are deeply rooted in the social and cultural fabric of South Asian communities. Trees in agricultural fields, village commons, and homesteads are frequently associated with cultural traditions, religious beliefs and communal identity. Sacred groves, which are part of TOF, culturally significant species, and community-managed trees all symbolise long-standing traditions of conservation and collaborative stewardship (Christopher *et al.*, 2026).

According to research, well-managed tree-based systems can increase the supply of both wood and non-wood forest products, boost overall land productivity and relieve pressure on natural forests by offering alternative sources of timber, fuelwood, fodder, and other resources. The systematic gathering and effective use of TOF-related information can increase the economic and

ecological valuation of these resources, allowing policymakers to overcome institutional and economic hurdles that prevent their sustainable utilisation and protection (Castro, 2001). A study conducted in Nepal's Siraha region found that TOF goods have a considerable impact on family economies. The survey found that TOF products generated an average yearly revenue of around US\$ 853.30 per household, accounting for approximately 20.57% of total household income. Fruit trees contributed the most to TOF income, accounting for roughly 61.16% (US\$ 521.90). Timber sales were the second largest contribution, accounting for approximately 25.17% (US\$ 214.77) of household income generated by TOF resources. The distribution of income from TOF goods varied with socioeconomic status; wealthier households generated more income from timber sales, whereas fruit-based income contributed significantly to rich, middle, and poor households alike. This implies that promoting TOF-based land-use systems can significantly contribute to improving rural livelihoods, strengthening agroforestry-based economies, and supporting sustainable landscape management (Yadav *et al.*, 2020).

6. Limitations and Challenges of Trees Outside Forests (TOF)

Insufficient policy support, complex harvesting and transport rules, unclear land and tree tenure, and poor coordination among forestry, agriculture, and rural development organizations limit the effective promotion and integration of TOF into national land-use and climate strategies (FAO, 2001).

Limited data and monitoring systems for TOF due to their dispersed distribution across farmlands, homesteads, and urban landscapes (Brandt and Stolle, 2020).

Lack of certified nurseries and superior can lead to low survival rates and hinder large-scale seedlings growth of TOF systems (WRI India, 2022).

Long tree rotation periods, underdeveloped markets for tree products, reliance on intermediaries, and inadequate access to financing, insurance, or incentive mechanisms diminish TOF's economic attractiveness to smallholder farmers (Najima Noushad *et al.*, 2026).

Limited farmer awareness of species selection, tree-crop interactions and management methods, along with inadequate agroforestry extension services, hinders successful adoption and management of TOF systems.

Farmers may be discouraged from incorporating trees into their farming systems due to socio-economic and cultural hurdles such as small landholdings, population pressure, conflicting land uses, and restricted participation by marginalized groups in decision-making.

Insufficient long-term ecological studies, limited understanding of tree-crop interactions, and fragmented research efforts restrict evidence-based planning and sustainable management of TOF systems. These research gaps hinder evidence-based decision making and large-scale implementation of TOF systems (Tejwani, 2020).

7. Conclusion

Trees Outside Forests (TOF) have evolved as an important component of sustainable landscapes, connecting forestry, agriculture, and livelihood systems. Although they occur outside of traditionally defined forest limits, their ecological, economic and social contributions are significant. TOF promote biodiversity conservation, improve soil and water resources, manage

local microclimates, and serve as a substantial source of biomass and carbon sequestration. In nations such as India and the tropics, they also serve as an important resource base for rural communities, providing lumber, fuelwood, fodder, fruits, and other goods that improve livelihood security and minimize strain on natural forests. TOF's widespread distribution across tropical and human-dominated environments demonstrates its expanding importance in the face of climate change, land degradation, and resource constraint. Geospatial technologies, remote sensing, UAVs, LiDAR, and artificial intelligence advancements have significantly increased the ability to map and monitor these dispersed tree resources, allowing for more accurate quantification of their biological functions and carbon storage potential. At the same time, evidence suggests that TOF can significantly contribute to national carbon budgets and climate mitigation obligations by increasing tree cover in agricultural, urban, and peri-urban areas. Despite its enormous potential, TOF remains underappreciated in policy, research, and management contexts. Poor institutional support, insufficient monitoring, poor market linkages, a shortage of quality planting material, and restricted extension services all continue to impede their full development. As a result, there is a clear need to better include TOF into national inventories, land-use planning, agroforestry initiatives, and climate policy. To fully realize TOF's ecological and socioeconomic potential, it will be necessary to strengthen research, improve governance, and create incentives for farmers and communities. In the future, a greater emphasis on TOF can have a transformative impact on climate-resilient landscapes, rural livelihoods, and achieving sustainable development goals.

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Chapter-8

Climate-Resilient Livestock Breeding: A Cornerstone for a Viksit Bharat

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ABSTRACT

Climate change poses significant challenges to the sustainability and productivity of India's livestock sector through rising temperatures, erratic rainfall, heat stress, emerging diseases, and declining feed resources. As India advances toward the vision of Viksit Bharat 2047, climate-resilient livestock breeding has emerged as a strategic pathway to safeguard livelihoods, nutritional security, and rural economies. This paper highlights the growing vulnerability of livestock systems and emphasizes genetic improvement as a long-term adaptation strategy. Selection for adaptive traits such as heat tolerance, disease resistance, feed efficiency, and water-use efficiency, combined with conservation and utilization of indigenous breeds, offers strong potential for enhancing resilience. Integration of advanced genomic tools, marker-assisted selection, climate-smart nutrition, precision health monitoring, and improved housing systems can significantly reduce climate-related productivity losses. Emerging technologies including thermal imaging, sensor-based monitoring, and decision support systems further enable data-driven livestock management. Strengthening research on feed efficiency, disease resistance, and low-carbon production systems is essential for sustainable growth. The study underscores that coordinated efforts involving breeding innovation, digital technologies, policy support, and farmer-centric extension services will be crucial to transform India's livestock sector into a resilient, productive, and environmentally sustainable system, contributing substantially to the realization of Viksit Bharat.

