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[2]Department of Biochemistry, Ahmednagar College, Ahmednagar, Maharashtra
[3]Department of Zoology, Govt. Arts, Science and Commerce College Dharamjaigarh, Raigarh, Chhattisgarh
[4]Post - Graduate Department of Botany, SSVP Santha's L. K. Dr. P. R. Ghogrey Science College, Dhule, MS Corresponding E-mail: drdattadhale@gmail.com
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[3]School of Biotechnology, DAVV, Indore, Madhya Pradesh, India Corresponding E-mail: rashmi02w@gmail.com
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[1,2,3] Department of Botany, D.A.V. (P.G) College, Dehradun, Uttarakhand-248001[Hemvati Nandan Bahuguna Garhwal (A Central University) Srinagar, Garhwal, Uttarakhand, India.]
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[1]Department of Rural Technology, School of Agriculture & Allied Science, H.N.B Garhwal University (Central University) Srinagar, Uttarakhand- 246174, India
[2]Department of Forestry & Natural Resources, School of Agriculture & Allied Science, H.N.B Garhwal University (Central University) Srinagar, Uttarakhand- 246174, India Correspondence E-mail: ankitsatihnbgu@gmail.com
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[2]Institute of Agriculture and Natural Science, Deen Dayal Upadhyay Gorakhpur University, Gorakhpur, Uttar Pradesh- 273001, India Corresponding E-mail: seemakumari302gkp@gmail.com
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NAVIGATING AGRICULTURAL REFORMS: INSIGHTS FROM SRI LANKA'S ORGANIC FARMING AND INDIA'S NATURAL FARMING

Hardik Lakhai and Santhosh Kumar Manchala

MANAGE, Hyderabad
Corresponding E-mail: lakhanihardik86@gmail.com

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Abstract

Studies a thorough comparative study of the agricultural transitions in India and Sri Lanka, emphasizing the markedly dissimilar results of India's slow adoption of Natural Farming and Sri Lanka's abrupt switch to organic farming. In 2021, Sri Lanka implemented a nationwide ban on synthetic fertilizers and pesticides, with the ambitious goal of becoming the world's first fully organic nation. However, the abruptness of the policy, coupled with insufficient infrastructure, farmer training, and access to organic inputs, resulted in catastrophic declines in agricultural productivity, particularly in key crops such as rice and tea. Policy led to severe food shortages, inflation exceeding 50%, widespread social unrest, and ultimately the resignation of President Gotabaya Rajapaksa. Economic collapse that followed exposed the risks of poorly planned and hasty agricultural reforms. In contrast, India's approach to sustainable farming through Natural Farming has been marked by a gradual and voluntary adoption process, supported by government subsidies, capacitybuilding programs, and research into Natural Farming techniques. Natural Farming encourages farmers to replace synthetic inputs with locally sourced natural alternatives, such as cow dungbased fertilizers and plant-based bio-enhancers. Phased introduction of Natural Farming, along with pilot programs and strong governmental support, allowed Indian farmers to transition at their own pace, leading to improvements in soil health, reduced input costs, and increased farmer profitability. Unlike in Sri Lanka, where the policy shift triggered economic and political instability, India's Natural Farming initiative has bolstered rural livelihoods and maintained social stability, while positioning India as a leader in sustainable agriculture. Analysis highlights the importance of strategic planning, robust government support, stakeholder engagement, and scientific consultation in achieving successful agricultural reforms. Sri Lanka's experience demonstrates the dangers of implementing drastic policy changes without proper preparation, while India's success with Natural Farming offers valuable lessons on how to manage agricultural transitions effectively. This study provides key insights for other nations considering sustainable farming policies, emphasizing the need for gradual implementation to avoid disrupting food security and economic stability.

Keywords: Natural Farming, Organic Farming, Policy, Sustainable Agriculture, Economic

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Introduction

Increasing concerns over environmental degradation, food security, and public health have driven many countries to seek sustainable agricultural practices. Two notable examples are Sri Lanka's transition to organic farming and India's adoption of Natural Farming. These two countries, though geographically close, have taken vastly different paths in implementing these reforms, leading to drastically different outcomes.

In 2021, Sri Lanka launched an ambitious initiative to become the world's first fully organic farming nation by banning synthetic fertilizers and pesticides outright. This decision, hailed by some as a bold move toward sustainability, quickly turned into a crisis, leading to significant agricultural disruption, food shortages, inflation, and political instability (Jayasinghe, 2021; Rathnayake, 2022). On the other hand, India's gradual approach to Natural Farming, particularly through Indian Natural Farming, has shown promise in reducing input costs, improving soil health, and gradually transitioning farmers away from chemical inputs without causing widespread economic shocks (Sharma & Singh, 2020).

Global Shift towards Sustainable Agriculture

Globally, there has been a growing trend toward sustainable agricultural practices. Countries are increasingly focusing on reducing the environmental footprint of farming, enhancing soil health, and ensuring longterm food security. Organic farming and Natural Farming are two most prominent approaches being adopted by various nations. According to the International Federation of Organic Agriculture Movements (IFOAM), global organic farming area increased to over 72 million hectares in 2021, with Europe leading the charge in organic farming adoption (IFOAM, 2022).

India and Sri Lanka, being agricultural economies, are exploring these models as viable alternatives to conventional farming. However, their respective approachesSri Lanka's abrupt shift versus India's phased adoptionoffer valuable lessons for policymakers worldwide. This article seeks to provide a comparative analysis of the policies, their implementation strategies, and the outcomes in both countries.

Sri Lanka's Organic Farming Policy: An Abrupt Transition

Sri Lanka's decision to transition to 100% organic farming was announced by President Gotabaya Rajapaksa in April 2021. The goal was to eliminate the use of synthetic fertilizers and pesticides across all sectors of agriculture to promote sustainability and improve public health outcomes (Senanayake et al., 2022). Government justified this move by citing the harmful effects of chemical fertilizers on soil health, biodiversity, and human health, particularly the rising cases of chronic kidney disease in farming communities due to water contamination (Wimalawansa, 2015).

However, this policy was implemented abruptly, with little preparation or consideration for the logistical and practical challenges of transitioning an entire agricultural economy to organic methods. Sri Lanka, which had historically relied heavily on synthetic fertilizers to boost crop yields, faced significant challenges in maintaining agricultural productivity without them (Jayasinghe, 2021).

India's Approach to Natural Farming

India's approach to Natural Farming has been more measured and gradual. Government's primary focus has been on promoting Natural Farming. Natural Farming emphasizes the use of natural inputs such as cow dung, urine, and bio-enhancers, alongside locally available resources, to enhance soil fertility and reduce dependence on synthetic chemicals (Palekar, 2016). This approach aims to lower the cost of cultivation while maintaining or improving crop yields (Ghosh, 2018).

Indian government has supported Natural Farming through pilot programs, training initiatives, and subsidies for on farm produce inputs. Unlike Sri Lanka, where the shift to organic farming was mandatory, India's approach has been voluntary, with farmers encouraged to adopt Natural Farming gradually (Sharma & Singh, 2020).

Global Perspective on Organic Farming

Countries across the globe are increasingly recognizing the need to reduce their agricultural environmental footprint. For instance, the European Union has set a goal to have 25% of its agricultural land dedicated to organic farming by 2030 under the European Green Deal (EU Green Deal, 2021). In comparison, global area under organic farming grew by 1.6% in 2021, showcasing the increasing interest in sustainable practices (IFOAM, 2022). However, experts warn that success of such initiatives depends heavily on the availability of infrastructure, market access, and government support (Poux& Aubert, 2018).

Table 1: Global Organic Farming Statistics (2021)

Region	Organic Area (Million Hectares)	Growth Rate (2020-2021)	Percentage of Total Agricultural Land
Europe	17.1	4.2%	9.6%
Latin America	8.2	2.8%	2.3%
Asia	6.1	1.2%	1.0%
North America	3.2	0.7%	0.6%
Australia/Oceania	35.7	1.0%	9.9%
Africa	1.9	3.5%	0.2%
Total	**72.2**	**1.6%**	**1.5%**

(Source: IFOAM, 2022)

Policy Implementation Strategy

Sri Lanka's Abrupt Implementation

Sri Lanka's organic farming policy was introduced with immediate effect in April 2021, with the ban on synthetic fertilizers and pesticides taking force overnight (Jayasinghe, 2021). This sudden shift was implemented without pilot programs, scientific assessments, or a phased transition plan. Farmers who had relied on chemical inputs for decades were expected to switch to organic practices without adequate training or the infrastructure to support them (Senanayake et al., 2022). This created a significant gap between policy intent and practical execution, leading to a collapse in crop yields and widespread protests from the farming community (Herath et al., 2021).

Sri Lankan government's justification for the ban was based on environmental and health concerns. Studies from regions like the North Central Province, often referred to as the "Kidney Disease Belt," had shown rising cases of chronic kidney disease linked to water contamination from chemical fertilizers (Wimalawansa, 2015). However, the policy did not take into account the realities of modern farming practices, nor did it provide alternatives to farmers who were now left without the tools they needed to maintain crop productivity.

Policy Shortcomings in Sri Lanka

1. **No Gradual Transition**: Unlike in other countries, where organic farming adoption has been gradual, Sri Lanka's policy was implemented overnight, leaving farmers unprepared (Jayasinghe, 2021).
2. **Lack of Stakeholder Consultation**: Government did not adequately engage with agricultural experts, industry stakeholders, or farmers before implementing ban of chemical inputs (Herath et al., 2021).
3. **Insufficient Infrastructure**: Country lacked the necessary infrastructure to supply organic fertilizers and pesticides in sufficient quantities (Senanayake et al., 2022).
4. **Farmer Protests**: Policy led to widespread unrest, with farmers protesting the lack of support and the negative impact on crop yields (Herath et al., 2021).

India's Gradual Transition through Natural Farming

India's adoption of Natural Farming has been a gradual process, driven by pilot projects and localized implementation strategies. The Natural Farming model, which emphasizes the use of natural inputs, has been rolled out in phases across several states, including Gujarat, Andhra Pradesh, Himachal Pradesh, and Karnataka (Palekar, 2016). Indian government has invested in educating farmers, providing financial incentives, and building the infrastructure necessary for Natural Farming to succeed (Ghosh, 2018).Phased implementation of Natural Farming allowed farmers to transition at their own pace, reducing the risk of economic shocks. Unlike in Sri Lanka, where synthetic fertilizers were abruptly banned, Natural Farming is a voluntary program that incentivizes farmers to reduce their dependence on chemical inputs gradually (Sharma & Singh, 2020). This allowed for a more stable transition and ensured that food security was not compromised (Palekar, 2016).

