Indian Journal of Ecology (2022) 49(3) (SI): 1057-1067
DOI: https://doi.org/10.55362/IJE/2022/3634

Manuscript Number:3634
NAAS Rating: 5.79

Phytoremediation: Current Techniques and Futuristic Opportunities

Acharya Balkrishna, Neelam Rawat Dabhade[1], Nidhi Sharma[1], Jyoti Sharma[1], Shalini Mishra[1] and Vedpriya Arya[2*]

Patanjali Organic Research Institute, Haridwar-249 405, India
[1]Patanjali Herbal Research Department, Patanjali Research Institute, Haridwar-249 405, India
[2]Department of Allied Sciences, University of Patanjali, Haridwar-249 405, India
**E-mail: vedpriya.arya@prft.in*

***Abstract*:** Rapid industrialization, current agricultural practices, and other human activities increase the quantity of toxic heavy metals in the atmosphere, which has a significant negative influence on all forms of life, altering their properties. This type of heavy metal pollution is harmful to both the environment and human health. Heavy metal exposure causes nervous system diseases in children by being mutagenic, endocrine disruptive, carcinogenic, and teratogenic. Phytoremediation is also an appropriate approach for the cleanup of water and soil adulteration. Furthermore, it has become increasingly popular. Phytoremediation helps to repair polluted soil and water by extracting and stabilizing polluting heavy metals, a process known as phytoextraction. Phytoremediation has evolved as a practical and successful method for removing a wide spectrum of pollutants in situ in recent years. It is often recognized as a more ecologically friendly alternative to conventional environmental restoration techniques. Significant progress has been made in the remediation of environmental pollutants in recent years. Phytoremediation, despite a number of challenges, is a promising technique with considerable prospective uses. The entire utilization of by-products, as well as the overall economic viability of phytoremediation, will remain the most crucial criteria for global acceptance. The present review looks at the existing status of environmental pollution, as well as the toxicity profiles of crude oil and polycyclic aromatic hydrocarbons (PAHs), global heavy metal leaks, and remediation technologies and applications. It also highlights the recent scientific developments and also, revises plant-based remediation approaches for damaged terrestrial and aquatic environments.

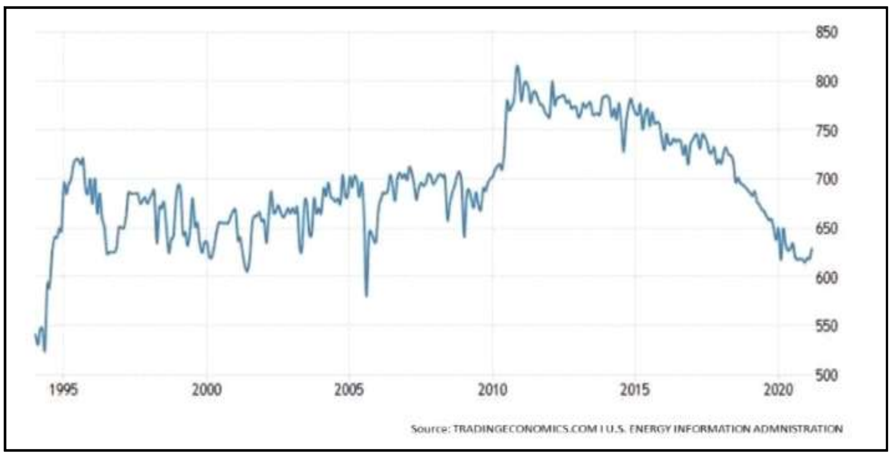
Keywords: PAHs, Heavy metals, Phytoremediation, Microorganisms, Nano-bioremediation

Environmental contaminants are a global problem that impacts both animal and human health. Phytoremediation is a novel approach for detoxifying the environment of hazardous contaminants, and it might be a low-cost, long-term solution for developing countries to improve their economies. It is the technique of reducing the amount of pollutants in the environment or their harmful effects by employing plants and associated soil microbes. Phytoremediation is well-known as a cost-effective environmental restoration method that is a potential alternative to soil-damaging engineering processes (Greipsson 2011). Phytoremediation is frequently employed because of its cost-effectiveness, environmental friendliness, and long-term viability (Emenike et al 2018, Li et al 2020b, Wu et al 2021). Phytoremediation, a green technology, is a method of regulating and conserving the soil medium from heavy metal contamination by using hyperaccumulator plant species (Saxena et al 2020). Plants and microorganisms are used in phytoremediation to remove contaminants from the soil through enzymatic reactions (Greipsson 2011). To clean polluted soils, phytoremediation is frequently employed in waste, agricultural, and industry regions (Urionabarrenetxea et al 2021). The primary goal of phytoremediation is to prevent contaminants from migrating into ecosystems (Wang et al 2020). This ecologically friendly and cost-effective technology works well and has a high tolerance for organic and inorganic contaminants. To increase the effectiveness of collecting and eliminating contaminants from contaminated soil, high biomass species such as herbaceous field crops are utilized (Bhardwaj et al 2014). The economic benefits of phytoremediation, such as biomass production and bioenergy generation, can help to boost the national economy. Plants with a high biomass are typically utilized to make wood and paper (Licht 2005). Human health has become more sensitive to hazardous metals as a result of anthropogenic and occupational activities such as industrial operations, current agricultural methods, untreated chemical waste, and municipal waste management (Rai 2019, Shazia Parveen 2021).

Oil (crude) spills and hydrocarbon contagion: One of the prime elements, causing long-term antagonistic effects on marine and terrestrial lives are oil spills (Mulani et al 2017).