Keywords: *Climate-resilient livestock; Indigenous breeds; Genomic selection; Heat stress adaptation; Precision livestock farming; Sustainable livestock production.*

1. Background: The Strategic Imperative for India

India is steadily advancing toward its vision of *Viksit Bharat* by 2047, where strengthening the sustainability and resilience of the agricultural sector remains a national priority. Within this framework, the livestock sector plays a pivotal role in the agrarian economy, contributing nearly 5.49% to the national Gross Value Added (GVA) and over 30% to the agricultural and allied GVA. It serves as a critical source of livelihood for millions of small and marginal farmers, particularly in rural regions where a significant share of the population resides, thereby supporting income stability, nutritional security, and inclusive rural development (Press Information Bureau, 2025). Beyond its economic contribution, livestock ensures nutritional security through the supply of essential protein and calcium, with India being the largest milk producer globally. Small ruminants, including goats and sheep, are particularly valued for their adaptability to challenging environments, with goat milk offering superior digestibility and a lower environmental footprint, while sheep contribute significantly to wool, meat and milk production in arid and mountainous regions (Panghal *et al.*, 2025; Malik *et al.*, 2024; Bangar *et al.*, 2022). Additionally, livestock holds significant cultural and social value across communities (Cheng *et al.*, 2022). However, this critical sector is increasingly threatened by the climate crisis. Rising temperatures, prolonged droughts, erratic rainfall patterns and an increased frequency of extreme weather events are pushing traditional livestock systems to their limits.

The scientific consensus is unequivocal: climate change is occurring and poses a significant threat, already affecting agricultural sectors worldwide, particularly the productivity of livestock (Singh *et al.*, 2024). These changes manifest as heat stress, water scarcity and the emergence of novel diseases, directly impacting productivity, fertility and survival rates (Oke *et al.*, 2024; Singh *et al.*, 2024). The sector is vulnerable in two primary ways: first, through the direct impacts of climate change on livestock production and performance and second, through the necessity for the sector to adapt its operations to mitigate these effects (Cheng *et al.*, 2022).

Climate-resilient livestock breeding has thus shifted from being a mere option to a strategic necessity. It moves beyond short-term, reactive mitigation to a proactive, long-term strategy of genetic adaptation. By integrating heat-tolerant, drought-resistant and disease-adapted breeds, livestock producers can stabilize performance, reduce climate-related losses and protect long-term profitability. The present paper outlines the challenges, explores cutting-edge strategies from genomics and nutrition to advanced housing and decision support systems and charts a pathway for India to build a robust, productive and sustainable livestock sector capable of weathering future climate shocks.

2. The Burden of Climate Change on Indian Livestock

Climate change affects livestock through both direct and indirect pathways (Cheng *et al.*, 2022; Singh *et al.*, 2024). The impacts are multifaceted and demand urgent attention:

Heat Stress: This is the most immediate and measurable threat. Heat stress, a major consequence of environmental changes during extreme summer months in arid tropical regions, occurs when animals are unable to dissipate excess body heat, leading to physiological and behavioral changes that negatively impact their performance (Cheng *et al.*, 2022). This includes reduced dry matter intake, decreased milk production and altered milk composition, poor growth rates and compromised reproductive function in both males and females—a phenomenon often termed "summer sterility" (Para *et al.*, 2108; Cheng *et al.*, 2022). Furthermore, heat stress weakens the immune system, impairing passive immunity transfer and reducing colostrum quality, thereby increasing susceptibility to diseases and compromising animal welfare (Cheng *et al.*, 2024; Sejian *et al.*, 2022).

Indirect Impacts: Climate change also affects the quantity and quality of feed and fodder. Elevated CO₂ levels can increase lignin formation in plant tissues, reducing digestibility (NAAS, 2016). Shrinking grazing lands due to land-use change and competition for resources further exacerbate these challenges.

Disease Dynamics: Changing climate patterns influence the distribution and prevalence of pathogens and vectors. High ambient temperature and humidity favor the growth of microorganisms responsible for infections such as mastitis, a major constraint in the dairy industry leading to substantial economic losses (Panghal *et al.*, 2025; Bourabah *et al.*, 2013). The emergence of novel diseases and the increased incidence of existing ones pose a constant threat to herd health.

GHG Emissions: The livestock sector is a significant contributor to global greenhouse gas (GHG) emissions, primarily methane from enteric fermentation and nitrous oxide from manure management (Cheng *et al.*, 2022). This creates a complex feedback loop, as the sector both contributes to and is victimized by climate change, necessitating mitigation strategies alongside adaptation efforts.

3. Strategies for Climate-Resilient Livestock Production

Building resilience requires a multi-pronged approach, integrating traditional knowledge with modern science. The goal is to create a system that can not only survive but thrive under stress.

3.1. Genetic Selection and Breeding Management

The foundation of resilience lies in the animal's genetic makeup. The shift from reactive management to proactive genetic adaptation is the core of climate-smart breeding (Bilotto *et al.*, 2024; Oke *et al.*, 2024).

Selecting for Adaptive Traits: Traditional selection focused heavily on high production under optimal conditions. Today, the focus must expand to include fitness traits like heat tolerance, disease resistance, feed efficiency and efficient water use (Oke *et al.*, 2024; Chaudhary *et al.*, 2025). Animals expressing these traits maintain more stable production levels during environmental stress.

Leveraging Indigenous Breeds: India's indigenous breeds, such as Sahiwal cattle and Harnali and Munjal sheep, represent invaluable genetic capital, having evolved over centuries to thrive in local, often harsh, environments (Chaudhary *et al.*, 2025; Malik *et al.*, 2024; Mehla *et al.*, 2013). Research has demonstrated that these breeds possess unique genetic adaptations, including heat shock protein pathways for thermotolerance and specific genes linked to production, reproduction and disease resistance (Chaudhary *et al.*, 2025; Mehla *et al.*, 2013). Furthermore, indigenous sheep breeds exhibit genetic diversity in key milk protein genes that influence milk yield, composition and udder conformation, highlighting their untapped potential for dairy production (Malik *et al.*, 2024).

Marker-Assisted Selection (MAS) for Enhanced Production and Health: The discovery of specific single nucleotide polymorphisms (SNPs) in key genes has provided a powerful toolkit for genetic improvement. Research has identified genetic markers associated with:

Milk Production and Udder Traits: Polymorphisms in the β -Lactoglobulin (β -LG) gene in sheep have been significantly associated with milk yield, fat and protein percentages and udder conformation traits, offering a direct route for selecting animals with superior dairy potential (Malik *et al.*, 2024).

Disease Resistance: Variants in immune-related genes such as *BRCA1* and *MBL1* in cattle and buffalo and *TLR2* in goats, have been linked to reduced susceptibility to clinical mastitis and lower somatic cell scores, providing markers for breeding healthier, more resilient animals (Magotra *et al.*, 2020; Kamaldeep *et al.*, 2021; Panghal *et al.*, 2025).