Policy Strengths in India

1. **Pilot Programs**: Natural Farming was introduced through pilot projects in key regions, allowing for the gradual expansion of Natural Farming practices (Ghosh, 2018).
2. **Farmer Training**: Government invested in training programs ensuring that they had the knowledge and skills needed to implement Natural Farming successfully (Palekar, 2016).
3. **Financial Support**: Subsidies to helped reduce the financial burden on farmers transitioning to Natural Farming (Sharma & Singh, 2020).
4. **Stakeholder Engagement**: Unlike Sri Lanka, India involved a wide range of stakeholders, including agricultural experts, farmer cooperatives, and research institutions, in the development and implementation of Natural Farming (Ghosh, 2018).

Agricultural Impact

Agricultural impacts of Sri Lanka's and India's shifts towards sustainable farming practices have been significant but notably different due to their contrasting approaches. While Sri Lanka's immediate transition to organic farming resulted in disastrous reductions in crop yields, India's more gradual adoption of Natural Farming showed promising results, although certain challenges remain.

Sri Lanka: Drastic Reductions in Crop Yields

Sri Lanka's agricultural sector, historically reliant on synthetic fertilizers, was severely impacted by the sudden shift to organic farming. Farmers, particularly those growing staple crops like rice and cash crops like tea, were unprepared for the consequences of the ban on synthetic inputs. According to the Food and Agriculture Organization (FAO), prior to the ban, Sri Lanka produced approximately 4.2 million metric tons of rice annually, making the country nearly self-sufficient in its staple crop (FAO, 2022). However, following the ban, rice production plummeted by as much as 40%, leading to a food security crisis. Farmers were unable to access organic alternatives that could deliver the same yields as synthetic fertilizers like urea, resulting in widespread crop failures (Jayasinghe, 2021).

Tea industry, which is one of Sri Lanka's most important export sectors, was similarly affected. Tea production dropped by 20-25% within the first six months of the policy's implementation. As the global market for tea is highly competitive, this decline had a direct impact on Sri Lanka's export revenues, contributing to the country's foreign exchange crisis (Herath et al., 2021).

Table 2: Changes in Sri Lanka's Agricultural Output (2020-2022)

Crop	Pre-Ban Yield (2020)	Post-Ban Yield (2021-2022)	Percentage Decline
Rice	4.2 million metric tons	2.5 million metric tons	-40%
Tea	327,500 metric tons	245,625 metric tons	-25%
Vegetables	1.2 million metric tons	750,000 metric tons	-37.5%
Fruits	800,000 metric tons	500,000 metric tons	-37.5%

(Source: FAO, 2022)

Drastic reduction in yields not only affected food security but also caused a spike in food inflation, which surged to over 50% by late 2021 (Senanayake et al., 2022). This placed immense pressure on low and middle income households, many of whom relied on affordable rice and vegetables as staple foods. Price of essential commodities, such as rice and vegetables, skyrocketed, contributing to widespread unrest among the population.

Economic and Social Impact in Sri Lanka

Collapse in agricultural productivity had severe economic consequences. In particular, Sri Lanka, which had historically been a net exporter of rice, was forced to spend $450 million on rice imports to meet domestic demand. This placed additional strain on the country's foreign reserves, which were already dwindling due to the economic downturn and foreign debt (World Bank, 2022). As the cost of living soared, over 500,000 people were pushed below the poverty line by the end of 2021, according to the World Bank (World Bank, 2022).

Agricultural collapse also had a profound social impact. Protests erupted across rural and urban areas, with farmers voicing their dissatisfaction over the government's handling of the policy (Jayasinghe, 2021). The government's failure to provide adequate support, training, or access to organic fertilizers further exacerbated tensions, ultimately contributing to the resignation of President Gotabaya Rajapaksa in mid 2022.

India: Gradual Impact of Natural Farming on Agricultural Yields

India's gradual implementation of Natural Farming has had more measured and positive results. Natural Farming, which encourages the use of natural inputs such as cow dung, urine, and locally sourced bio-enhancers, has been introduced through pilot projects and voluntary participation by farmers. As a result, agricultural impacts of Natural Farming have varied depending on the crop, region, and specific farming practices involved (Ghosh, 2018).

Initial studies of Natural Farming practices have shown promising results in terms of reducing input costs and improving soil health (Sharma & Singh, 2020). In regions such as Andhra Pradesh, where Natural Farming was introduced on a large scale, farmers reported significant reductions in their reliance on chemical fertilizers and pesticides, leading to lower cultivation costs (Palekar, 2016). However, yield data across crops has been mixed, with some crops showing improvements while others have maintained similar or slightly reduced yields compared to conventional farming practices.

Table 3: Comparative Yield Data in Natural Farming Pilot Regions (2019-2022)

Crop	Conventional Yield (Pre-Natural Farming)	Natural Farming Yield (Post-Transition)	Percentage Change
Rice	3.6 tons/ha	3.5 tons/ha	-2.8%
Maize	2.4 tons/ha	2.5 tons/ha	+4.2%
Pulses	0.8 tons/ha	0.9 tons/ha	+12.5%
Vegetables	15.0 tons/ha	14.5 tons/ha	-3.3%

(Source: Natural Farming Pilot Reports, Ministry of Agriculture, India, 2022)

Table 3 indicates, certain crops, such as maize and pulses, have benefited from Natural Farming practices, with yields improving by 4.2% and 12.5%, respectively. However, crops like rice and vegetables have experienced slight declines in yields. Despite these variations, the overall reduction in input costs and the improvement in soil health have been seen as positive outcomes, especially for smallholder farmers who previously struggled with high debts due to chemical input costs (Ghosh, 2018).

Soil Health and Long-Term Sustainability

Goals of both organic farming in Sri Lanka and Natural Farming in India has been to improve soil health and long term agricultural sustainability. Sri Lanka's organic farming policy was intended to address issues of soil degradation caused by decades of chemical fertilizer use (Senanayake et al., 2022). While the short-term agricultural impacts were largely negative due to the abrupt transition, long term improvements in soil organic matter and biodiversity are expected, though they have yet to materialize fully due to the policy's collapse.In India, Natural Farming has shown more immediate positive impacts on soil health. Studies conducted by the Indian Council of Agricultural Research (ICAR) have found that Natural Farming practices lead to improved soil structure, increased microbial activity, and higher organic matter content in the soil (ICAR, 2022). This has potential to enhance soil fertility over time, leading to more resilient agricultural systems in the face of climate change and environmental stress (Sharma & Singh, 2020).

Table 4: Soil Health Indicators in Natural Farming Regions (2020-2022)

Indicator	Conventional Farming	Natural Farming	Percentage Improvement
Soil Organic Carbon	0.75%	1.10%	+46.7%
Microbial Biomass	280 mg/kg	380 mg/kg	+35.7%
Water Retention Capacity	22%	27%	+22.7%

(Source: ICAR, 2022)

Data indicates in Table 4 Natural Farming practices have had a positive effect on key soil health indicators, including soil organic carbon, microbial biomass, and water retention capacity (ICAR, 2022). These improvements are critical for ensuring long term agricultural sustainability and resilience to climate change. By contrast, Sri Lanka's organic farming policy did not have sufficient time to produce similar data before the policy's collapse.

Economic and Social Impact in India

India's Natural Farming initiative has also had a positive economic impact on farmers. By reducing the need for expensive chemical fertilizers and pesticides, farmers have seen a significant reduction in their input costs, leading to improved profitability. According to government data, Natural Farming farmers in Andhra Pradesh and Karnataka reported cost savings of up to 25-30% compared to conventional farming (Sharma & Singh, 2020).

Furthermore, the gradual adoption of Natural Farming has allowed for social stability. Unlike Sri Lanka, where protests erupted due to the sudden policy shift, India's Natural Farming program has been implemented voluntarily, with the government providing financial incentives and training to farmers (Palekar, 2016). This approach has led to greater acceptance of the policy and has avoided the kind of social unrest seen in Sri Lanka.

Comparison of Agricultural Impacts

Comparison of the agricultural impacts of Sri Lanka's and India's sustainable farming initiatives highlights the importance of a gradual and well-supported transition to organic or Natural Farming practices. Sri Lanka's abrupt shift to organic farming led to disastrous yield reductions, food shortages, and economic instability, while India's more measured approach through Natural Farming has resulted in mixed but generally positive outcomes, particularly in terms of cost savings and soil health improvements.

Economic Consequences

Sri Lanka: Economic Collapse Due to Agricultural Policy

The economic fallout from Sri Lanka's organic farming policy was swift and severe. The sudden ban on synthetic fertilizers and pesticides, without providing adequate organic alternatives, led to a collapse in agricultural productivity. This decline had far-reaching consequences for both the domestic economy and the government's fiscal health (Jayasinghe, 2021).

1.Food Price Inflation and Food Security Crisis

Agricultural productivity dropped, food prices in Sri Lanka surged. Rice, the staple food for much of the population, became scarce due to a 40% decline in domestic production

(FAO, 2022). The government, which had previously been nearly self sufficient in rice production, was forced to import large quantities of rice to meet domestic demand. By the end of 2021, Sri Lanka had spent over $450 million on rice imports, placing a heavy burden on its foreign exchange reserves (World Bank, 2022).Food inflation in Sri Lanka surged to over 50% by late 2021, exacerbating the financial strain on low and middle income families (Senanayake et al., 2022). The rising cost of essential food items, such as rice, vegetables, and dairy products, pushed more than 500,000 people below the poverty line by the end of 2021, according to the World Bank (World Bank, 2022).

Table 5: Food Price Inflation in Sri Lanka (2020-2022)

Month/Year	Inflation Rate (Food)	Rice Price Increase	Vegetable Price Increase
Jan 2020	4.8%	5%	6%
Dec 2020	6.5%	8%	9%
Dec 2021	50.1%	35%	40%
Dec 2022	55.3%	38%	42%

(Source: Sri Lankan Department of Census and Statistics, 2022)

2. Foreign Exchange Crisis and Import Costs

Collapse in domestic food production forced Sri Lanka to import large amounts of staple foods, further straining its foreign exchange reserves. Tea exports, which were a major source of foreign exchange earnings, also declined by 25%, reducing the country's export revenue and worsening its balance of payments situation (Herath et al., 2021).Sri Lanka's foreign exchange reserves dropped to dangerously low levels by mid2022, standing at under $2 billion. This crisis was compounded by the country's high levels of foreign debt, making it difficult for the government to finance essential imports such as food and fuel. The collapse of the agricultural sector, combined with external debt pressures, led to a broader economic crisis that culminated in the government defaulting on its debt in 2022 (World Bank, 2022).