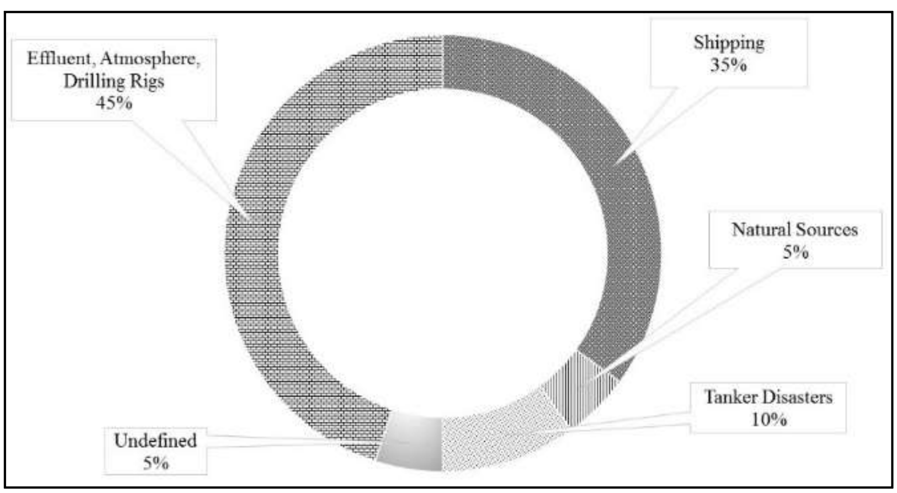
Oceans carry most of the worldwide oil production henceforth, coastal and marine environs are exposed to accidental oil spills (McGenity et al 2012, US EIA 2014). Hydrocarbon segment has been experiencing radical changes worldwide leading to increased industrial activities (Mandal et al 2011). From 1994 to 2021, India's crude oil output averaged 693.53 BBL/D/1K, with a high of 813 BBL/D/1K in 2010 and a low of 526 BBL/D/1K in 1994. The country produced 613.21 BBL/D/1K crude oil in 2021 (Trading Economics 2021). The main hydrocarbon components of crude oil include saturates, aromatics, resins, and asphaltenes. Saturates are categorized into alkanes (paraffin's) and cycloalkanes (naphthenes) on account of their chemical structures (Margesin and Schinner 2001). The presence of one or more aromatic rings distinguishes aromatic fractions. Because of their persistence, mutagenicity, and toxicity, polycyclic aromatic hydrocarbons are a major source of concern (Ovalles et al 2012). Polar compounds make up resins and asphaltenes. Asphaltenes and resins are expected to make up about 10% of the crude oil content (Gaspar et al 2012).

Oil contamination: sources and magnitudes: Natural disasters, oil seepages, incidents with vessels, either collisions or groundings, or from offshore oil platforms, either through human error or due to technical and mechanical faults in oil exploration activities/storage, account for a significant portion of the oil that enters the marine waterways (McKew et al 2007, Mei and Yin 2009, Sheppard et al 2013). Greater threats have been impersonated by marine oil spills, causing widespread damage to the marine coastal environments (Venosa and Zhu 2005). Oil spills will always be a possibility, even of the most advanced technologies in offshore drilling and vessel navigational equipment, necessitating the development of a treatment technique (LaMontagne et al 2004). Prime route-causes of oil spill incidents are given in Figure 2.



Source: www.tradingeconomics; US energy information administration

Fig. 1. Crude oil production in India



Source: World ocean review maribus

Fig. 2. Major route-causes of the oil spill incidents

Prime oil spill occurrences: Inland oil spills have garnered less attention than sea oil spills. Freshwater spills, on the other hand, are fairly prevalent (Fingerman and Nagabhushanam 2005).

Global status: Oil spills have taken place all over the world and even in India (Table 1). During the Gulf War in 1991, the largest oil spill happened in Kuwait (www.cleanerseas.com). The 2010 Gulf of Mexico oil leak is known as the world's greatest unintentional disaster (en.wikipedia.org).

National status: In India, there have been around 70 oil spills near the coast (IMO, 2011). The largest oil leak in India was reported in 2017, with an estimated 800 tonnes of oil spilled. Paradip Port incident, 2009 is another occurrence that has been reported (Bhambi 2013).

Indian hydrocarbon impurity menace: Developing countries, such as India, should be prepared to deal with oil spills in the future (Bhambi 2013). The National Oil Leak Disaster Contingency Plan was first created in India in 1996 (and updated in 2002) with the goal of preventing oil spill disasters in India's Maritime Zones (Fig. 3). The Indian refining industry has done a fantastic job of establishing itself as a worldwide agency (Indian-petroleum-refining-industry). Indian ports and refineries (Table 2 & 3) are a major shipping corridor of India

Curative measures: Catastrophic oil spills and environmental warning have increased public recognition of storage and transportation risks. Therefore, effective therapies to deal with this problem are obligatory (environmentalpollutioncenters.org).

Remediation methods: conventional: Traditional remediation methods contain physical removal of adulterated materials (Table 4). These procedures use chemicals, mainly shoreline cleaners, usually organic solvents with or without surface-active agents (worldwidescience.org).

Physical methods: Physical confinement and mass or free oil recovery is the preferred response option for cleaning up oil spills in freshwater and marinecoastal environments (Fig. 4).

Chemical methods: Due to differences in their effectiveness and concerns about their long-term toxicity and environmental impact, chemical methods have not yet been widely used (Fig. 5).

Biological methods: Bioremediation is considered an effectual and environment-friendly treatment strategy for polluted shorelines (Nikolopoulou et al 2013). It is cost-effective, has fewer disturbances on site and is more environments friendly (Oh et al 2000). There are 4 different methods for bioremediation (Fig. 6). The demonstration of different limiting factors of bioremediation is being shown in Fig. 7.

Bioremediation: Available products: Most of the methods are currently used to clean up a large number of oil spills including biological agents. There are several companies and research institutions all over the world dedicated to the development of new technologies (Fig. 8). These organizations/companies have created and offer a variety of microbial bioremediation products for agricultural, industry, commercial, aquatic pond management, and home use, as shown in Table 5. In India, the Tata Energy Research Institute (TERI) has developed an indigenous bacterium and obtained a consortium of patents, known as Oilzapper.