Balanced Selection: Some studies have revealed trade-offs, where genotypes associated with higher milk production may also be more susceptible to disease (Magotra *et al.*, 2020). This underscores the critical need for balanced selection indices that optimize both production and resilience traits simultaneously.

Crossbreeding for Hybrid Vigor: Strategic crossbreeding can combine the resilience of indigenous breeds with the high productivity of exotic breeds, as seen in the development of Harnali sheep and Hardhenu cattle (Malik *et al.*, 2024; Pushpa *et al.*, 2023). However, such programs must be carefully managed to preserve the adaptive traits of the indigenous parent. Climate-resilient genotypes, such as *Bos indicus* breeds, have also been shown to have significantly lower water requirements compared to *Bos taurus* breeds, a crucial trait for drought-prone regions (Ahlberg *et al.*, 2019; Hooper *et al.*, 2019).

Advanced Genetic Tools (Genomics): The "omics" era provides powerful tools to accelerate

genetic gain. Genome-wide selection signatures can pinpoint regions under strong selective pressure, identifying genes critical for adaptation (Chaudhary *et al.*, 2025). Genomic selection, using genome-wide markers to estimate breeding values, is particularly useful for selecting low-heritability traits like disease resistance and for shortening breeding cycles (Oke *et al.*, 2024). The success of these tools, however, depends on robust data integration from sensors, performance records and genetic analysis (Bilotto *et al.*, 2024).

3.2. Nutrition and Immunomodulation

Genetics provides the potential, but nutrition unlocks it. Climate-appropriate nutrition is essential for supporting the genetic potential of resilient breeds (Oke *et al.*, 2024; Singh *et al.*, 2024).

Climate-Smart Feeding: This involves using water-efficient forage crops, drought-tolerant pastures and locally available feed resources. Adjusting rations to include energy-dense, easily digestible feed during heat stress reduces metabolic heat production. Alternate feeding regimes, such as feeding during cooler periods, can also minimize heat load (Cheng, M., *et al.*, 2022).

Dietary Supplements and Nutraceuticals: Nutritional interventions can help animals cope with stress. Immunomodulators like probiotics, prebiotics and ascorbic acid can reduce heat stress and boost immune function (Oke *et al.*, 2024). Phytogetic feed additives support gut health and reduce oxidative stress, while electrolyte and vitamin supplementation in water helps maintain hydration and thermoregulation (Cheng, M., *et al.*, 2022; Oni *et al.*, 2024).

Feed Efficiency and Low-Carbon Footprint: Selecting for feed efficiency—animals that produce more per unit of feed—directly reduces the carbon footprint per unit of production. Research on Residual Feed Intake (RFI) is critical for identifying animals with lower feed requirements and consequently lower methane emissions (Bilotto *et al.*, 2024). Optimizing rumen function through diet to reduce enteric methane production is another key mitigation strategy.

3.3. Advanced Health Monitoring and Housing Management

Even the most resilient animal can be overwhelmed by extreme conditions without adequate management. Advanced monitoring systems and housing designs are essential for early detection and mitigation.

Infrared Thermography (IRT) for Health Monitoring: As a non-invasive, real-time tool, IRT aligns perfectly with precision livestock farming principles. Research has demonstrated its efficacy in detecting udder inflammation (mastitis) through localized temperature variations, showing strong correlations with conventional tests and offering a rapid, labor-saving method for routine herd health monitoring, particularly in late lactation (Panghal *et al.*, 2025). Beyond mastitis, thermal imaging can be used to detect early-stage heat stress and identify sick animals through thermal anomalies, enabling prompt intervention.

Thermal Imaging Camera-Based Modules: Integrating IRT into fixed or mobile systems allows for:

Early Detection: Identifying elevated body temperatures before visible signs of distress appear.

Automated Alerts: AI-powered systems can automatically alert farm managers when an animal's temperature exceeds a threshold.

Housing Assessment: Monitoring the effectiveness of cooling systems and identifying poorly ventilated or shaded areas.

Advanced Housing Design: Modern housing must prioritize natural or forced ventilation, ample

shade and cooling technologies like misters and fans to mitigate heat stress (Cheng *et al.*, 2022).

Decision Support Systems (DSS) for Farmers: The complexity of climate adaptation requires integrated decision-making tools. A robust DSS would integrate multiple data streams—weather forecasts, animal genetics (including marker information), real-time physiological data (from sensors and IRT), health records and farm resources—to provide farmers with actionable, real-time recommendations for feeding, breeding and health management, thereby enhancing adaptive capacity (Bilotto *et al.*, 2024).

4. Research Frontiers for Sustainable Production

To achieve truly sustainable and climate-resilient production, research must focus on several key areas.

Residual Feed Intake (RFI) and Feed Efficiency: Continued research is needed to identify the genomic basis of RFI, develop low-cost phenotyping methods and understand the relationship between feed efficiency and other important traits like fertility and disease resistance to avoid negative trade-offs (Bilotto *et al.*, 2024).

Disease Resistance and Immunology: Expanding genomic studies to identify markers for resistance to a wider range of climate-sensitive diseases is crucial. Research on immunogenomics—understanding how climate stress impacts the immune system at a molecular level—will be vital for developing resilient immune phenotypes and effective vaccines (Panghal *et al.*, 2025; Magotra *et al.*, 2020; Kamaldeep *et al.*, 2021).

Small Ruminant Production Systems: Given the importance of goats and sheep in India, focused research is needed to validate genetic markers for milk production, udder conformation and heat tolerance across a wider range of indigenous breeds and agro-climatic zones (Malik *et al.*, 2024; Panghal *et al.*, 2025). Integrating IRT with genomic information for comprehensive health and productivity monitoring in small ruminants represents a promising frontier.

Water Efficiency: Characterizing the genetic basis of water intake and identifying physiological markers for water-use efficiency are critical for breeding animals suited to drought-prone regions (Ahlberg *et al.*, 2019).

Alternate Feeding Regimes and Circular Systems: Research must focus on evaluating the nutritional value and GHG mitigation potential of unconventional feeds (e.g., agro-industrial by-products, seaweeds) and developing integrated crop-livestock systems that recycle nutrients and reduce reliance on high-footprint feeds (Bilotto *et al.*, 2024; Black *et al.*, 2021).

Reducing Carbon Footprint: Life cycle assessments are needed to identify GHG hotspots in different Indian production systems. Scaling up promising methane mitigation interventions (feed additives, breeding for low methane) and promoting carbon sequestration in grazing lands through improved management are essential pathways to net-zero livestock production (Bilotto *et al.*, 2024; Sándor *et al.*, 2020).