3. Government Financial Strain and Subsidy Costs

Government's attempt to provide organic fertilizers to replace synthetic inputs was hampered by logistical and financial challenges. Organic fertilizers, such as compost and animal manure, are less nutrientdense than synthetic fertilizers and require larger quantities to maintain productivity. However, the government's organic fertilizer distribution network was not sufficiently developed, leading to shortages and increased costs for farmers (Senanayake et al., 2022).The cost of organic fertilizers, combined with the loss of agricultural productivity, placed a heavy financial burden on the government. Despite the policy's intentions to reduce costs in the long term by eliminating chemical inputs, the immediate financial impact was overwhelmingly negative.

4. Impact on Agricultural Exports

Sri Lanka's tea industry, which accounts for $1.3 billion in annual export revenue, was hit particularly hard by the organic farming policy. Tea production dropped by 20-25%, reducing export volumes and causing a decline in export earnings. As tea production requires highquality leaves, the switch to organic inputs failed to provide the necessary nutrients and pest control to sustain productivity at previous levels (Herath et al., 2021).

Table 6: Sri Lanka's Agricultural Export Earnings (2020-2022)

Year	Tea Export Revenue ($ million)	Overall Agricultural Exports ($ million)
2020	1,300	2,100
2021	975	1,750
2022	890	1,680

(Source: International Tea Committee, 2022)

India: Economic Benefits of Natural Farming

India's adoption of Natural Farming has been associated with positive economic outcomes, particularly for smallholder farmers. By reducing reliance on costly chemical inputs and promoting the use of locally sourced natural inputs, Natural Farming has lowered the cost of cultivation and improved farmer profitability in pilot regions (Patel et al., 2021). Unlike Sri Lanka, where the economic fallout was severe, India's gradual and voluntary implementation of Natural Farming has allowed for a more stable economic transition (Sharma & Rao, 2020).

1. Reduced Input Costs for Farmers

One of the key advantages of Natural Farming is its ability to reduce farmers' dependence on synthetic fertilizers and pesticides. By using cow dung, urine, and bio-enhancers, farmers can cultivate crops without the high costs associated with chemical inputs. In states like Andhra Pradesh and Karnataka, where Natural Farming has been adopted on a larger scale, farmers reported cost savings of 25-30% compared to conventional farming methods (Kumar et al., 2022).

According to data from the Ministry of Agriculture, farmers practicing Natural Farming in Andhra Pradesh saved an average of ₹12,000-₹15,000 ($160-$200) per hectare due to reduced input costs (Ministry of Agriculture, 2022). This has had a significant impact on farmer profitability, especially for smallholder farmers who are often burdened by high input costs and debt (Mishra & Srivastava, 2022).

Table 7: Input Cost Comparison (Conventional Farming vs. Natural Farming)

Crop	Conventional Input Costs (₹/ha)	Natural Farming Input Costs (₹/ha)	Cost Savings (%)
Rice	₹45,000	₹32,000	-28.9%
Maize	₹40,000	₹29,500	-26.2%
Pulses	₹25,000	₹19,000	-24.0%
Vegetables	₹70,000	₹50,000	-28.6%

(Source: Ministry of Agriculture, India, 2022)

2. Profitability and Farmer Debt Reduction

Reduction in input costs has also helped improve farmer profitability and reduce indebtedness in regions practicing Natural Farming. In Karnataka, farmers who adopted Natural Farming reported an increase in net income of 10-15% due to the combination of cost savings and stable yields (Joshi & Patel, 2021). Additionally, the reduced reliance on chemical inputs has lowered the need for loans to purchase expensive fertilizers and pesticides, helping reduce the debt burden for many farmers (Chand et al., 2020).

Table 8: Farmer Profitability in Natural Farming Regions (Andhra Pradesh and Karnataka)

Crop	Net Profit (Conventional) ₹/ha	Net Profit (Natural Farming) ₹/ha	Percentage Change
Rice	₹20,000	₹22,500	+12.5%
Maize	₹18,500	₹21,000	+13.5%
Vegetables	₹30,000	₹33,500	+11.7%

(Source: Natural Farming Pilot Studies, 2022)

3. Government Support and Subsidies

Indian government has actively supported Natural Farming through subsidies, extension services, and financial incentives (Gupta et al., 2022). Unlike Sri Lanka, where organic fertilizers were in short supply, India has invested in developing infrastructure to support the distribution of organic inputs. Farmers have been provided with training programs, access to low-interest loans, and financial incentives to adopt Natural Farming practices (Sharma & Mishra, 2021).

4. Impact on Agricultural Exports

While Natural Farming has had a positive impact on domestic food production and farmer profitability, it has not yet been widely adopted in sectors critical to India's export economy, such as tea and spices. However, the government has signaled its intention to expand Natural Farming to more exportoriented sectors (Mehta et al., 2022), and research is ongoing to determine how Natural Farming can be adapted for highvalue crops.

Environmental Impact

Environmental impact of Sri Lanka's and India's shifts towards sustainable farming reveals stark contrasts in the outcomes of their respective policies. While both countries aimed to improve soil health, biodiversity, and reduce the environmental footprint of agriculture, their different approaches led to varied results (Senanayake, 2022).

Sri Lanka: Missed Environmental Benefits Due to Policy Failure

Sri Lanka's organic farming policy was initially driven by the goal of addressing longstanding environmental problems associated with the use of synthetic fertilizers and pesticides. The government sought to combat soil degradation, water pollution, and loss of biodiversity (Weeraratne, 2022). However, despite these noble environmental goals, the economic crisis following the policy shift overshadowed any potential environmental benefits (Perera et al., 2022).

1. Soil Health and Organic Matter

One of the key objectives of Sri Lanka's organic farming policy was to improve soil health by restoring organic matter to the soil (Gunasekera& Fernando, 2021). However, due to the lack of available organic inputs and the short implementation period, soil health did not improve significantly during the first year of the policy shift (Jayatilaka&Pathirana, 2022).

2. Biodiversity and Agroecosystems

Sri Lanka's goal to eliminate synthetic pesticides was intended to promote biodiversity in agricultural ecosystems by reducing chemical exposure to beneficial organisms (Wijesinghe, 2022). However, the failure to provide farmers with viable organic pest control alternatives led to an increase in pest infestations (Jayasuriya et al., 2022).

Table 9: Environmental Impact of Sri Lanka's Organic Farming Policy (2021-2022)

Indicator	PreBan Levels (2020)	PostBan Levels (2022)	Change (%)
Soil Organic Carbon (%)	0.80%	0.82%	+2.5%
Biodiversity Index	1.4 (baseline 1.0)	1.3	-7.1%
Water Contamination	0.5 mg/L (Cadmium)	0.4 mg/L	-20%

(Source: Sri Lanka Agricultural and Environmental Studies, 2022)

India: Positive Environmental Outcomes from Natural Farming

India's Natural Farming model, which emphasizes natural inputs and agroecological principles, has produced more promising environmental outcomes. Natural Farming was developed with the primary objective of improving soil health, reducing dependency on chemical inputs, and enhancing biodiversity on farms (Patel et al., 2021).

1. Soil Health Improvements

Natural Farming has demonstrated clear improvements in soil health across regions where it has been adopted. Studies conducted by the Indian Council of Agricultural Research (ICAR) in Andhra Pradesh and Karnataka have shown that soil organic matter content increased by 10-15% after three years of Natural Farming implementation (ICAR, 2022).

Table 10: Soil Health Improvements in Natural Farming Pilot Regions (2019-2022)

Indicator	Conventional Farming	Natural Farming	Improvement (%)
Soil Organic Carbon (%)	0.75%	1.10%	+46.7%
Microbial Biomass	290 mg/kg	400 mg/kg	+37.9%
Earthworm Population	25	40	+60.0%

(Source: ICAR, 2022)

2. Biodiversity and Ecosystem Services

Natural Farming's emphasis on eliminating synthetic pesticides and promoting biological pest control has enhanced biodiversity. Farmers reported increases in beneficial organisms such as pollinators and earthworms, essential for maintaining ecosystem balance (Joshi et al., 2022).

Table 11: Biodiversity Improvements in Natural Farming Farms (2019-2022)

Indicator	Conventional Farming	Natural Farming	Improvement (%)
Biodiversity Index	1.2 (baseline 1.0)	1.6	+33.3%
Pollinator Population	10	15	+50.0%
Beneficial Insects	30	50	+66.7%

(Source: Natural Farming Pilot Studies, 2022)

3. Reduction in Chemical Runoff and Water Pollution

One of the significant environmental benefits of Natural Farming has been the reduction in chemical runoff and water pollution. By eliminating synthetic fertilizers and pesticides, Natural Farming has minimized contamination of water bodies with harmful chemicals (Chaturvedi et al., 2022). This has contributed to improved local water quality and sustainability of agricultural systems in water-scarce regions.

Table 12: Water Quality Improvements in Natural Farming Regions (2019-2022)

Indicator	Conventional Farming	Natural Farming	Reduction (%)
Nitrate Levels (mg/L)	5.0 mg/L	2.5 mg/L	-50.0%
Phosphorus Levels (mg/L)	2.0 mg/L	1.0 mg/L	-50.0%
Pesticide Residue (µg/L)	10.0 µg/L	3.0 µg/L	-70.0%

(Source: ICAR, 2022)

Improvements in water quality, combined with enhanced soil health and biodiversity, make Natural Farming a promising model for sustainable farming in India, especially in regions facing environmental degradation due to conventional farming practices (Singh et al., 2021). The reduction in nitrate and phosphorus levels indicates a significant decline in nutrient leaching into water bodies, while the decreased pesticide residues demonstrate a lower environmental contamination risk (Chhabra et al., 2022).

Sri Lanka: Social Unrest and Farmer Protests

The sudden implementation of the organic farming policy in Sri Lanka led to widespread social unrest, particularly among the farming community. Sri Lanka's rural economy is heavily dependent on agriculture, with over 25% of the workforce engaged in farming, and the abrupt policy shift placed tremendous pressure on farmers who were ill-prepared for the transition (World Bank, 2021).

1. Farmer Protests and Political Instability

One of the most immediate social consequences of Sri Lanka's organic farming policy was the eruption of protests across the country. Farmers, who had long relied on synthetic fertilizers to maintain high crop yields, were suddenly left without adequate inputs to sustain their livelihoods (Kumar & Fernando, 2022). The government's failure to provide organic alternatives, combined with a sharp decline in agricultural productivity, led to widespread discontent among farmers (Jayatilaka & Pathirana, 2022).