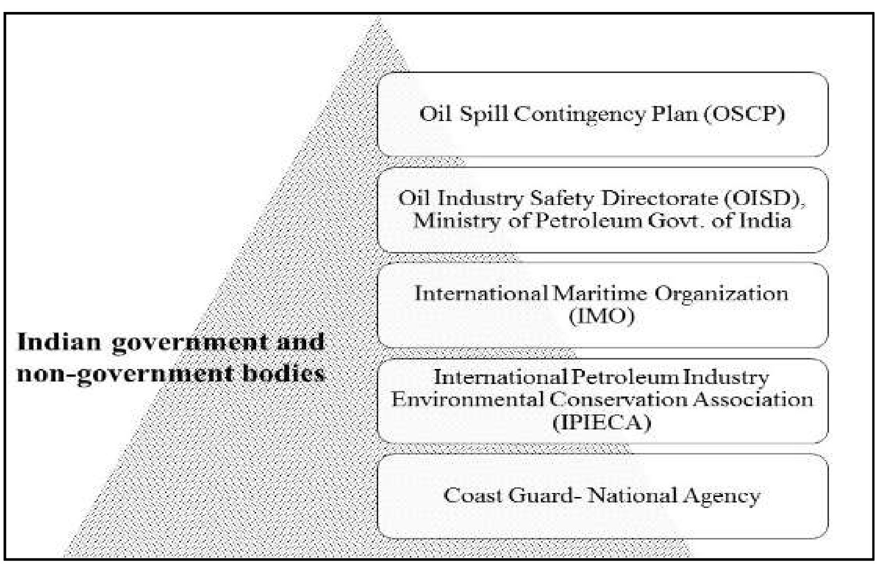


Fig. 3. Indian government and non-government bodies engaged in the monitoring and handling the oil spill disasters

Table 1. Major oil spill incidents in India and the world in chronological order

Spill/Vessel	Location	Date of incident	Maximum spilled (in tons)	Route of spill
Emerald	Israel, Mediterranean shoreline	11.02.21	Unknown	Via an attack on an Iranian tanker that went awry,
Chevron Richeavy metalond Refinery	United States, California, Richeavy metalond	09.02.21	1.9	Pipeline leak
El Palito Refinery	Venezuela, Golfo Triste	08.08.20	2,700	Pipeline leak
2020 Colonial Pipeline gasoline spill	United States, North Carolina, Huntersville	08.08.20	38,000	Pipeline leak
2020 Pointe D'Esny MV Wakashio oil spill	Mauritius, Ile Aux Aigrettes and Mahebourg	25.07.20	4,300	Leakage
Trans-mountain oil spill	Canada, British Columbia, Abbotsford	14.06.20	184.87	Leakage
Diesel (Norilsk) fuel spill	Russia, Norilsk, Krasnoyarsk Krai	29.05.20	17,500	Leakage
Pumping of sludge from a vessel by Tanker truck	New Zealand, Tauranga, Bay of Plenty	30.03.20	1.7	Accident
T.G. Williams Well No. 1 tank battery	United States, Texas, Oakland Creek, Longview	30.03.20	Unknown	Leakage
Greka Energy oil facility	United States, California, Santa Maria	30.03.20	Unknown	Leakage
True Oil pipeline	United States, North Dakota, Red Wing Creek	27.03.20	Unknown	Pipeline leakage
Tanker truck rollover	United States, California, Santa Maria, Cuyama River	21.03.20	19.5	Break in a pipeline
Keystone Pipeline 2019 spill	United States, North Dakota, Walsh County, North Dakota	29.10.19	1,240	Leak caused by collision of tankers
Willowton Oil	South Africa, KwaZulu-Natal, near Pietermaritzburg and Durban	08.08.19	Unknown	Pipeline leakage
Brazil (North East) oil spill (suspected source: NM Bouboulina)	Brazil, 733 km from Paraiba	29.07.19	Unknown	Pipeline leakage
Guarello Island iron ore	Chile, Guarello Island, Magallanes	27.07.19	35.4	Pipeline leakage
export terminal diesel spill	Region			
MV Chrysanthi S bunkering spill at sea	South Africa, Algoa Bay, Port of Ngqura	06.07.19	0.4	Pipeline leakage
MV *Solomon Trader* fuel oil spill	Solomon Islands, Rennell Island	05.02.19	80	Pipeline leakage
SeaRose FPSO production ship spill	Canada, St. John's, Newfoundland and Labrador	16.11.18	219	Break in a pipeline
Ulysse-Virginia collision	North of Corsica (international waters)	10.10.18		Pipeline leakage
Port Erin diesel spill (source unknown)	Isle of Man	23.07.18	Unknown	Pipeline break
Doon, Iowa derailment	United States, Lyon County, Iowa	22.06.18	520	Break in a pipeline
Sanchi oil tanker collision with CF Crystal	East China Sea	06.01.18	138,000	Tanker Collision
Keystone Pipeline 2017 spill	United States, Marshall County, South Dakota	16.11.17	1,322	Pipeline break
Delta House floating production platform spill	United States, Gulf of Mexico, near Louisiana	11,12.10.17	1,280	Pipeline break
Agia Zoni II	Greece, Saronic Gulf, Salamis	10.09.17	2,500	Pipeline break
East River insulating oil spill	United States, New York	07.05.17	101	Pipeline break
Energy Transfer Partners Dakota Access Pipeline Leak	United States, North Dakota	04.04.17	0.27	Pipeline break
Ennore oil spill	India, Chennai, Ennore Port, India	28.01.17	251	Collision of Petroleum tanker

Cont...