5. The Way Forward: Challenges and Opportunities for Viksit Bharat

Achieving a climate-resilient livestock sector requires a concerted effort to address critical gaps and harness opportunities.

5.1. Addressing Critical Gaps

Gap	Impact	Way Forward
Uncharacterized Indigenous Breeds	Inability to fully utilize the genetic potential of native breeds for climate adaptation.	Establish a National Gene Bank Repository linked to phenotypic and climate data for all registered indigenous breeds.
Lack of Standardized Phenotypic Data	Absence of robust data on heat stress responses, disease incidence and reproductive performance under varied climates.	Create a National Database using digital/sensor-based technologies (including IRT) for large-scale, standardized phenotyping across breeds and regions. For future implementation of Artificial intelligence-based support systems for farmers
Limited Understanding of Genotype-Environment Interactions (GxE)	Inability to predict breed or crossbred performance across different agro-ecological zones.	Develop GxE Models using advanced statistical and machine learning techniques.
Antimicrobial Resistance (AMR)	Increased disease incidence under climate stress leads to higher antibiotic use and AMR risk.	Promote AMR Stewardship by focusing on genetic selection for disease resistance (using markers validated on local breeds like <i>BRCA1</i> , <i>MBL1</i> , <i>TLR2</i>) and improved management to reduce disease incidence (Magotra <i>et al.</i> , 2020; Kamaldeep <i>et al.</i> , 2021; Panghal <i>et al.</i> , 2025).
Trade-offs Between Production and Resilience	Selection for high production can inadvertently increase disease susceptibility.	Develop Balanced Selection Indices that weigh production traits against health, fertility and longevity (Magotra <i>et al.</i> , 2020).

5.2. Harnessing Opportunities

Sensor-Based Solutions and Startups: Encourage agri-tech startups to develop affordable, AI-powered sensor solutions (wearables, thermal cameras) and decision support platforms for Indian farmers.

Data Integration and Digital Twins: Invest in the development of "digital twins" virtual farm replicas to simulate outcomes of different management decisions by integrating data from sensors, genetics, nutrition and environment, enabling virtual testing and optimization of interventions (Bilotto *et al.*, 2024).

Strengthening Extension Services: Equip extension services with the latest knowledge on climate-smart practices, including the use of genetic markers, DSS and IRT, delivered in accessible formats to farmers.

Conclusion

India stands at a pivotal moment where its livestock sector can drive inclusive growth, resilience, and sustainability. Transforming this sector is central to achieving the vision of Viksit Bharat, as it directly supports livelihoods, nutrition, and rural prosperity. Harnessing the strength of indigenous breeds alongside advanced genomic tools can enhance productivity and disease resistance while preserving adaptability. Climate-smart feeding, precision management, and technologies such as thermal imaging and decision support systems will enable farmers to make informed, efficient choices. A coordinated approach involving scientists, policymakers, industry, and farmers will accelerate innovation and bridge critical knowledge gaps. Strengthening extension

systems, promoting data-driven practices, and ensuring access to modern technologies will empower smallholders and improve outcomes. With focused policy support and collective action, the livestock sector can evolve into a future-ready system that delivers economic growth, environmental sustainability, and nutritional security for the nation.

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Chapter-9

Reimagining Agriculture through Entrepreneurship and Startups in Jammu & Kashmir`

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ABSTRACT

Agriculture remains a critical driver of livelihoods in Jammu & Kashmir, yet it faces persistent challenges such as fragmented landholdings, weak market linkages and limited value addition. This study examines the role of agri-entrepreneurship and startups in transforming the agricultural sector through improved market integration, innovation and sustainability. Drawing on secondary data and policy analysis, the paper highlights how digital platforms, value chain interventions and institutional support mechanisms enhance farmer income and reduce inefficiencies. Initiatives such as Startup India, RKVY-RAFTAAR and the Jammu and Kashmir Competitiveness Improvement Project play a significant role in strengthening the agri-startup ecosystem. The findings indicate that startups can improve price realization, reduce post-harvest losses and promote sustainable agricultural practices. However, constraints related to finance, infrastructure and digital literacy persist. The study concludes that a coordinated policy approach is essential to scale agri-entrepreneurship and ensure inclusive and resilient agricultural development.

Keywords: *Agri-entrepreneurship; Agricultural startups; Market linkages; Value chain development; Sustainable agriculture*

1. Introduction

Agriculture continues to play a pivotal role in the socio-economic development of India, contributing approximately 17–18% to the Gross Domestic Product (GDP) while providing livelihood support to nearly 45–46% of the country's workforce (Government of India, 2024; World Bank, 2023). Despite rapid structural transformation, the sector remains central to ensuring food security, rural employment and poverty alleviation, particularly in economies dominated by smallholder farming systems (Food and Agriculture Organization, 2018). India's agricultural structure is predominantly characterized by small and marginal farmers, accounting for more than 85% of total holdings, with an average farm size of approximately 1.08 hectares (Agricultural Census, 2021). These structural limitations restrict economies of scale, limit access to mechanization and reduce farmers' bargaining power in markets. Additionally, inefficiencies in agricultural marketing systems such as fragmented supply chains, multiple intermediaries and inadequate storage infrastructure result in post-harvest losses ranging from 6% to 18% and suboptimal price realization (World Bank, 2021). In the Union Territory of Jammu & Kashmir (J&K), agriculture and allied sectors hold even greater significance due to the region's diverse agro-climatic conditions, mountainous terrain and dependence on horticulture-based livelihoods. Crops such as apple, walnut, saffron and basmati rice contribute substantially to the regional economy (Government of J&K, 2023). However, the sector faces persistent challenges including geographical isolation, fragmented landholdings, weak market linkages and limited value addition infrastructure, particularly in remote and hilly areas.

To address these structural bottlenecks and promote inclusive agricultural development, targeted interventions such as the Jammu and Kashmir Competitiveness Improvement Project have

been implemented. Supported by the International Fund for Agricultural Development (IFAD), JKCIP focuses on enhancing market access, value chain development and livelihood diversification in selected districts of Jammu & Kashmir. The programme promotes the formation and strengthening of Farmer Producer Organizations (FPOs), supports agribusiness development and facilitates linkages between farmers and markets. By encouraging entrepreneurship, improving infrastructure and strengthening institutional capacity, JKCIP plays a crucial role in fostering a more competitive and market-oriented agricultural system in the region (IFAD, 2022).