Table 13: Timeline of Farmer Protests in Sri Lanka (2021-2022)

Date	Event Description
May 2021	Farmers begin protesting lack of organic inputs
August 2021	National protests escalate due to food shortages
December 2021	Food inflation reaches over 50%; protests grow
July 2022	President Rajapaksa resigns amid mass protests

(Source: Sri Lankan Government Reports, 2022)

2. Impact on Rural Livelihoods

The decline in agricultural productivity, particularly for key crops such as rice and tea, had a devastating impact on rural livelihoods. According to studies by Weeraratne (2022), the transition to organic farming resulted in a 25-30% reduction in yields for rice and tea, severely affecting farmers' income. Many farmers were unable to afford the organic fertilizers and pest control methods required to sustain their crops (Perera et al., 2022).

3. Food Insecurity and Public Health

The collapse in agricultural production led to widespread food insecurity. Sri Lanka's dependency on rice as a staple food exacerbated this crisis, with malnutrition and hunger affecting vulnerable populations (Fernando et al., 2021). Despite the initial goal of reducing chemical contamination, the sharp rise in food prices created more pressing public health challenges, including malnutrition (Samarawickrama et al., 2022).

India: Social Stability and Improved Farmer Livelihoods

India's gradual adoption of Natural Farming has yielded more positive outcomes, particularly in enhancing smallholder farmer livelihoods. By reducing input costs and promoting sustainable practices, Natural Farming has contributed to improved income for farmers while maintaining social stability (Ministry of Agriculture, India, 2022).

1. Improved Farmer Livelihoods

A key benefit of Natural Farming has been its ability to reduce reliance on costly chemical fertilizers and pesticides. Research by Patel et al. (2021) indicates that farmers practicing Natural Farming in Andhra Pradesh and Karnataka saw a 25-30% reduction in input costs, directly improving their profitability. Moreover, Natural Farming has contributed to alleviating debt burdens by lowering production costs (Sharma & Rao, 2020).

Table 14: Impact of Natural Farming on Farmer Livelihoods (2019-2022)

Indicator	Conventional Farming	Natural Farming	Improvement (%)
Input Costs (₹/ha)	₹45,000	₹32,000	-28.9%
Net Farmer Income (₹/ha)	₹20,000	₹25,000	+25.0%
Farmer Debt (₹/farmer)	₹50,000	₹35,000	-30.0%

(Source: Ministry of Agriculture, India, 2022)

2. Farmer Training and Capacity Building

India's success with Natural Farming can also be attributed to extensive farmer training programs. Governmentsupported programs helped farmers develop skills in producing natural fertilizers and pest control methods using locally available resources (Chaturvedi& Singh, 2021). Extension services provided ongoing support to help farmers troubleshoot challenges specific to local environmental conditions (Pawar& Mishra, 2021).

3. Social Acceptance and Community Engagement

Unlike Sri Lanka, where abrupt policy changes led to social unrest, India's gradual approach, supported by community organizations and local cooperatives, helped foster trust among farmers (Joshi et al., 2022). Financial incentives and subsidies further encouraged the adoption of Natural Farming methods (Mehta et al., 2021).

Sri Lanka: Political Instability and the fall of the Rajapaksa Government

1. Organic Farming Policy as a Populist Move

Decision to implement an organic farming policy was initially seen as a bold environmental initiative, intended to make Sri Lanka the world's first fully organic nation (Jayasuriya, 2022). However, critics argue that the move was politically motivated and lacked a scientific basis, as it did not account for the complex needs of Sri Lanka's agricultural sector (Perera et al., 2022).

2. Protests and Political Backlash

Protests that followed the food shortages and inflation were a clear expression of widespread dissatisfaction with the Rajapaksa administration. Research by Gunasekara and Samarasinghe (2022) highlights the direct link between food inflation and the escalation of political instability in Sri Lanka.

Table 15: Timeline of Political Events and Protests in Sri Lanka (2021-2022)

Date	Event Description
April 2021	Organic farming ban announced by President Rajapaksa
August 2021	First major farmer protests in rural areas
December 2021	Food inflation surges; nationwide protests escalate
April 2022	Mass protests in Colombo; demands for Rajapaksa's resignation
July 2022	President Rajapaksa resigns amid political instability

(Source: Sri Lankan Government Reports, 2022)

3. Collapse of the Rajapaksa Administration

Policy's failure led to the resignation of President Gotabaya Rajapaksa in July 2022, marking a significant shift in Sri Lanka's political landscape. The mishandling of the organic farming policy is often cited as a key factor in the administration's downfall (Wijesinghe, 2022).

4. Loss of Public Trust in Environmental Policies

Failure of Sri Lanka's organic farming policy also had broader implications for public trust in environmental and agricultural policies. The government's mishandling of the policy not only undermined confidence in organic farming as a viable model for sustainable agriculture but also damaged the credibility of future environmental initiatives. The abrupt policy shift, combined with the government's failure to provide adequate support and infrastructure for farmers, left many in the farming community skeptical of any future agricultural reforms.

India: Political Stability and Rural Development through Natural Farming

In contrast to Sri Lanka's experience, India's gradual adoption of Natural Farming has had a more positive political impact. The Indian government, under Prime Minister Narendra Modi, has used Natural Farming as part of its broader strategy for rural development and agricultural reform. The success of Natural Farming in improving farmer livelihoods and promoting sustainable agriculture has enhanced the government's credibility in rural areas and contributed to social and political stability.

1. Natural Farming as Part of India's Agricultural Reform Agenda

Natural Farming has been a key component of India's agricultural reform agenda, which aims to reduce farmer dependence on chemical inputs, lower cultivation costs, and improve agricultural sustainability. Unlike Sri Lanka's sudden policy shift, India's approach has been gradual and voluntary, allowing farmers to adopt Natural Farming at their own pace. This phased implementation has helped avoid the kind of social unrest and economic shocks experienced in Sri Lanka. Promotion of Natural Farming has been framed as part of Prime Minister Modi's vision for a "New India" that emphasizes rural development, selfreliance, and sustainability. The government's support for Natural Farming has included subsidies for organic inputs, farmer training programs, and investments in agricultural research. These efforts have been wellreceived by the farming community, particularly in states like Andhra Pradesh and Karnataka, where Natural Farming has been widely adopted.

2. Strengthening Political Support in Rural Areas

One of the key political benefits of Natural Farming has been its ability to strengthen the government's support base in rural areas. Smallholder farmers, who make up the majority of India's agricultural workforce, have been the primary beneficiaries of Natural Farming, as the model has helped reduce input costs and improve farmer incomes. By addressing the economic challenges faced by smallholder farmers, Natural Farming has helped the Modi government maintain its political support in rural communities.Unlike Sri Lanka, where the government's policies alienated rural voters, India's Natural Farming initiative has been embraced by many farmers as a viable alternative to conventional farming. The government's efforts to engage with farmers through consultations, pilot programs, and financial incentives have helped build trust and ensure that the policy is tailored to the needs of rural communities.

3. Reduced Farmer Protests and Political Stability

India's agricultural sector has historically been a source of political tension, with farmer protests often erupting in response to government policies. However, the gradual implementation of Natural Farming has helped reduce the risk of social unrest by allowing farmers to transition to natural farming methods at their own pace. The government's emphasis on capacity building, subsidies, and financial support has ensured that farmers are not left to bear the full cost of the transition. Success of Natural Farming in improving farmer livelihoods has also contributed to social and political stability in rural areas. Farmers who have adopted Natural Farming have reported lower debts, higher incomes, and greater financial stability, all of which have reduced the likelihood of protests and social unrest. This has helped the Modi government maintain its political stability and avoid the kind of widespread protests that plagued Sri Lanka.

4. Political Gains from Environmental Leadership

In addition to its economic and social benefits, Natural Farming has also positioned India as a leader in sustainable agriculture. The government's promotion of Natural Farming as a model for reducing chemical inputs, improving soil health, and enhancing biodiversity has helped India gain recognition on the global stage for its commitment to environmental sustainability. This has strengthened the Modi government's political capital both

domestically and internationally, as it has been able to frame Natural Farming as part of its broader efforts to combat climate change and promote sustainable development.

Table 16: Political and Social Benefits of Natural Farming in India (2019-2022)

Indicator	Before Natural Farming (2018)	After Natural Farming (2022)	Change (%)
Farmer Protests (per year)	100+	30	-70.0%
Rural Support for Government (%)	55%	65%	+10.0%
Farmer Trust in Government (%)	50%	68%	+18.0%

(Source: Ministry of Agriculture, India, 2022)

Lessons Learned from Sri Lanka's failure

1. The Importance of a Gradual Transition

One of the most critical lessons from Sri Lanka's failure is the importance of a gradual transition when shifting from conventional to sustainable farming practices. Sri Lanka's government implemented an immediate ban on synthetic fertilizers and pesticides without a phased approach, leaving farmers unprepared to adapt to organic methods. This abrupt shift led to a collapse in agricultural productivity, food shortages, and economic instability.In contrast, India's Natural Farming model emphasized a gradual and voluntary adoption of natural farming practices. By allowing farmers to transition at their own pace and providing pilot programs to test the viability of Natural Farming, India minimized the risk of economic shocks and maintained social stability. The phased implementation of Natural Farming enabled farmers to experiment with the model before committing to a full transition, ensuring that they were better equipped to handle the challenges of natural farming.

2. Government Support is Essential for Success

Another major lesson from the comparison is the critical role of government support in ensuring the success of agricultural transitions. Sri Lanka's government failed to provide sufficient support to farmers during the shift to organic farming. Organic fertilizers and pest control alternatives were in short supply, and the infrastructure needed to produce and distribute organic inputs was inadequate. Additionally, the government did not provide enough training or financial assistance to help farmers adopt organic methods.India's Natural Farming, on the other hand, benefited from substantial government support. The Indian government provided subsidies for organic inputs, facilitated farmer training programs, and invested in research and development to improve the effectiveness of Natural Farming practices. This support reduced the financial burden on farmers and ensured that they had access to the resources and knowledge needed to successfully transition to natural farming.

3. Stakeholder Engagement and Expert Consultation

Sri Lanka's policy failure can also be attributed to the government's lack of consultation with agricultural experts, scientists, and key stakeholders before implementing the ban on synthetic inputs. The decision to transition to organic farming was made without sufficient research into its feasibility or the potential economic and agricultural consequences. Farmers, who are the most affected by such policies, were not adequately consulted or

involved in the decision making process, leading to widespread resistance and protests.In contrast, India's Natural Farming model was developed through extensive consultation with agricultural experts, farmers, and local communities. Pilot programs were launched to test Natural Farming methods, and farmers were encouraged to provide feedback on their experiences. The government worked closely with research institutions and farmer cooperatives to ensure that the policy was scientifically sound and practically feasible.