Table 1. Major oil spill incidents in India and the world in chronological order

Spill/Vessel	Location	Date of incident	Maximum spilled (in tons)	Route of spill
Belle Fourche	US, North Dakota	05.12.16	571	Pipeline leak
Fox Creek	Canada, Alberta	06.10.16	240	Pipeline leak
BP Clair	UK, Shetland, Clair platform	02.10.16	105	Leakage
Colonial Pipeline Leak	US, Alabama	12.09.16	1092	Pipeline Leak
North Battleford	Canada, North Battleford	21.07.16	210	Pipeline spills
ConocoPhillips	Canada, Alberta	09.06.16	323	Pipeline leak
Union Pacific oil	US, Oregon, Mosier	03.06.16	152	Train fire
Shell Gulf of Mexico oil spill	US, Louisiana	12.05.16	316	Released from the pipeline
Refugio oil spills	US, California	19.05.15	330	Pipeline broke
Yellowstone River oil spill	US, Montana, near Glendive	17.01.15	160	Break in a pipeline
OT Southern Star, 7	Bangladesh, Sundarbans	09.12.14	300	Leak caused by collision of tankers
Trans-Israel	Israel, Eilat	06.12.14	4,300	Pipeline
Mid-Valley	US, Louisiana	13.10.14	546	Pipeline
North Dakota	US, North Dakota, Hiland	21.03.14	110	Pipeline spills
North Dakota	US, North Dakota, Casselton	30.12.13	1300	Train collision
North Dakota	US, North Dakota, Tioga	25.08.13	2810	Pipeline spills
Rayong oil spills	Thailand, Rayong	27.07.13	163	The oil leak (from a pipeline)
Napocor Powe Barge 103	Philippines	08.11.13	520	Typhoon Haiyan (Cyclone)
Guarapiche River	Venezuela, Maturin, Monagas	04.02.12	41,000	Pipeline leakage
Nigeria, Bonga Field	Nigeria	21.12.11	5,500	Tanker accident
TK Bremen	France, Brittany	16.12.11	220	High winds have beached a cargo ship
Campos Basin	Brazil, Campos Basin,	07.11.11	400	Shipping activity
Rena oil spills	New Zealand, Tauranga	05.10.11	350	Grounding of MV *Rena* on the Astrolabe Reef
North Sea oil	UK North Sea	10.08.11	216	Accidents
Bohai Bay oil spill	China, Bohai Bay	04.06.11	204	Sea Floor Leak
Little Buffalo oil spills	Canada, Alberta	29.04.11	3800	Damage in the rainbow pipeline system
Mumbai-spill	India, Mumbai, Arabian Sea	21.01.11	55	Pipeline urban spill
Mumbai oil spill /	India, Mumbai, Arabian Sea	09.08.10	800	Collision between Ships
Xingang Port oil spill	China, Yellow Sea	16.07.10	90,000	Explosion of two crude oil pipelines
Deepwater Horizon	The US, Gulf of Mexico	20.04.10	6,27,000	Drilling
Port Arthur oil spills	US Port Arthur, Texas	23.02.10	1500	Oil tanker accidents

Source: List of oil spills, 2021

Many traditional cleaning processes only clean up a portion of an oil spill, whereas current mechanical technologies generally recover more than 10-15% of the oil after a spill. Chemical solutions are more expedient, but they affect the biota in the leaky environment. Due to the widespread use of petroleum hydrocarbons in factories, these production processes have caused a lot of pollution. Bioremediation has become one of the most promising alternative therapy, but little is known and practiced. In short, these same factors need to be emphasized and corrected.