In recent years, agri-entrepreneurship and startup-led innovations have emerged as transformative drivers in addressing systemic inefficiencies within the agricultural sector. Agri-startups are redefining the value chain through the integration of digital platforms, precision agriculture, supply chain innovations and direct marketing models, thereby improving efficiency and farmer income (NITI Aayog, 2022). India's agri-startup ecosystem has expanded rapidly, supported by flagship initiatives such as Startup India and RKVY-RAFTAAR, which provide financial assistance, incubation support and policy incentives.

Furthermore, agri-startups contribute significantly to the development of sustainable and resilient food systems by promoting climate-smart agriculture, efficient resource utilization and reduction of food losses (FAO, 2018). The integration of traditional knowledge systems with modern technologies is particularly relevant in ecologically fragile regions like Jammu & Kashmir, where sustainability and resilience are critical. Against this backdrop, the present study examines the role of agri-entrepreneurship and startups in transforming agriculture in Jammu & Kashmir, with a specific focus on strengthening market linkages, enhancing value addition and promoting sustainable agricultural practices. It also highlights the role of institutional interventions such as JKCIP in building a robust and inclusive agri-entrepreneurial ecosystem.

2. Agri-Entrepreneurship and Startups

Agri-entrepreneurship represents a paradigm shift from subsistence-oriented farming to a market-driven, innovation-led agricultural system, where farmers and rural youth actively engage in value addition, agribusiness development and supply chain integration. In recent years, the rise of agri-startups has significantly transformed the agricultural landscape in India by introducing technology-enabled solutions, digital platforms and innovative business models across the value chain (NITI Aayog, 2022).

India's agri-startup ecosystem has experienced rapid growth, expanding from a few hundred startups in the early 2010s to several thousand enterprises operating across diverse domains such as input delivery, farm mechanization, precision agriculture, post-harvest management, logistics and e-commerce platforms. These startups are increasingly leveraging emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT), remote sensing and blockchain to enhance productivity, optimize resource use and improve supply chain transparency (World Bank, 2021).

Government initiatives such as Startup India and RKVY-RAFTAAR have played a catalytic role in strengthening this ecosystem by providing financial support, incubation facilities, mentoring and market access opportunities. Under these programs, more than 1,000 agri-startups have received incubation and financial assistance, contributing to the development of a vibrant innovation ecosystem (Government of India, 2024).

Agri-startups are also contributing significantly to income enhancement and employment generation. Studies indicate that the adoption of agritech solutions can increase farmers' incomes by 20–35% through improved efficiency, reduced transaction costs and better price realization

(IFAD, 2022; World Bank, 2021). Furthermore, these enterprises are generating employment opportunities for rural youth, particularly in areas such as processing, logistics, digital services and agribusiness management, thereby addressing the issue of rural unemployment and migration.

In the context of Jammu & Kashmir, agri-entrepreneurship holds immense potential due to the region’s comparative advantage in high-value horticultural crops, medicinal plants and niche products. Startups and entrepreneurial ventures can facilitate value addition through grading, packaging, branding and processing, enabling farmers to access premium markets. Institutional support from agricultural universities, especially SKUAST-Jammu, along with programs like the Jammu and Kashmir Competitiveness Improvement Project, is playing a crucial role in nurturing entrepreneurial capacity and strengthening value chains in the region.

Moreover, agri-startups are increasingly integrating Farmer Producer Organizations (FPOs) into their business models, enabling collective action, aggregation of produce and improved bargaining power. This integration enhances market efficiency and ensures better price realization for farmers, particularly in geographically challenging regions like Jammu & Kashmir.

Table 1: Key Domains of Agri-Startups in India

Domain	Functions	Evidence from Literature
Input Supply	Seeds, fertilizers, advisory	Improves productivity and input efficiency
Farm Technology	AI, IoT, precision tools	Enhances resource optimization
Post-Harvest	Storage, grading, processing	Reduces post-harvest losses
Logistics	Supply chain, cold storage	Improves market access
Market Platforms	Digital marketing, F2C	Enhances price realization

Source: Compiled by authors based on National Institution for Transforming India (2022), World Bank (2021) and Food and Agriculture Organization (2018).

Table 2: Impact of Agri-Startups on Farmers’ Income

Indicator	Traditional System	Startup-enabled System
Input Cost	High	Optimized
Productivity	Moderate	Increased
Price Realization	Low	Higher (20–35%)
Market Access	Limited	Expanded
Risk	High	Reduced

Source: Compiled and adapted from World Bank (2021); International Fund for Agricultural Development (2022); and Government of India (2024).

3. Market Linkages and Value Chain Development

Market linkages play a critical role in determining the profitability and sustainability of agricultural systems, particularly in regions dominated by smallholder farmers. Efficient linkages ensure that farmers are connected to input markets, output markets, financial services and advisory systems, thereby improving productivity and income realization. In India, however, traditional agricultural marketing systems are often characterized by fragmented supply chains, multiple intermediaries and information asymmetry, which significantly reduce farmers’ share in consumer prices (World Bank, 2021).

In the context of Jammu & Kashmir, the importance of robust market linkages is even more pronounced due to geographical constraints, poor connectivity in hilly terrains and limited access to organized markets. Farmers in remote areas often rely on local traders or intermediaries, resulting in distress sales and lower price realization, particularly for perishable horticultural produce such as apples, vegetables and flowers (Government of J&K, 2023).

Agri-startups and institutional interventions are increasingly addressing these challenges by strengthening both forward and backward linkages within the agricultural value chain. Backward linkages involve access to quality inputs, credit, insurance and extension services, while forward linkages focus on aggregation, processing, transportation and market access (Food and Agriculture Organization, 2018).

Digital platforms and agritech startups have emerged as key enablers of market integration. These platforms provide real-time price information, demand forecasting, digital payments and direct farmer-to-consumer (F2C) marketing channels, thereby reducing dependence on intermediaries. Evidence suggests that farmers connected to digital and organized market platforms can achieve 15–30% higher price realization compared to traditional marketing channels (NITI Aayog, 2022; World Bank, 2021).

Furthermore, improvements in post-harvest management and logistics, including cold storage facilities, grading, packaging and transportation, play a crucial role in reducing post-harvest losses, which are estimated to range between 6% and 18% in India (World Bank, 2021). In horticulture-dominated regions like Jammu & Kashmir, investments in cold chain infrastructure can significantly enhance shelf life and enable access to distant and high-value markets.

Institutional initiatives such as the Jammu and Kashmir Competitiveness Improvement Project have been instrumental in strengthening value chains by promoting Farmer Producer Organizations (FPOs), aggregation models and market-oriented production systems. By facilitating collective marketing and improving bargaining power, FPOs help farmers achieve better price realization and reduce transaction costs (IFAD, 2022).