4. The Need for Infrastructure and Access to Inputs

A key reason for the failure of Sri Lanka's organic farming policy was the lack of infrastructure to produce and distribute organic inputs. Organic fertilizers, such as compost and animal manure, are less nutrientdense than synthetic fertilizers, requiring larger quantities to achieve similar results. However, Sri Lanka's organic fertilizer production infrastructure was not adequately developed to meet the demands of the country's farmers. This led to widespread fertilizer shortages, contributing to the collapse of crop yields.India's Natural Farming model, on the other hand, placed a strong emphasis on locally sourced inputs. Natural Farming farmers are encouraged to produce their own biofertilizers and pest control agents using readily available materials such as cow dung, urine, and plantbased bio-enhancers. This focus on local inputs reduced dependence on external suppliers and ensured that farmers could access the resources they needed to maintain crop productivity.

5. Communication and Transparency

Lack of clear communication and transparency from the Sri Lankan government regarding the shortterm and longterm impacts of the organic farming policy also contributed to its failure. Farmers were not adequately informed about how the transition would be managed, what challenges they could expect, or how the government would support them during the shift. This led to confusion, mistrust, and widespread protests as farmers struggled to adapt to the new system.India's government, in contrast, made communication and transparency a priority in its promotion of Natural Farming. Farmers were informed about the potential benefits and challenges of Natural Farming through training programs, workshops, and government outreach initiatives. The government was also transparent about the financial incentives available to support farmers during the transition, building trust and encouraging participation in the program.

6. Balancing ShortTerm and LongTerm Goals

Both Sri Lanka and India aimed to achieve longterm environmental benefits through their agricultural policies, including improved soil health, reduced chemical use, and enhanced biodiversity. However, the difference in their approaches to balancing shortterm and longterm goals is stark.Sri Lanka's focus on immediate environmental benefits, such as the elimination of synthetic fertilizers and pesticides, came at the expense of shortterm agricultural productivity. The government failed to account for the fact that organic farming practices often result in lower yields in the short term, particularly in the early stages of the transition. This focus on longterm environmental goals without considering the immediate needs of farmers led to a collapse in crop yields and widespread food shortages.India's Natural Farming model, on the other hand, struck a better balance between shortterm and longterm goals. Natural Farming practices were introduced gradually, allowing farmers to maintain productivity while adopting more sustainable practices over time. This approach ensured that food security was not compromised during the transition and that the longterm environmental benefits of natural farming could be achieved without sacrificing short term economic stability.

7. The Role of Research and Development

Research and development (R&D) played a critical role in the success of India's Natural Farming model. The Indian government invested in agricultural research institutions to study the effectiveness of Natural Farming practices, improve biofertilizers, and develop regionspecific solutions for natural farming. This focus on R&D ensured that Natural Farming was based on scientific evidence and that farmers had access to the latest innovations in sustainable agriculture.In Sri Lanka, the lack of scientific research and preparation before implementing the organic farming policy was a major factor in its failure. The government did not conduct sufficient trials or pilot programs to assess the viability of organic farming for different crops and regions. As a result, the policy was poorly suited to the realities of Sri Lanka's agricultural sector, leading to widespread crop failures.

Conclusion

Contrasting outcomes of Sri Lanka's and India's attempts to transition to sustainable agricultural practices offer a wealth of insights for policymakers and agricultural experts. Both countries were motivated by the need to improve environmental sustainability, enhance soil health, and reduce reliance on chemical inputs. However, their drastically different approaches—Sri Lanka's sudden shift to organic farming versus India's gradual adoption of Natural Farming produced contrasting results, with important lessons for other nations seeking to implement similar policies.The abruptness of Sri Lanka's transition to organic farming led to widespread economic, social, and political consequences. The government's decision to ban synthetic fertilizers and pesticides overnight, without sufficient preparation or support for farmers, resulted in a sharp decline in agricultural productivity. This, in turn, caused food shortages, inflation, and social unrest. The collapse of the Rajapaksa administration was a direct consequence of the public dissatisfaction caused by the policy's failure, highlighting the critical importance of policy design and stakeholder engagement.India's Natural Farming model, by contrast, offers a more promising example of how to approach the transition to sustainable agriculture. Through a phased and voluntary approach, combined with substantial government support, India has been able to gradually scale up natural farming practices without causing economic disruption. Natural Farming has helped reduce input costs for farmers, improved soil health, and promoted environmental sustainability, while maintaining political and social stability. These successes demonstrate the value of a wellplanned, researchbacked approach to agricultural reform.

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HARNESSING BAMBOO: THE GREEN REVOLUTION IN CLIMATE CHANGE MITIGATION AND ADAPTATION

Clara Manasa P. A[1], Supriya K Salimath[1], Ramakrishna Hegde[1] and Manjunath Gooli[2]

[1]College of Forestry, Ponnampet, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, 571216, India
[2]Karnataka Forest Department, Karnataka, 571216, India
Corresponding E-mail: claramanasapa@gmail.com

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Abstract

Climate change is accelerating at an unprecedented rate, driven primarily by manmade greenhouse gas emissions, especially CO_2. Various mitigation strategies have been proposed to limit the global temperature rise to 2°C. While forests have been prioritized in carbon sink management within climate policies, bamboo-dominated systems remain underexplored. This review article highlights bamboo's potential for climate change mitigation and adaptation. Bamboo, often referred to as the "green gold" and "poor man's timber," has garnered the attention of researchers due to its unique qualities, including adaptability, rapid growth, flexibility, and ability to thrive in diverse soil conditions. It has significant potential for carbon substitution through biomass-based energy sources like biochar and bamboo-based wood products. Remarkably, bamboo can sequester more carbon in its early years of establishment than many forest trees. Moreover, bamboo's versatile growing nature, renewability, and wide range of uses make it an excellent option for climate change adaptation efforts. Its applications extend beyond environmental benefits to economic advantages, as bamboo cultivation can provide sustainable livelihoods for rural communities.

Keywords: Carbon dioxide, Carbon sequestration, Carbon trading, Fast growing, Green House Gas

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Introduction

Various natural factors contribute to the Earth's ongoing climate changes. Nonetheless, human-induced global warming, driven by the release of heat-trapping greenhouse gases (GHGs), is the leading factor behind the swift and dramatic shifts in climate patterns globally. This warming effect is linked to rising sea levels and increased climate variability, resulting in events like heat waves, severe droughts, and intense storms. The consequences of climate change and its variability are projected to adversely affect the economy, society, and the environment significantly (FAO, 2013). The primary driver of global warming is the emission of GHGs, with carbon dioxide (CO_2) and methane (CH_4) responsible for over 90% of these emissions. Major sources include the combustion of fossil fuels (coal, oil, and natural gas) for energy, alongside contributions from agriculture, deforestation, and industrial activities. There is unanimous agreement among national and international scientific bodies regarding the human influence on climate change.

Climate feedback mechanisms involve changes in carbon sinks on land and in oceans, the reduction of sunlight-reflecting snow and ice cover, and increasing water vapor (a GHG), among other factors (Mollah *et al*., 2021). Compared to the baseline average from 1951 to 1980, surface air temperatures from 2011 to 2020 have risen. Since the late 19th century, the global average temperature has increased by over 1.2°C (NASA, 2020). Several policies and measures have been introduced to tackle climate change. A notable initiative is the Intergovernmental Panel on Climate Change (IPCC), which addresses climate change adaptation and mitigation. The Clean Development Mechanism (CDM) under the Kyoto Protocol (KP) aims to support sustainable development in developing countries while helping industrialized nations meet their carbon reduction targets. The IPCC offers various recommendations (IPCC, 2007) to mitigate the rate of climate change, including the development of cleaner and more efficient energy sources, improvements in transportation, building practices, industry, and waste management, as well as modifications in agricultural practices to reduce methane from paddy fields and manure, and lower nitrous oxide emissions from fertilizers. Additionally, the IPCC suggests enhancing forest management, increasing afforestation and reforestation, reducing deforestation, and boosting the natural ability of ecosystems to absorb CO_2 to decrease atmospheric CO_2 levels (Quiroga *et al*., 2013). Understanding the carbon sequestration capabilities of forests can enhance our grasp of their role in the global carbon cycle and inform the implementation of these strategies.

Carbon sequestration refers to a geoengineering method for capturing and storing CO2 that would otherwise enter the atmosphere (Manasa *et al*., 2016). Artificial carbon sequestration methods, such as capturing and storing CO_2 emissions from fossil fuel power plants in underground reservoirs, are gaining traction. However, biological carbon sequestration is also an effective natural mechanism. During photosynthesis, plants absorb CO2 and store the carbon within their tissues. According to Dixon *et al*. (1993) and Brown *et al*. (1996), increasing tree cover is a cost-effective way to mitigate climate change. Recent research on conservation, restoration, and improved land management suggests a potential for mitigating up to 23 $GtCO_2$. Efforts in this domain largely focus on reduced deforestation, reforestation, and better forest management, especially in tropical areas (Houghton, 2013; Canadell and Schulze, 2014; Grace *et al*., 2014; Houghton *et al*., 2015). This review paper aims to highlight the potential role of forests in carbon sink management within climate policies, with a particular emphasis on bamboo-dominated systems, which have received relatively less attention.

Bamboo Resources and their Importance

Bamboo, often known as "green gold," "poor man's timber" or "timber from cradle to coffin" is a woody grass that belongs to the Poaceae family and plays a crucial role in many forest ecosystems. Over the past few decades, bamboo has garnered global attention due to its versatile utility, ranging from household items to rural housing and industrial raw materials (Dransfield and Widjaja, 1995). Traditionally, bamboo has been used for fuel, food, rural housing, shelter, fencing, tools, and other purposes. In certain regions of Asia, bamboo has been so intricately woven into the fabric of human culture and history that it is often referred to as a "bamboo civilization" (Nath *et al*., 2015). Consequently, the view of bamboo stands is undergoing a dramatic transformation, evolving from being seen merely as the "poor people's trees" to "high-tech industrial raw resources" that can substitute timber and other materials traditionally sourced from natural forests (Lobovikov *et al.*, 2009). The unique characteristics of bamboo, compared to other forest species, significantly enhance its utility.

Bamboo's flexibility and ability to thrive in varied soils make it suitable for re-greening degraded areas, wastelands, and other problematic regions. It is the fastest-growing species, maturing in four to five years. Most bamboo species can be harvested around this age due to their early maturity, with new culms adding to the clump annually, thus supporting the surrounding ecology. Bamboo's extensive rhizomatous root system helps hold soil and control landslides, making it suitable for planting near rivers and on steep slopes to prevent soil erosion (Manasa *et al.*, 2022). The leaf litter of most bamboo species is favored by earthworms and bacteria, aiding in transforming poor soil into rich soil. Bamboo groves have a superior ability to recharge groundwater and effectively purify local water compared to natural stands, thus playing a crucial role in regulating the water cycle. The lush green canopy of most bamboo species provides an excellent under storey, making them ideal for agroforestry systems. Consequently, bamboo is considered an asset that supports poverty reduction, economic development, and environmental conservation (Paudyal *et al.*, 2019).