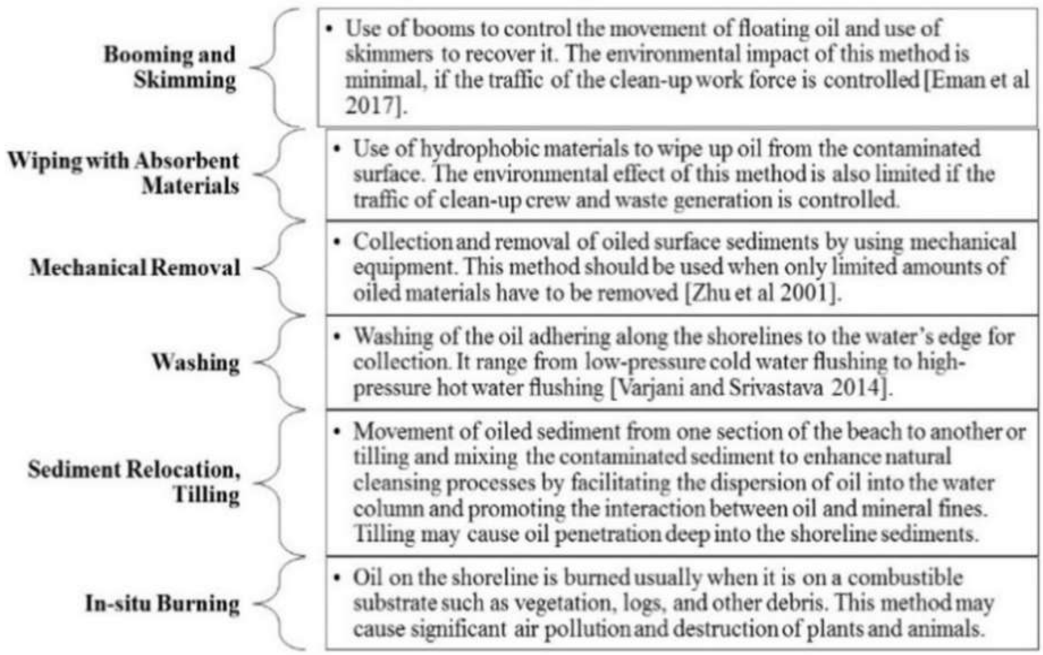


Fig. 4. Commonly used physical methods

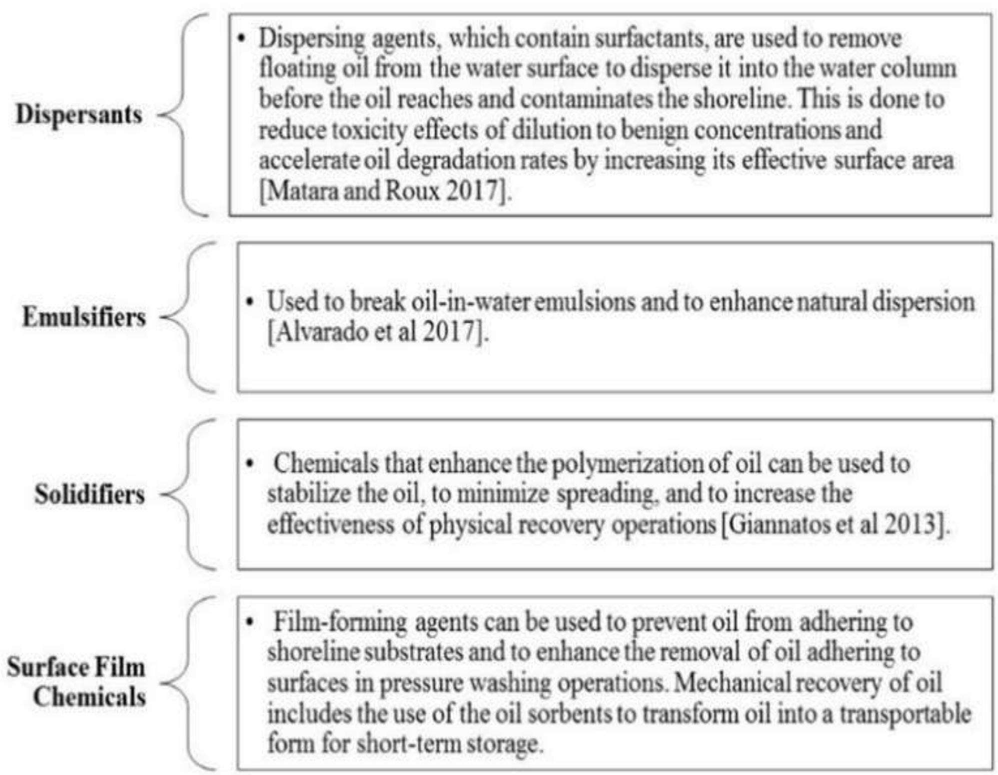


Fig. 5. Commonly used chemical methods

Scope of diverse corrective methods: Compared with physical and chemical methods, phytoremediation or bioremediation provides a very practical alternative method for dealing with oil spills. The current idea of developing phytoremediation tools is to evolve a biotechnological tool to effectively manage contaminants, contaminated water, and soil. Phytoremediation applications that achieve commercial utility includes, plant extraction, plant transformation, plant volatilization, plant stimulation, and plant stabilization.

Mechanistic insights of phytoremediation: Fast-growing grass species are proposed as an efficient strategy for phytoremediation of PAHs in polluted soils. Trees with broad

Table 2. Oil ports transmission in India

Port name	State/ territory
Visakhapatnam Oil Port	Andhra Pradesh
Bharuch Oil Port	Gujarat
Jamnagar Oil Port	Gujarat
Kandla Oil Port	Gujarat
Uran Oil Jetty	Gujarat
Mangalore Oil Port	Karnataka
Kochi Oil Port	Kerala
Mumbai Oil Port	Maharashtra
Mumbai Oil Port II	Maharashtra
Chidambaranar Oil Jetty	Tamil Nadu
Manali Chennai Oil Port	Tamil Nadu