Value addition is another critical component of market linkage development. Activities such as processing, branding, packaging and certification (e.g., organic, GI tagging) enhance the market value of agricultural products and open opportunities for accessing premium markets. In Jammu & Kashmir, value addition in products such as apple, walnut, saffron and rajmash holds significant potential for income enhancement and export promotion.

Table 3: Components of Agricultural Market Linkages

Linkage Type	Components	Functional Role
Backward Linkages	Inputs, credit, advisory services	Enhance productivity
Forward Linkages	Aggregation, processing, marketing	Improve income
Institutional Linkages	FPOs, cooperatives, govt schemes	Collective strength
Digital Linkages	e-markets, apps, platforms	Transparency & efficiency

Source: Compiled by authors based on Food and Agriculture Organization (2018); World Bank (2021); NITI



Figure: Aayog(2022).

1: Value Chain Strengthening through Startups in Agriculture

A conceptual framework illustrating the role of agri-startups, Farmer Producer Organizations (FPOs) and digital platforms in strengthening agricultural value chains. The model highlights the integration of key stages—input supply, production, aggregation, processing, logistics and marketing—leading to improved market access, enhanced value addition and increased farmer income. Supporting elements such as innovation, institutional mechanisms and government schemes act as enablers for a more efficient and sustainable agricultural ecosystem.

4. Institutional Support and Ecosystem

The growth of agri-entrepreneurship and startup-led innovations in India is strongly supported by an evolving institutional and policy ecosystem, which plays a crucial role in enabling access to finance, technology, markets and capacity building. One of the key initiatives is Startup India, which provides a comprehensive framework for promoting entrepreneurship through tax incentives, funding support, ease of doing business and incubation facilities. Complementing this, RKVY-RAFTAAR specifically targets the agriculture sector by supporting startups through seed funding, incubation, mentoring and agribusiness development programs. Under this scheme, selected agri-startups receive financial assistance of up to ₹25 lakh along with technical and business support (Government of India, 2024). In addition, the role of financial institutions such as National Bank for Agriculture and Rural Development is critical in strengthening the rural entrepreneurial ecosystem. It facilitates credit flow, rural infrastructure development and promotion of Farmer Producer Organizations (FPOs). The Government of India has also launched a dedicated scheme for the formation and promotion of 10,000 FPOs, aimed at enhancing collective action, improving market access and increasing farmers’ bargaining power (NABARD, 2024).

In the Union Territory of Jammu & Kashmir, the institutional ecosystem has been further strengthened through region-specific policies and programs. The J&K Startup Policy (2024–27) provides targeted support to startups through seed funding, venture capital assistance, patent support and incubation services, thereby creating a conducive environment for innovation and entrepreneurship. Agricultural universities, particularly SKUAST-Jammu, are playing a pivotal role by establishing agribusiness incubation centers, offering training, mentorship and technology

transfer to aspiring entrepreneurs. A significant intervention in the region is the Jammu and Kashmir Competitiveness Improvement Project, supported by the International Fund for Agricultural Development (IFAD). The project focuses on value chain development, FPO strengthening, market linkage creation and livelihood diversification. By promoting entrepreneurship and facilitating access to markets, JKCIP contributes to building a more competitive and inclusive agricultural economy in Jammu & Kashmir (IFAD, 2022). Furthermore, digital initiatives such as e-NAM (National Agriculture Market) and other agritech platforms are enhancing market transparency, price discovery and direct marketing opportunities, thereby reducing inefficiencies in agricultural marketing systems. Public–private partnerships (PPPs) are also emerging as effective mechanisms for improving infrastructure, particularly in areas such as cold storage, logistics and processing facilities.

Table 4: Key Institutional Support Mechanisms for Agri-Entrepreneurship

Institution/Scheme	Type of Support	Impact
Startup India	Policy, tax benefits, funding	Promotes entrepreneurship
RKVY-RAFTAAR	Seed funding, incubation	Supports agri-startups
NABARD	Credit, FPO promotion	Strengthens rural economy
JKCIP	Value chains, FPOs, market linkages	Enhances competitiveness
SKUAST-Jammu	Training, incubation, R&D	Capacity building

Source: Compiled by authors based on National Bank for Agriculture and Rural Development (2024); IFAD (2022); Government of India (2024).

Table 5: Policy Interventions and Their Outcomes

Policy Area	Intervention	Outcome
Finance	Startup funding, subsidies	Increased investment
Infrastructure	Cold chains, logistics	Reduced losses
Capacity Building	Training, incubation	Skill development
Digitalization	e-platforms, apps	Market transparency
Institutional Support	FPOs, PPPs	Collective strength

Source: Adapted from NITI Aayog (2022); NABARD (2024); World Bank (2021).

5. Sustainable Food Systems

The concept of sustainable food systems has gained increasing prominence in recent years, particularly in the context of climate change, resource degradation and growing food demand. A sustainable food system is defined as one that ensures food security and nutrition for all while minimizing environmental impact, enhancing economic viability and promoting social equity (Food and Agriculture Organization, 2018). Agriculture is both a contributor to and a victim of environmental challenges. Globally, the agricultural sector accounts for approximately 20–25% of total greenhouse gas (GHG) emissions, primarily due to activities such as livestock production, fertilizer use and land-use change (IPCC, 2022). In regions like Jammu & Kashmir, where agriculture is closely linked with fragile ecosystems, the need for climate-resilient and resource-efficient farming practices becomes even more critical.

Agri-startups and entrepreneurial innovations are playing a transformative role in promoting sustainability by introducing climate-smart technologies, precision agriculture tools and efficient resource management practices. These include the use of IoT-based irrigation systems, remote sensing for crop monitoring and AI-driven advisory services, which help optimize the use of water, fertilizers and energy (World Bank, 2021). Such interventions can lead to 10–20% savings in water use and improved input efficiency, thereby reducing environmental stress. In addition, startups are actively promoting organic farming, natural farming and residue-free production systems, which not only reduce chemical inputs but also fetch premium prices (20–30% higher) in niche markets (FAO, 2018). In Jammu & Kashmir, the promotion of organic products such as saffron, rajmash and traditional crops presents significant opportunities for sustainable agriculture and export growth.