Approaches for Climate Change with Bamboo

Bamboo has proven to be extremely important for humanity on numerous levels over time. It should be seen as a potential tool for addressing the issue of climate change adaptation and mitigation (Kuehl *et al.*, 2011). Globally, climate change is being addressed in various ways and the Strategies include:

1. Mitigation: Reducing GHG emissions and stabilizing atmospheric levels.
2. Adaptation: Adjusting to ongoing climate changes.

The International Network of Bamboo and Rattan (INBAR) has shown that managed bamboo can outperform some tree species in carbon sequestration (INBAR, 2009). Sustainable harvesting and durable bamboo products contribute to its effectiveness as a carbon sink (INBAR, 2009). Bamboo's rapid growth, renewability, and economic advantages make it a valuable tool for reducing greenhouse gas emissions and expanding bamboo forests (Sandhu *et al.*, 2010; Tewari *et al*., 2016; Terefe *et al*., 2019).The schematic representation (Figure 1) below illustrates how bamboo can be used to address the issue of climate change through mitigation and adaptation (Kuehl *et al*., 2011).

Bamboo for Climate Change Mitigation

Mitigation with the help of bamboo can be approached in two ways:

a) Sequestration: Bamboo, as a woody perennial, has the potential to sequester atmospheric CO_2 and store it in its biomass as carbon. The biomass and atmospheric CO_2 sequestered by bamboo are also stored in the soil as organic carbon (Hinkle *et al*., 2019).

b) Substitution: Substituting bamboo for standing biomass acts as a long-term carbon sink by converting bamboo culms into durable products even after their harvest. To maintain its status as a net carbon sink, the bamboo system must ensure that carbon is stored in different forms so that the total carbon sequestered exceeds the amount released into the atmosphere. This is crucial because bamboo culms, which reach maturity in 5-10 years, decompose quickly afterwards, returning carbon from the biomass to the environment (Singh *et al.,* 2012; Kuehl *et al*., 2011).

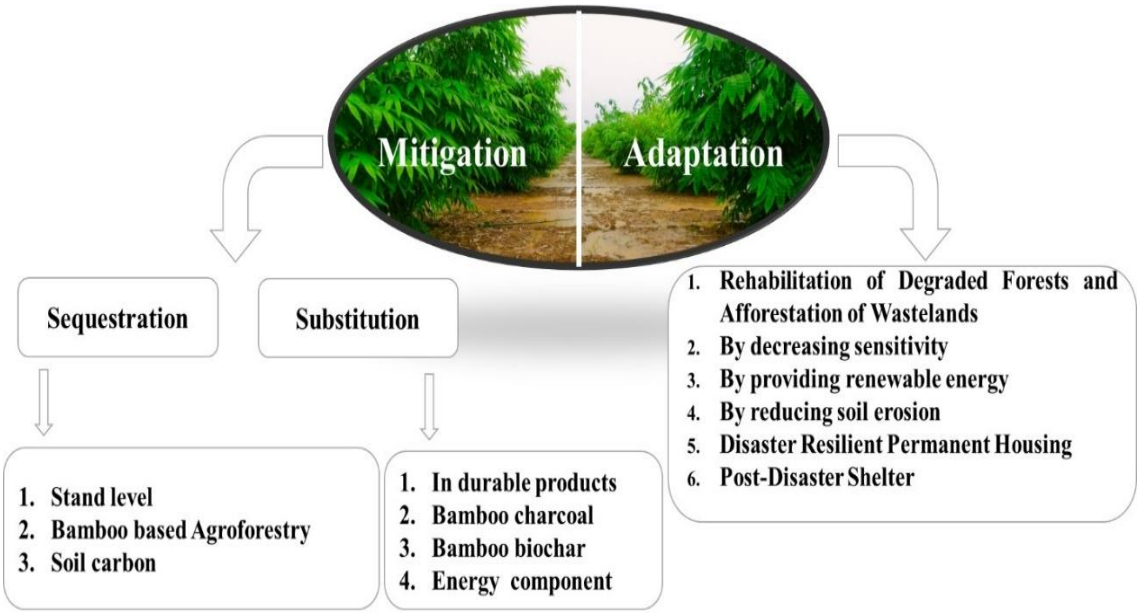

Figure 1: Schematic Representation Displaying the Approaches for Climate Change Mitigation with Bamboo

Bamboo for Sequestration

Sequestration at Stand Level

Human activities are estimated to produce approximately 30 billion tons of CO_2 equivalent annually. The rate of biomass production and storage in vegetation systems is crucial for quantifying system output and sustainability, thereby determining the carbon sequestration potential for mitigating climate change (Salimath *et al.,* 2022). Bamboo offers one of the most efficient methods for removing large amounts of CO_2 from the atmosphere and can generate up to 35 percent more oxygen compared to an equivalent stand of carbon-storing trees. Bamboo forests have the potential to produce biomass carbon storage ranging from 30 to 121 t ha^{-1}, with an annual sequestration rate of 6 to 13 t ha^{-1} (Andreola *et al*., 2022). Bamboo grows its full height in just a year, although it takes a few more years to mature, during which its biomass increases due to ongoing chemical and structural changes. Carbon sequestration in bamboo involves both the growth of new culms and the biomass in older ones. Early in its life, bamboo sequesters more carbon than trees (Yuen *et al.,* 2017; Hinkle *et al*., 2018). Studies show that *Guadua angustifolia*, a timber bamboo from Latin America, sequesters more carbon than three North American tree species (Hinkle *et al*., 2019), and Moso bamboo is 2.5 times more efficient than several fast-growing Asian woods (Nath *et al*., 2015). Managed bamboo stands can produce up to three times more biomass compared to unmanaged ones. For instance, managed Moso bamboo forests can sequester more carbon than fast-growing trees like Chinese fir (Kuehl and Yiping, 2012). Conversely, unmanaged bamboo stands have lower productivity and release stored carbon more quickly when older culms decay.

Managed bamboo can sequester up to 62 t CO_2 per hectare annually, while a young forest of similar size sequesters only 15 t CO_2. A *Guadua* plantation in Costa Rica absorbs about 17 t CO_2 per hectare each year (Janseen, 2000). A typical Moso bamboo ecosystem stores 106.36 t of carbon per hectare, with 34.30 t in above-ground vegetation and 72.20 t in the soil (Zhou and Jiang, 2004). Bamboo forests fix 5.10 t of carbon per hectare annually, surpassing tropical rainforests and Chinese fir at various growth stages (Zhao *et al*., 2009). Total carbon storage in bamboo forests increased from 318.60 Tg C (1950-1962) to 631.60 Tg C (1999-2003) (Chen *et al*., 2009). Bamboo, with its high carbon content, is highly effective for carbon fixation. Carbon storage capacity rises with culm diameter and density (Hauchhum and Singson, 2019). For *Guadua angustifolia*, above-ground biomass is about 200 tonnes per hectare, storing 100 tonnes of carbon, similar to some tree species like Chinese fir (Quiroga *et al*., 2013). Carbon stocks vary among bamboo species, from 13.13 t C ha^{-1} in *Oxytenanthera abyssinica* to 67.78 t C ha^{-1} in *Phyllostachys aurea* (Barnabas *et al*., 2020), and range from 36.34 to 64.00 t ha^{-1} in *Bambusa tulda* and 50.11 to 65.16 t ha^{-1} in *Dendrocalamus longispathus* (Devi and Singh, 2021).

Sequestration in Bamboo-Based Agroforestry

Recently, the demand for bamboo has surged faster than its supply, making it necessary to expand bamboo cultivation both within and outside forested areas to meet this increasing demand. Agroforestry and farm forestry are viable approaches for sustaining bamboo supply for commercial use. Dev *et al.* (2020) highlight the significant potential for bamboo-based agroforestry due to its low capital investment requirements and resilience to extreme climatic conditions. There is also a focus on incorporating bamboo into agroforestry systems on harsh, eroded lands, and hill slopes to ensure productivity and rapid returns (Kishwan *et al*., 2005). Additionally, bamboo is being considered for planting along riverine areas and irrigation canals as part of bund and boundary-based agroforestry systems (Manasa *et al*., 2022). These systems are promising for Clean Development Mechanism (CDM) projects and climate change mitigation (Dhyani *et al*., 2016; Nath and Das, 2012).

In the context of climate change, agroforestry has emerged as a highly attractive economic and ecological strategy for mitigating greenhouse gas emissions (Dhyani *et al*., 2016). Nath and Das (2012) explored the ecological benefits of integrating bamboo into village agroforestry systems as a global climate change mitigation strategy. In homegardens managed by farmers, where fresh culms are not harvested, the carbon sequestered by bamboo can be considered a net gain, demonstrating that smallholder bamboo farming systems can effectively sequester carbon while fulfilling essential rural needs through the harvest of mature culms. In Northern Ethiopia, older culms of *Oxytenanthera abyssinica* stored more carbon than younger culms, with 3.80, 3.90, and 3.50 kg of carbon per culm for age classes less than one year, and one to three years, respectively (Darcha and Birhane, 2015). The carbon storage potential of traditional agroforestry systems in waterlogged conditions in northeastern India was documented by Sarkar *et al.* (2021), identifying these systems as excellent carbon sinks and promising components for climate change mitigation.

Sequestration under Bamboo Soil

Soil carbon sequestration (SOC) is a vital strategy for mitigating the increasing CO_2 concentrations in the atmosphere due to climate change. Bamboo soils, like those in tropical forests, play a significant role in this process. Carbon sequestration in bamboo stands varies significantly, with storage levels between 54.39 and 89.28 tons of carbon per hectare, averaging 66.52 tons per hectare. The organic carbon content is approximately 2.90% (Borisade *et al*., 2018). In the North East region of India, the carbon content in forest floor material is approximately 115.3 kilograms per hectare. Here, leaf litter contributes the largest amount at 76.32 kilograms of carbon per hectare, followed by sheath and branch material at 35.34 and 3.64 kilograms of carbon per hectare, respectively, based on data from 100 home gardens and 40 bamboo groves (Nath and Das, 2012). Additionally, research by Sirsat *et al.* (2021) indicates that carbon storage in the soil is influenced by the age of bamboo plantations, with surface layer carbon stocks ranging from 13.52 to 22.97 tons per hectare and subsurface layer stocks ranging from 12.44 to 22.34 tons per hectare. This indicates that older bamboo plantations tend to have higher carbon sequestration potential. Zhuang *et al.* (2011) reported significant carbon accumulation in *Phyllostachys praecox* f. *prevernalis* soils when large volumes of organic material were used for mulching.