Source: Global Energy Observatory, US

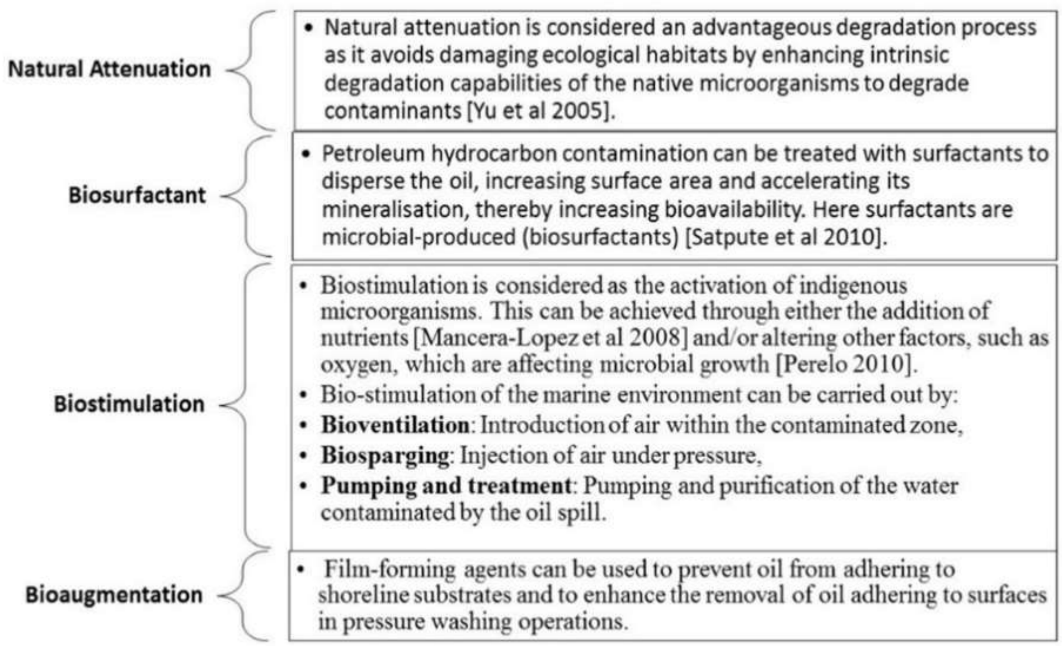


Fig. 6. Commonly used biological methods

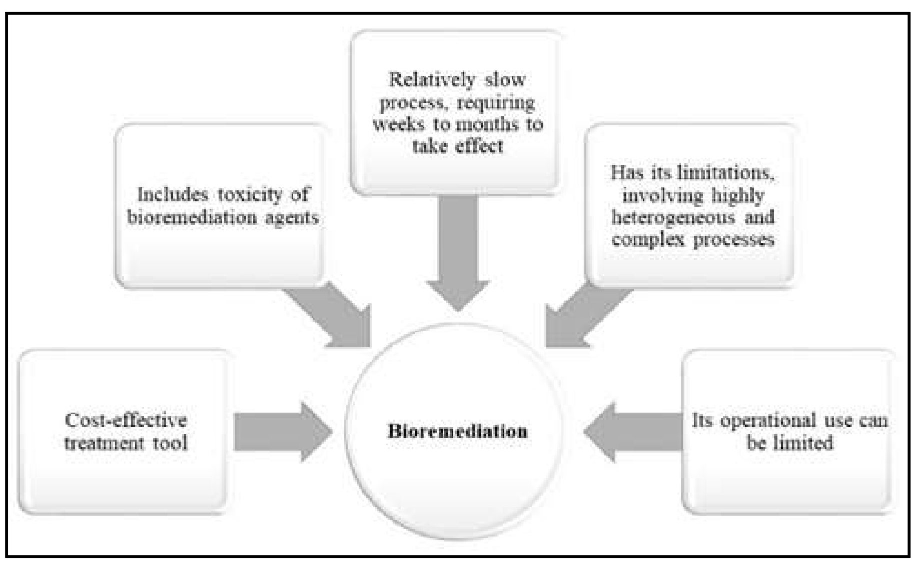


Fig. 7. Limitation factors of bio-remediation

Table 3. Indian oil refineries

Refinery	Oil company	State	Location
Barauni Refinery	Indian Oil Corporation Limited	Bihar	Barauni
Gujarat Refinery	-do-	Gujarat	Koyali
Haldia Refinery	-do-	West Bengal	Haldia
Mathura Refinery	-do-	Uttar Pradesh	Mathura
Panipat Refinery	-do-	Haryana	Panipat
Digboi Refinery	-do-	Assam	Digboi
Bongaigaon Refinery	-do-	Assam	Bongaigaon
Guwahati Refinery	-do-	Assam	Guwahati
Paradip Refinery	-do-	Odisha	Paradip
HPCL	Hindustan Petroleum Corporation Limited	Maharashtra	Mumbai
Visakhapatnam Refinery	-do-	Andhra Pradesh	Visakhapatnam
Heavy Metalel	HPCL-Mittal Energy Limited	Punjab	Bathinda
Mumbai Refinery Mahaul	Bharat Petroleum Corporation Limited	Maharashtra	Mumbai
Kochi Refineries	-do-	Kerala	Kochi
Bina Refinery	Bharat Oman Refineries Limited	Madhya Pradesh	Bina
CPCL	Chennai Petroleum Corporation Limited	Tamil Nadu	Chennai
Nagapattnam Refinery	-do-	Tamil Nadu	Nagapattinam
Numaligarh Refinery	Bharat Petroleum, Oil India and Govt. of Assam	Assam	Numaligarh
Tatipaka Refinery	Oil & Natural Gas Corporation	Andhra Pradesh	Tatipaka
Mangalore Refinery and Petrochemicals Limited	ONGC-Mangalore Refineries and Petrochemicals Ltd	Karnataka	Mangalore
Jamnagar Refinery	Reliance Industries Ltd	Gujarat	Jamnagar (DTA)
Jamnagar Refinery	Reliance Industries Ltd	Gujarat	Jamnagar (SEZ)
Essar Refinery	Essar Oil Ltd	Gujarat	Vadinar

Table 4. Conventional shoreline clean-up options (US, EPA guidelines, 2001)

Response option categories	Technology examples
Natural method	Natural attenuation
Physical method	Washing, Sediment relocation/Surf-washing, Tilling, Booming, Skimming, Manual removal (Wiping), Mechanical removal, Washing, Sediment relocation/Surf-washing In-situ burning
Chemical method	Surface film chemicals, dispersants, demulsifiers, solidifiers

Table 5. Available bioremediation products in the market and their application and limitations

Commercial name of the technologies	Company	Application	Limitations
Micro clean-One TM	Alpha BioSystems, USA	Biological Hydrocarbon Degreaser	A clean-up level of 600 ppm was achieved just took a week
BioWorld Hydrocarbon Treatment (BHT)	BioWorld Products Inc., USA	Bioremediation Enhancer	The product reported as Hazardous
Industrial Class Microbial Blends	Alabaster Corp., USA	Specifically designed for bioremediation of oil spill waste.	Time durability for bioremediation is 2-6 months.
BP Marine Enercare TM	BP Oil International Ltd., UK	Microbiological degradation arises from the contamination of oils	Time durability
UltraMicrobes Facts	Oil spill Contaminant Solutions, USA	Oil spill and industrial application	Time durability
Petro Clean™	Alabaster Corporation, Texas	Hydrocarbon or fuel spill	Time durability
Bactus 303HC	Sanzyme Ltd. (Unisankyo Ltd)	Hydrocarbons, Oily Sludge Bioremediation	Time durability
SDS-043	Halliburton, U.S.A.	Degradation of Drilling Fluids	Certain complex hydrocarbon products such as PAHs and heavy tars are not easily removed by biodegradation.

root systems and high transpiration rates, such as Poplar (*Populus* spp.) and Willow (*Salix* spp.), are good for phytoremediation. Plants immobilise, store, volatilize, and convert these chemicals to varying degrees, depending on the compound, ambient circumstances, and plant genotype. Plants utilize phytoextraction, phytodegradation, phytostabilization, phytovolatilization, and rhizodegradation to assist remediation, as illustrated in Table 6.

Myco-phytoremediation: Fungal phytoremediation, also known as myco-remediation, is a type of bioremediation in which fungus use their degradative ability to remove or neutralize hazardous pollutants in soil and water. However, for hydrophobic organic pollutants, the water phase functions as a nutrition transporter (Kumar et al 2019).