Another critical dimension of sustainable food systems is the reduction of post-harvest losses and food waste, which remain a major challenge in developing countries. Inefficient supply chains, lack of cold storage and inadequate processing facilities result in significant losses, particularly for perishable commodities. Agri-startups are addressing this issue through innovations in cold chain logistics, storage solutions and supply chain optimization, thereby enhancing efficiency and sustainability. Institutional interventions such as the Jammu and Kashmir Competitiveness Improvement Project further contribute to sustainability by promoting diversified livelihoods, climate-resilient practices and value chain development in rural areas. By integrating sustainability with entrepreneurship, such programs help build resilient agricultural systems capable of withstanding climatic and market uncertainties (IFAD, 2022).

Moreover, the integration of traditional knowledge systems with modern technologies is particularly relevant in the context of Jammu & Kashmir, where indigenous practices have historically supported ecological balance. Combining these practices with scientific innovations can enhance sustainability while preserving cultural heritage.

Table 6: Role of Agri-Startups in Promoting Sustainable Agriculture

Intervention	Description	Impact
Precision Agriculture	AI, IoT, remote sensing	Resource efficiency
Organic Farming	Chemical-free production	Premium pricing
Cold Chain Systems	Storage & logistics	Reduced food losses
Digital Advisory	Real-time guidance	Improved productivity
Climate-Smart Practices	Water & soil conservation	Environmental sustainability

Source: Compiled by authors based on Food and Agriculture Organization (2018); World Bank (2021); IFAD (2022).

6. Challenges and Constraints

Despite the significant potential of agri-entrepreneurship and startup-led innovations in transforming agriculture, the ecosystem continues to face several structural, institutional, financial and socio-economic challenges. These constraints are particularly pronounced in regions like Jammu & Kashmir, where geographical isolation and infrastructural limitations further complicate agricultural development. One of the major challenges is limited access to finance, especially for early-stage agri-startups. Unlike technology startups, agribusiness ventures often involve longer

gestation periods and higher risks due to weather variability, market fluctuations and biological uncertainties, making them less attractive to private investors (World Bank, 2021). Although schemes like Startup India and RKVY-RAFTAAR provide financial support, access remains uneven, particularly in remote and hilly regions.



Another critical constraint is the inadequacy of rural infrastructure, including poor road connectivity, lack of cold storage facilities and weak logistics networks. These infrastructural gaps result in high transaction costs and significant post-harvest losses, particularly for perishable commodities such as fruits and vegetables. In Jammu & Kashmir, difficult terrain and climatic conditions further exacerbate these challenges, limiting market access for farmers and entrepreneurs (Government of J&K, 2023).

Digital literacy and technology adoption also remain key barriers. While digital platforms and agritech solutions are expanding rapidly, a large proportion of farmers, especially smallholders, lack the necessary skills and awareness to effectively utilize these technologies. This digital divide restricts the scalability and impact of agri-startups, particularly in rural and underserved areas (Food and Agriculture Organization, 2018). Regulatory and institutional challenges further hinder the growth of agri-startups. Complex procedures related to business registration, licensing, compliance and taxation can discourage new entrepreneurs. Additionally, limited coordination among government agencies, financial institutions and market players often leads to inefficiencies in policy implementation (NITI Aayog, 2022).

Climate change and environmental risks represent another significant challenge. Increasing frequency of extreme weather events, erratic rainfall patterns and temperature fluctuations adversely affect agricultural productivity and increase uncertainty for agri-startups operating in the sector (IPCC, 2022). In ecologically sensitive regions like Jammu & Kashmir, these risks are even more pronounced. Moreover, the lack of skilled human resources and entrepreneurial capacity in rural areas limits the growth of agribusiness ventures. Although programs such as the Jammu and Kashmir Competitiveness Improvement Project are addressing these gaps through training and capacity building, the scale of intervention needs to be significantly expanded to achieve widespread impact (IFAD, 2022).

Table 7: Major Challenges in the Agri-Startup Ecosystem

Category	Key Challenges	Implications
Financial	Limited access to capital, high risk	Slow startup growth
Infrastructure	Poor roads, lack of cold storage	High losses & costs
Technological	Low digital literacy	Limited adoption of innovations
Institutional	Regulatory hurdles, weak coordination	Delayed implementation
Environmental	Climate risks, resource degradation	Increased uncertainty
Human Capital	Skill gaps, low awareness	Reduced entrepreneurial activity

Source: Compiled by authors based on World Bank (2021); Food and Agriculture Organization (2018); NITI Aayog (2022); IFAD (2022).

Table 8: Challenges Specific to Jammu & Kashmir

Dimension	Issues
Geography	Hilly terrain, poor connectivity
Market Access	Limited organized markets
Infrastructure	Inadequate storage & logistics
Awareness	Low digital and entrepreneurial literacy
Institutional Reach	Limited penetration of schemes

Source: Adapted from Government of J&K (2023); IFAD (2022).

7. Policy Recommendations

Addressing the challenges faced by the agri-startup ecosystem requires a multi-dimensional and coordinated policy approach involving government agencies, financial institutions, research organizations and private sector stakeholders. Strategic interventions must focus on improving access to finance, infrastructure development, capacity building, digital inclusion and institutional strengthening, particularly in regions like Jammu & Kashmir. One of the foremost priorities is to enhance access to finance for agri-startups and rural entrepreneurs. Establishing dedicated agri-startup funds at the state or district level, along with expanding credit guarantees and venture capital support, can help reduce financial barriers. Institutions such as National Bank for Agriculture and Rural Development can play a pivotal role in facilitating credit linkages, refinancing and risk mitigation mechanisms (NABARD, 2024). Strengthening rural infrastructure is equally critical. Investments in cold chain systems, storage facilities, rural roads and logistics networks can significantly reduce post-harvest losses and improve market access. Public-private partnerships (PPPs) should be encouraged to mobilize resources and enhance efficiency in infrastructure development (World Bank, 2021). Initiatives aligned with Startup India can further accelerate digital transformation in agriculture. Capacity building and skill development are essential for fostering entrepreneurship in rural areas. Agricultural universities, including SKUAST-Jammu, should strengthen agribusiness incubation centers, entrepreneurship training programs and extension services to equip farmers and rural youth with the necessary skills. Programs like RKVY-RAFTAAR can be expanded to cover more beneficiaries and regions.

Institutional strengthening through the promotion of Farmer Producer Organizations (FPOs) and cooperatives can enhance collective action and improve market bargaining power. Scaling up successful models under the Jammu and Kashmir Competitiveness Improvement Project can further strengthen value chains and improve market integration in Jammu & Kashmir (IFAD, 2022). Additionally, there is a need to promote cluster-based development approaches, particularly for high-value crops such as apple, saffron, walnut and rajmash. Encouraging women and youth entrepreneurship is another critical dimension of inclusive growth. Targeted interventions such as skill training, financial support and mentorship programs can empower marginalized groups and enhance their participation in agribusiness activities.