In North East India, bamboo-based agroforestry systems demonstrated a SOC rate of 0.59 t ha^{-1} yr^{-1}, which was compared favorably with other tropical agroforestry systems at similar soil depths (Nath *et al.*, 2015). Dev *et al.* (2017) confirmed an increase in organic carbon content over time in bamboo-based agroforestry systems. Similarly, extensively managed Moso bamboo plantations in subtropical China were found to enhance soil organic carbon, aggregate stability, and amorphous iron, indicating that increased soil carbon stocks were attributed to greater carbon input and improved preservation due to enhanced shrub diversity (Yang *et al*., 2021).

3.1.2 Bamboo for Substitution

Bamboo species mature and degrade quickly, releasing carbon from their biomass into the atmosphere (Liese, 2009). This process leads to a stable level of above-ground carbon, where emissions from older culms balance the carbon capture. To keep bamboo as a net carbon sink, it is crucial to store carbon in various forms to ensure that retained solid carbon exceeds what is released into the air (Singh *et al*., 2012).

Substitution: In Durable Products

In bamboo forests, culms are regularly harvested for product manufacturing. Consequently, the forest's carbon sequestration capability relies on the usage, longevity, and durability of the harvested material and its products (Kuehl *et al*., 2011). Bamboo is highly efficient in minimizing waste, as nearly every part can be used in production. Durable bamboo products can sequester carbon for extended periods, maintaining carbon storage until the products are discarded or incinerated. INBAR reports that bamboo has over 10,000 recognized uses globally, with its use and market expected to grow significantly. Bamboo's strength and stiffness surpass those of wood, brick, and concrete, and it exhibits tensile strength comparable to steel. The absence of rays and knots in bamboo's stem results in more uniform yield stress strength compared to wood (Baghel and Thakkar, 2017). Its qualities—such as pest resistance, durability, flexibility, and availability—make it ideal for various construction applications, including walls, piers, roofs, floors, and room dividers. These structures are valued not only for their aesthetic appeal but also for bamboo's exceptional engineering properties (Ogunbiyi *et al.,* 2015). Nath *et al.* (2009) reported that bamboo's tensile strength is 17 percent greater than steel, 27 percent greater than red oak, and 13 percent harder than hard maple.

In managing carbon sinks amid climate change, key factors include (i) the sustainability and renewability of the product, (ii) its carbon sink capacity, and (iii) the longevity of the stored carbon. Traditional bamboo products, despite retaining substantial CO_2, often have a short lifespan, which limits their effectiveness in long-term carbon sink management (Ray *et al*., 2020). Therefore, effective preservative treatments are essential for extending the lifespan of bamboo products. The carbon transfer rate affects the carbon stock in bamboo products: higher carbon stocks are achieved with better carbon transfer ratios during production. Since boiling and carbonizing processes can lead to significant carbon loss, improving these methods can enhance carbon retention and reduce the carbon footprint of bamboo products (Baghel and Thakkar, 2017). Efficient preservative treatments can extend product durability, thereby increasing the longevity of sequestered carbon. Advances in technology have enabled the creation of more durable bamboo items, ensuring that stored carbon remains sequestered for longer periods and enhancing bamboo's carbon storage potential (Terefe *et al.*, 2019).

Substitution: Bamboo Charcoal

Bamboo charcoal, a by-product of anoxic bamboo pyrolysis, has a range of applications, including the potential to replace coal in thermal processes (Chen *et al.*, 2016). Pyrolyzing 38 tonnes of dry bamboo biomass can produce approximately 9.5 tonnes of charcoal, assuming a conservative charcoal yield of 25 percent. The net calorific value of bamboo charcoal is 25,000 MJ t^{-1} (Ganesh, 2003). Compared to wood charcoal, bamboo charcoal is three times more porous, releases more energy, and provides a substantial fuel backup (Hossain *et al.*, 2015). Bamboo charcoal is also beneficial for nutrient conservation and heavy metal stabilization due to its high adsorption capabilities. Chen *et al.* (2010) found that adding bamboo charcoal to pig manure composting effectively reduced total Kjeldahl nitrogen loss and controlled the mobility of copper (Cu) and zinc (Zn). Similarly, Li *et al.* (2017) perceived that bamboo charcoal decreased the bioavailability of Cu and Zn in chicken manure composting, thereby reducing the co-selection pressure from heavy metals. Furthermore, bamboo charcoal briquettes are commercialized in Asian and African countries, primarily for cooking and heating applications (Montaño and van Dam, 2021).

Substitution: Bamboo Biochar

Biochar, durable solid rich in pyrogenic carbon, can persist in soil for millennia. When biochar is produced through anaerobic combustion and integrated into soil, it sequesters roughly half of the carbon initially present in the biomass. Bamboo biochar, in particular, stands out as an effective long-term carbon sink, benefiting both energy production and agricultural practices. By converting biomass into biochar, we enhance the retention of carbon in the soil, as it mitigates CO_2 emissions by offsetting the rate of organic matter decomposition (Lehmann and Joseph, 2015; Maulana *et al.*, 2021). Compared to traditional wood charcoal, bamboo biochar is far superior, offering about five times greater porosity and ten times higher absorption capacity. It also demonstrates exceptional performance in environmental applications. For instance, a bamboo biochar and montmorillonite composite has been shown to effectively treat industrial effluents or wastewater, particularly those contaminated with anionic pollutants like nitrates (Viglašová *et al.*, 2018). Moreover, bamboo-derived porous biochar holds promise as a desulfurization adsorbent, aiding in the production of ultra-clean fuel oils (Yang *et al.*, 2018). Its diverse applications accentuate its value in both environmental management and resource recovery.

Substitution: Other Energy Components

Bioenergy is a low greenhouse gas emitter with minimal net radiative forcing on the atmosphere. Bamboo, with its substantial biomass production, presents a compelling bioenergy source in tropical regions (Fielden, 1999). Utilizing bamboo for bioenergy helps conserve carbon sequestered in fossil fuels and it can contribute to preserving natural forests (Seethalakshmi *et al.*, 2009). Recently, bamboo has gained recognition as a key player in bioenergy production due to its availability and socio-economic feasibility (Sharma *et al.*, 2018). Rathour *et al.* (2022) advocate for promoting bamboo as a potential feedstock because of its high biomass yield, making it a viable commercial source for producing next-generation biofuels like bioethanol. Bamboo can be utilized as an energy source through various methods, enhancing its role in bioenergy. Several bamboo biomass energy conversion processes are discussed below (Figure 2) (Dube, 2008; Truong and Le, 2018).

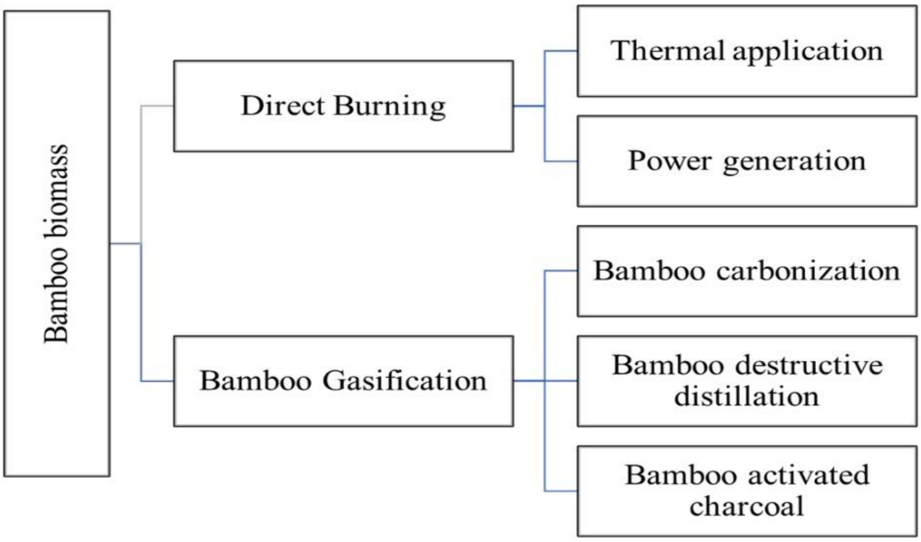

Figure 2: Bamboo Bioenergy Conversion Processes *(Source: Dube, 2008)*

Bamboo biomass, like any other biomass, can be directly burned for heat and electricity generation. It has the potential to replace coal in thermal applications. With a net calorific value of 16 GJ t^{-1} dry matter, a CO_2 emission factor of 96.1 t CO2 TJ^{-1} (IPCC, 2006), and a 75 percent thermal conversion efficiency, bamboo can achieve an emission reduction of 44 t CO2 ha^{-1} per rotation. Each rotation's biomass from a hectare of bamboo crop contains 608 GJ of energy, which can generate 56 MWh of power, assuming a power-generating efficiency of 33 percent (Dube, 2008).Bamboo gasification is an industrial technology where heated bamboo produces goods without or with a limited air supply. Bamboo is heated in brick kilns or mechanical kilns with limited air, using heat from burning firewood to pyrolyze bamboo and make bamboo charcoal. The carbonization and activation processes of bamboo determine its usage and can impact structural qualities like surface area, pore volume, adsorption, and conductivity (Isa *et al*., 2017). Carbonized bamboo, often used for flooring, is considered an environmentally favorable building material because it matures in three years and regenerates without replanting. The charcoal manufacturing process softens bamboo fibers by 20% - 30%, and the fibers must be treated for strength and endurance (Willard, 2017). Bamboo activated carbon is produced by heating bamboo material in a brick kiln and an activated kiln. Khuong *et al.* (2021) found that hydrothermal treatment can efficiently convert bamboo and its solid byproducts into porous carbon using CO2 for physical activation. The resulting solid residue is particularly promising for producing activated carbon because of its low ash content.

Bamboo is an appealing resource for bioethanol production due to its rapid growth and plentiful, sustainable supply in tropical regions (Kuttiraja *et al*., 2013). Bioethanol derived from bamboo is both technically and economically comparable to gasoline. Nevertheless, new strategies are required to lower bioethanol production costs to enhance its feasibility. These approaches may involve improving sugar extraction through more efficient pre-treatments and reducing enzyme usage, securing affordable bamboo feedstock, or choosing feedstocks with higher or more readily available cellulose content (Littlewood *et al*., 2013). Barathi (2018) reported that four kilograms of bamboo can yield 1.20 liters of ethanol, and an acre of bamboo can produce 10,000 liters of ethanol annually.