Fungal phytoremediation: A mechanistic approach: Fungal phytoremediation processes could be engineered as sequestration and avoidance mechanisms. Biosorption, precipitation, uptake or efflux, and sequestration, all of which reduce metal toxicity, including the formation of compounds for intracellular chelation and further dilution in plant tissues due to plant growth, exclusion from uptake through precipitation, and chelation in the rhizosphere (Danesh et al 2013). Fungal phytoremediation is influenced by plant and fungus species, the strength of their linkages, plant-soil interaction, soil physical and chemical properties, and biophysical features

Fig. 8. Worldwide companies and research institutes engaged in developing new technologies

Table 6. Phyto-technology mechanisms and significance

Phytotechnology	Levels	Mechanism	Plant	Pollutants
Phytoextraction	Whole plant	Hyperaccumulation in plant	*Helianthus annuus* and *Brassica juncea*	Organic pollutants and metals) Cd, Cr, Co, Pb, Hg, Ni, Ag, Zn) and radionuclides
Phytodegradation	Whole plant	Breakdown and eradication of contaminants	Algae, poplars, and stonewort	Chlorinated solvents, petroleum
Phytovolatilization	Shoot	Volatilization of contaminants in modified from by leaves through transpiration process	Poplars, alfalfa, and *Brassica juncea*	Chlorinated solvents, metals (Se, Hg, and As)
Phytostabilization	Root	Sorption of contaminants	Grasses, *Brassica juncea*, and poplars	Inorganica (Cd, Cu, Cr, Pb)
Rhizodegradation	Root	Decomposition of contaminants by presence of microbes in rhizosphere	Agropyron *smithii* and *Bouteloua gracilis*	Chlorinated solvents, petroleum products

Source: Srivastav et al 2019

Phytoremediation: Role of medicinal and aromatic plants: Aromatic plants are devoid of the possibility of heavy metal buildup from plant biomass, preventing heavy metals from entering food. Because of its application in soaps, detergents, insect repellents, cosmetics, perfumes, and food processing, essential oil export, like phytoremediation, is a major economic concern (Gupta et al 2013).

CONCLUSION

For the eco-restoration of contaminated sites, phytoremediation is an emerging eco-sustainable and clean-green approach. Because of its low cost and solar-powered nature, it offers tremendous potential for application in underdeveloped countries. To minimize environmental pollution, toxicity reduction, and for enhancing phytoremediation efficiency, the employability of cheap, eco-friendly, non-toxic, and degradable organic soil amendments is suggested. Although genetic engineering of metal-accumulating plants and associated microbes with desired characteristics could be a highly useful technology for improved phytoremediation, the risks connected with field use must also be considered. Linking energy crops with phytoremediation could be a cost-effective way to increase biofuel/energy production and metal recovery while also providing other eco-environmental benefits; however, quality testing of biofuels produced is strongly recommended. To improve economic returns, it is advised that novel and existing technologies for the post-treatment of contaminated materials be researched and reevaluated. Detailed and long-term field studies are needed in order to document time and cost data for framing recommendations and persuade regulators, decision-makers, and the general public of phytoremediation's low-cost applicability. The use of nanoparticles for environmental applications is fast growing, and their reactivity is substantially boosted for chemical or biologically induced interactions. The efficiency of phytoremediation can also be boosted by using genetically modified plants. Combining phytoremediation and electro-kinetic remediation could be a great way to improve metal mobility in polluted soil and thus enable plant uptake and phytoremediation.

AUTHOR CONTRIBUTIONS

AB: Conceptualization, funding acquisition, resources; NRD: Supervision, investigation, visualization, validation, writing – review & editing; NS: Data curation, visualization, formal analysis, writing and review – original draft; JS: Data curation, visualization, formal analysis, writing and review – original draft; SM: Data curation, visualization, formal analysis, writing and review – original draft; VA: Project administration, supervision, reviewing and editing.

CONFLICT OF INTEREST

The authors declare that they have no competing interests in the work they have submitted.

REFERENCES

Bhambi RP 2013. Protecting India's Coastline to prevent a repeat of Uttarakhand. *Freedom First Archieve,* 555, 42.

Poonam, Bhardwaj P, Sharma R, Handa R, Kaur N, Kaur H, Sirhindi R, Thukral G 2014. Prospects of Field Crops for Phytoremediation of Contaminants, pp 449-470. In: Ahmad P and Rasool, S (eds.). *Emerging Technologies and Management of Crop Stress Tolerance* (Vol. 2). Elsevier, Cambridge, USA.

Danesh AN, Baumann A, Kolotylo C, Lawlor Y, Tompkins C and Lee R 2011. Perceptions of professionalism among nursing faculty and nursing students. *Western Journal of NursingResearch* **35**(2): 248-271.

Dyksterhouse SE, Gray JP, Herwig RP, Lara JC and Staley JT 1995. *Cycloclasticus pugetii* gen. nov., sp. nov., an aromatic hydrocarbon-degrading bacterium from marine sediments. *International Journal of Systematic Bacteriology* **45**(1): 116-123.

Emenike CU, Jayanthi B, Agamuthu P and Fauziah SH 2018. Biotransformation and removal of heavy metals: A review of phytoremediation and microbial remediation assessment on contaminated soil. *Environmental Reviews* **26**(2): 156-168.

Fingerman M and Nagabhushanam R 2005. *Bioremediation of aquatic and terrestrial ecosystems*. Science publishers, CRC Press Press, UK. p 397.

Gaspar A, Zellermann E, Lababidi S, Reece J and Schrader W 2012. Impact of different ionization methods on the molecular assignments of asphaltenes by FT-ICR mass spectrometry. *Analytical Chemistry* **84**(12): 5257-5267.

Greipsson S 2011. Phytoremediation. *Nature Education Knowledge* **3**(10): 1-5.

Gupta VK, Scheunemann L, Eisenberg T, Mertel S, Bhukel A, Koemans TS, Kramer JM, Liu KS Y, Schroeder S, Stunnenberg HG, Sinner F, Magnes C, Pieber TR, Dipt S, Fiala A, Schenck A, Schwaerzel M, Madeo F and Sigrist SJ 2013. Restoring polyamines protects from age-induced memory impairment in an autophagy-dependent manner. *Nature Neuroscience* **16**(10): 1453-1460.

International Maritime Organization (IMO) 2011. Oil spill response contingency plan. Available online: https://www.imo.org/en/OurWork/Environment/Pages/Oil%20 Spill%20Contingency%20Planning.aspx (accessed on 25 August 2021).