Table 9: Strategic Interventions for Strengthening Agri-Startup Ecosystem

Intervention Area	Strategy	Expected Outcome
Finance	Startup funds, credit support	Increased investment
Infrastructure	Cold chains, logistics	Reduced losses
Digitalization	Rural internet, apps	Improved access
Capacity Building	Training, incubation	Skill enhancement
Institutional Strengthening	FPOs, PPPs	Collective efficiency
Cluster Development	Processing hubs	Value addition
Inclusion	Women & youth programs	Inclusive growth

Source: Compiled by authors based on National Bank for Agriculture and Rural Development (2024); World Bank (2021); IFAD (2022); NITI Aayog (2022).



Sustainable Agriculture

Figure 2: Policy–Startup–Impact Linkage in Agricultural Transformation

A conceptual framework illustrating the interrelationship between policy support, startup growth and agricultural outcomes. The model demonstrates how enabling policies and institutional support foster the development of agri-startups, which in turn enhance value chain efficiency through improved technologies, market linkages and supply chain innovations. These improvements lead to increased farmer income and ultimately contribute to the development of a sustainable and resilient agricultural system.

8. Conclusion

The present study highlights the transformative potential of agri-entrepreneurship and startup-led innovations in reshaping the agricultural landscape of Jammu & Kashmir. By strengthening market linkages, enhancing value addition and promoting sustainable practices, agri-startups are emerging as key drivers of income enhancement, employment generation and rural development. The integration of digital technologies, innovative business models and value chain interventions has significantly improved efficiency and reduced traditional bottlenecks in agricultural marketing

systems. Government initiatives such as Startup India and RKVY-RAFTAAR, along with financial and developmental institutions like National Bank for Agriculture and Rural Development, have played a pivotal role in enabling startup growth. Region-specific interventions such as the Jammu and Kashmir Competitiveness Improvement Project further demonstrate how targeted efforts can strengthen value chains, promote Farmer Producer Organizations (FPOs) and enhance market access in geographically challenging regions.

However, the study also identifies several structural challenges, including limited access to finance, infrastructural gaps, low digital literacy and climate-related risks, which continue to constrain the growth of the agri-startup ecosystem. Addressing these challenges requires a coordinated and multi-stakeholder approach, integrating policy reforms, institutional strengthening and technological innovation.

Looking ahead, there is a need to focus on scaling up successful models, particularly those involving FPOs, cluster-based development and startup–farmer linkages. Strengthening rural infrastructure, expanding digital connectivity and enhancing entrepreneurial capacity among youth and women can significantly accelerate the pace of transformation. Additionally, promoting sustainable and climate-resilient agricultural practices must remain a central priority to ensure long-term environmental and economic viability. Future research should focus on empirical evaluation of agri-startup impacts, comparative analysis across regions and assessment of policy effectiveness in different agro-ecological contexts. Such evidence-based insights will be crucial for designing targeted interventions and optimizing resource allocation.

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About SKUAST-Jammu (Host Institute)

Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (SKUAST-Jammu) was established on 20th September, 1999, following an amendment to the Sher-e-Kashmir University of Agricultural Sciences and Technology Act, 1982, enacted by the State Legislature. The creation of the university was driven by a clear vision, strong commitment, and a missionary zeal to address the region-specific needs of the Jammu Division through excellence in education, research, and extension in agriculture and allied sectors.



The University is mandated to undertake basic, strategic, and applied research aimed at enhancing productivity and sustainability in agriculture and allied domains, including livestock health and quality production systems. SKUAST-Jammu continuously strives to achieve high standards of academic and research excellence for the overall development and welfare of the farming community.

SKUAST-Jammu encompasses a diverse range of faculties, namely the Faculty of Agriculture, Faculty of Basic Sciences, Faculty of Veterinary Sciences & Animal Husbandry, Faculty of Horticulture and Forestry, Faculty of Dairy Technology, Faculty of Agricultural Engineering, and the Institute of Biotechnology. As a multi-campus institution, its headquarters are located at Chatha, Jammu. The Chatha campus spans 578 acres, while the R.S. Pura campus covers 84.13 acres. The University's total landholding, including Research Stations, Sub-Stations, and Krishi Vigyan Kendras (KVKs), extends to approximately 1,223 acres.

The University has established a robust extension system to ensure effective transfer of technologies from laboratory to field. Regular scientist–farmer interactions, capacity-building programmes for departmental functionaries, and skill enhancement trainings are integral components of its outreach activities. Technologies developed and refined by the University are disseminated through adaptive trials and frontline demonstrations conducted across its network of nine Krishi Vigyan Kendras.



In addition, SKUAST-Jammu operates ten Research Stations and Sub-Stations strategically located across diverse agro-climatic zones of the Jammu region to address location-specific agricultural challenges. Recognized for its academic and research excellence, SKUAST-Jammu is an ICAR-accredited institution with Grade 'A' status and has been ranked 23rd in the NIRF rankings. The University actively undertakes cutting-edge research supported by coordinated research projects and funding from various national and state agencies, reinforcing its role as a leading institution in advancing agricultural innovation and sustainability.

About Indian Ecological Society

The Indian Ecological Society (IES) was established in 1974 at College of Agriculture, Punjab Agriculture University, Ludhiana, Punjab, India, under Prof. A.S. Atwal, an eminent ecologist, educationist and administrator, as the Founder President. The Society, one of the pioneering organizations of India, is engaged in advances in ecological sciences and environmental protection. It is managed by senior faculty members, assisted voluntarily by scientists from various fields, in addition to their regular assignments. During that era the main emphasis was on increasing production which leads to 'Green Revolution', however, its impact on ecology, natural resource, environment etc. were not the prime issues. These objectives were amended time to time keeping in mind the priority areas in the field of ecology and environment.



Objectives

- To advance the cause of ecology in India
- To encourage and promote ecological studies in the country and to integrate research in different fields of ecology
- To cooperate with organizations with related aims and interests, and provide opportunities for communication among ecologists
- To provide technical know-how for reducing environmental pollution through proper recycling of industrial and agricultural wastes

The Society attempts to fulfill the above objectives by publishing the Indian Journal of Ecology (<https://www.indianjecol.org/>), proceedings and such other publications as may be considered desirable. The journal is considered a premier journal reporting research findings in the field of basic and applied ecology.

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