Kumar A, Chaturvedi AK, Yadav K, Arunkumar KP, Malyan SK, Raja P, Kumar R, Khan SA, Yadav KK, Rana KL, Kour D, Yadav N and Yadav AN 2019. Fungal Phytoremediation of Heavy Metal Contaminated Resources: Current Scenario and Future Prospects, pp 437-461. In: Yadav AN, Singh S, Mishra S and Gupta A (eds). *Recent Advancement in White Biotechnology Through Fungi* (Vol. 3). Springer Nature, Switzerland.

LaMontagne MG, Leifer I, Bergmann S, Van De Werfhorst LC and Holden PA 2004. Bacterial diversity in marine hydrocarbon seep sediments. *Environmental Microbiology* **6**(8): 799-808.

Licht LA and Isebrands JG 2005. Linking phytoremediated pollutant removal to biomass economic opportunities. *Biomass and Bioenergy* **28**: 203-218.

Li S, Zhao B, Jin M, Hu L, Zhong H and He Z 2020b. A comprehensive survey on the horizontal and vertical distribution of heavy metals and microorganisms in soils of a Pb/Zn smelter. *Journal of Hazardous Materials* **400**: 1-15.

Mandal AK, Sarma PM, Singh B, Jeyaseelan CP, Channashettar VA, Lal B and Datta J 2011. Bioremediation: A sustainable eco-friendly biotechnological solution for environmental pollution in oil industries. *Journal of Sustainable Development and Environmental Protection* **1**(3): 5-23.

Margesin R and Schinner F 2001. Biodegradation and bioremediation of hydrocarbons in extreme environments. *Applied Microbiology and Biotechnology* **56**(5-6): 650-663.

McGenity TJ, Folwell BD, McKew BA and Sanni GO 2012. Marine crude-oil biodegradation: A central role for interspecies interactions. *Aquatic Biosystems* **8**(1): 1-19.

McKew BA, Coulon F, Osborn AM, Timmis KN and McGenity T J 2007. Determining the identity and roles of oil-metabolizing marine bacteria from the Thames estuary, UK. *Environmental Microbiology* **9**(1): 165-176.

Mei H and Yin Y 2009. Studies on marine oil spills and their ecological damage. *Journal of Ocean University of China* **8**(3): 312-316.

Mulani N, Fulke AB, D'Souza E, Ram A, Maloo A, Sayed F and Gajbhiye SN 2017. Biodegradation of crude oil using marine *Bacillus* species from Vadinar coast, Gujarat, India. *Current Science* **112**(3): 569-576.

Nikolopoulou M, Pasadakis N, Norf H and Kalogerakis N 2013. Enhanced ex-situ bioremediation of crude oil contaminated beach sand by supplementation with nutrients and rhamnolipids. *Marine Pollution Bulletin* **77**(1-2): 37-44.

Oh YS, Maeng J and Kim SJ 2000. Use of microorganism-immobilized polyurethane foams to absorb and degrade oil on water surface. *Applied Microbiology and Biotechnology* **54**(3): 418-423.

Ovalles C, Rogel E, Moir M, Thomas L and Pradhan A 2012. Characterization of heavy crude oils, their fractions, and Hydrovisbroken products by the asphaltene solubility fraction method. *Energy and Fuels* **26**(1): 549-556.

Rai PK, Lee SS, Zhang M, Tsang, YF, Kim KH 2019. Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International* **125**: 365-385.

Saxena G, Purchas D, Mulla SI, Saratale GD, Bharagava RN 2020. Phytoremediation of heavy metal contaminated sites: Eco-environmental concerns, field studies, sustainability issues, and future prospects. *In Reviews of Environmental Contamination and Toxicology* **249**: 71-131.

Received 16 January, 2022; Accepted 23 May, 2022

Sheppard PJ, Adetutu EM, Young A, Manefield M, Morrison PD and Ball AS 2013. Stable Isotope Probing- a tool for assessing the potential activity and stability of hydrocarbonoclastic communities in contaminated seawater. *Journal of Bioremediation and Biodegradation* **4**(5): 1-8.

Srivastav A, Yadav KK, Yadav S, Gupta N, Singh JK, Katiyar R and Kumar V 2019. Nano-phytoremediation of Pollutants from Contaminated Soil Environment: Current Scenario and Future Prospects, pp 383-401. In: Ansari AA, Gill SS, Gill R, Lanza, GR and Newman L (eds.). *Phytoremediation* (Vol. 6). Springer Nature, Switzerland.

Trading Economics 2021. *India Crude Oil Production*. Available online: https://tradingeconomics.com/india/crude-oil-production?embed&embed/forecast/ (accessed on 23 August 2021).

Urionabarrenetxea E, Garcia-Velasco N, Anza M, Artetxe U, Lacalle R, Garbisu C, Becerril T, Soto M 2021. Application of in situ bioremediation strategies in soils amended with sewage sludges. *Science of the Total Environment* **766**: 1-13.

US Energy Information Administration 2014. *Annual Energy Outlook 2014 report.* US Energy Information Administration, Washington, D.C., USA. Available online: https://www.eia.gov/todayinenergy/detail.php?id=16171(accessed on 24 August 2021).

Venosa AD and Zhu X 2005. Bioremediation of aquatic and Terrestial ecosystems, pp 141-172. In: Fingerman M and Nagabhushanam R (eds.). *Guidance for the bioremediation of oil-contaminated wetlands, marshes, and marine shorelines*. CRC Press Press, Boca Raton, Florida.

Wang L, Hou D, Shen Z, Zhu J, Jia X, Ok YS, Tack FMG, Rinklebe J 2020. Field trials of phytomining and phytoremediation: A critical review of influencing factors and effects of additives. *Critical Reviews in Environmental Science and Technology* **50**: 2724-2774.

Wu B, Peng H, Sheng M, Luo H, Wang X, Zhang R, ... and Xu H 2021. Evaluation of phytoremediation potential of native dominant plants and spatial distribution of heavy metals in abandoned mining area in Southwest China. *Ecotoxicology and Environmental Safety* **220**: 1-10.