Bamboo for Climate Change Adaptation

The IPCC describes adaptation as "modifications in ecological, social, or economic systems in response to present climate shifts and their impacts." It involves altering existing practices or preparing for future environmental changes to adapt to a changing climate. The aim is to decrease our susceptibility to the negative consequences of climate change, such as rising sea levels, extreme weather events, and food scarcity. Bamboo, with its capacity to flourish in diverse climates and environments, renewability, and multiple applications, presents an excellent choice for climate change adaptation strategies.

Adaptation through the Restoration of Degraded Forests and Afforestation of Wastelands

Bamboo can be instrumental in restoring productive and functional ecosystems, especially in areas affected by climate change or unsuitable for traditional cultivation (Baghel and Thakkar, 2017). Ideal for deforested and degraded lands, bamboo plantings improve soil quality and boost the productivity of surrounding crops. In an INBAR project near Allahabad, India, bamboo species were used to restore soil damaged by brickfield mining. Within a few years, bamboo cultivation on the residual soil significantly improved its quality (Dwivedi *et al.*, 2019). Projects in India and Nepal have demonstrated bamboo's effectiveness in converting degraded regions into economically viable systems, enhancing soil quality, raising water tables, and reducing dust storms (Yiping *et al*., 2010; Gautam *et al*., 2018). Bamboo cultivation on such lands supports diverse agricultural systems, including medicinal plants and fisheries.In Central India, Eco-Rejuvenation Technology (ERT) using five bamboo species—*Bambusa balcooa* Roxb., B. *vulgaris* var. vittata, *B. vulgaris* var. *striata* (Yellow), *B. nutans* Wall. ex. Munro, and *Dendrocalamus asper* Backer—was implemented to reclaim and restore degraded land. This approach significantly increased soil biomass and carbon sequestration capacity within a year (Singh *et al*., 2020).Bamboo's role in eco-restoration of degraded lands has garnered significant attention from foresters, ecologists, and soil scientists. Consequently, bamboo plantations positively impact soil erosion control, biodiversity preservation, and enhancement of capacities in degraded land restoration (Mishra *et al.*, 2014).

Adaptation by Reducing Sensitivity

Developing adaptation strategis for a changing climate is a prolonged, ongoing process. Bamboo, being a rapidly growing species, helps establish productive stands within a few years, with culms ready for harvest in 3–6 years depending on the species. This swift establishment enhances flexibility in management and harvesting practices in response to climate changes and reduces susceptibility to external threats such as fires or severe weather (Kuehl *et al*., 2011). For instance, flooding in 2010 inundated fields in four Village Development Committees in Madi, within Chitwan National Park, Nepal. The flood destroyed banks, causing extensive property damage. In response, the Adoption of Bamboo and Rattan Initiatives (ABARI) and WWF launched the Hariyo Ban project in October 2014, planting 10,000 bamboo clumps for biodiversity conservation and land restoration, using 24 bamboo species for ecosystem management (FAO and INBAR, 2018).

In the winter of 2008, heavy snowfall in central and southern China caused numerous bamboo culms to break. By 2010, the forest had been restored, with new culms replacing the damaged ones (Kuehl *et al.,* 2011). Similarly, after forest fires, bamboo can recover more swiftly than trees and other crops. The underground rhizome survives the fire, and its stored resources enable vigorous regrowth, allowing bamboo to outcompete other plants for space in the burnt area (Ferreira *et al.,* 2020).

Adaptation by Providing Renewable Energy

With rising energy demands in many developing countries, deforestation for domestic energy has become a significant contributor to greenhouse gas emissions. Bamboo charcoal and firewood are increasingly recognized as environmentally friendly alternatives to meet the energy needs of rural and urban populations. They can help mitigate deforestation by offering a more sustainable energy source compared to traditional wood. Bamboo, like other biomass, can be converted into liquid, solid, or gaseous fuels, as well as other chemical compounds, heat, and power through various conversion processes (Montaño and Van Dam, 2021). Integrating multi-purpose perennial bamboo crops into Indonesia's energy systems could significantly help the country achieve its renewable energy targets (Sharma *et al.,* 2018). Additionally, it can support land restoration efforts by offsetting the substantial costs associated with meeting the Bonn Challenge's restoration goals.

Adaptation by Reducing Soil Erosion

Bamboo is particularly valuable in areas prone to runoff, such as steep slopes, riverbanks, or degraded fields, due to its extensive root and rhizome systems that stabilize the soil, holding up to 6 m^3 of soil. As an evergreen plant, bamboo provides a dense canopy and ground cover, preventing direct splash erosion and enhancing infiltration. Its deep roots assist in soil absorption, making it advantageous for riverbank stability. Furthermore, bamboo can collect and store rainwater for later use, reducing water flow in streams and rivers and minimizing erosion. Planting bamboo along riverbanks for five years can reduce soil erosion by up to 85 percent *(Singh et al., 2021)*. The bamboo species *Ochlandra spirostylis* is particularly suited for riverbank stabilization. The biological interaction between microorganisms in the topsoil and the fibrous root systems of *Ochlandra* species produces water-stable macroaggregates. Consequently, pure reed patches of *Ochlandra* species are considered a stable vegetation climax capable of improving soil's physical properties, stabilizing slopes, and preventing land degradation (SijiMol *et al.,* 2016).

Disaster-Resilient Permanent Housing

One of the key aspects of climate change adaptation is enhancing resilience against unpredictable natural disasters in the context of future climate conditions. During the reconstruction phase, a mix of technical, economic, and social factors is used to ensure that new structures are not only earthquake-resistant but also sustainable and livable. It is crucial that earthquake-resistant construction techniques become a standard practice among builders and homeowners. Bamboo emerges as a promising material for this purpose, with its potential to improve architectural design, making it more functional, durable, safe, eco-friendly, climate-responsive, and socially acceptable. However, to fully realize its potential, bamboo must be treated with technical measures to qualify as a structurally safe and long-lasting building material (Baghel and Thakkar, 2017). In India, various bamboo house designs demonstrate its versatility and cultural importance. Examples include the Chang

Ghar, a bamboo hut elevated on stilts; bamboo huts built directly on the ground; and the Ekra house, also known as the Assam-type house, which combines bamboo with other local materials (Das and Mukhopadhyay, 2018). Each of these constructions illustrates how bamboo can be integrated into various architectural styles and adapted to different environmental conditions, underscoring its role in sustainable building practices.

Post-Disaster Shelter

Bamboo is an excellent material for post-disaster shelter construction due to its rapid growth, sustainability, and strength. Its natural flexibility makes it highly resistant to earthquakes, reducing the risk of structural collapse (INBAR, 2011). Following the Lombok earthquake in 2018, a unique prototype of a temporary bamboo house, called Akin, was developed to assist local populations in rebuilding their homes (Fajrin *et al.*, 2021). In Assam, India, annual floods create a critical need for effective post-disaster shelters. According to Dev and Das (2020), traditional tents become uncomfortable in the hot and humid weather following floods and increase the risk of vector-borne diseases. Thus, developing housing structures using bamboo, with wall cladding made from woven bamboo mats measuring 120 cm × 250 cm, was essential. In terms of construction, bamboo offers excellent insulation properties, helping to maintain comfortable temperatures inside shelters. Its natural hollow structure allows for effective ventilation, enhancing the living conditions for occupants. The aesthetic appeal of bamboo also contributes to the psychological well-being of disaster survivors, promoting a sense of stability and normalcy. Sil (2016) highlighted that bamboo composites are attractive due to their low embedded energy (the energy required for manufacturing), particularly compared to materials like aluminum and steel. Furthermore, bamboo composites offer excellent impact resistance, thermal and acoustic insulation, and corrosion resistance, making them ideal for construction. Additionally, bamboo bio-concrete (BBC), made by combining bamboo particles, conventional Portland cement, and materials like metakaolin and fly ash, offers a valuable climate change adaptation option by enhancing carbon storage and reducing operational carbon (Caldas *et al.*, 2019). In regions where bamboo is abundant, BBC provides a viable solution for mitigating and adapting to the adverse effects of climate change (Caldas *et al.*, 2020).

Opportunities for Carbon Trading and Carbon Farming

Carbon has become a marketable commodity due to the growing climate financing mechanisms (Salam and Dube, 2009). Carbon trading is a market-based approach to reducing greenhouse gas (GHG) emissions. It involves the buying and selling of carbon credits, which represent the reduction, removal, or avoidance of one metric ton of carbon dioxide or its equivalent in other GHGs. Companies or entities that exceed their emission reduction targets can sell their excess credits to those that are unable to meet their targets, creating a financial incentive for reducing emissions. Carbon farming, on the other hand, refers to agricultural and land management practices that increase the amount of carbon stored in soil and vegetation. It encompasses activities like reforestation, agroforestry, and the use of cover crops, all aimed at enhancing carbon sequestration and improving soil health (Sileshi and Nath, 2017; Smith *et al.*, 2014). Carbon farming not only helps mitigate climate change but also offers co-benefits such as increased biodiversity, improved water retention, and enhanced soil fertility.

The inclusion of bamboo in carbon trading schemes offers several opportunities:

1. *Increased Carbon Credit Generation*: Due to its fast growth and high biomass production, bamboo can generate more carbon credits per unit area compared to many other crops or trees. This makes it an attractive option for landowners and farmers looking to participate in carbon trading markets.
2. *Sustainable Land Use*: Bamboo can be grown on degraded or marginal lands that are not suitable for conventional agriculture. This not only restores the land but also provides an additional income stream through carbon credits, promoting sustainable land use practices.
3. *Integration into Agroforestry Systems*: Bamboo can be integrated into existing agroforestry systems, providing multiple benefits. It can act as a windbreak, improve soil health, and offer additional products such as bamboo shoots for food and bamboo poles for construction, all while sequestering carbon.
4. *Corporate and Governmental Partnerships*: Companies and governments seeking to offset their carbon emissions can invest in bamboo plantations. Such partnerships can provide funding and resources for large-scale bamboo projects, enhancing their feasibility and impact.

Challenges and Solutions for Bamboo Carbon Projects

Despite its potential, there are challenges to the widespread adoption of bamboo for carbon trading and farming: Accurately measuring and verifying the carbon sequestration potential of bamboo can be complex due to its botanical classification as a grass rather than a tree (Yiping *et al.*, 2010). Developing standardized methodologies and protocols is crucial for ensuring credibility and transparency in carbon trading markets. Bamboo-based carbon credits may face challenges in gaining recognition and acceptance in existing carbon markets. Additionally, establishing bamboo plantations requires initial investment and time before realizing returns through carbon credits.To maximize the potential of bamboo, continued investment in research, policy support, and capacity building is essential. Governments, private sector stakeholders, and international organizations must collaborate to create enabling environments for bamboo-based carbon projects. By doing so, the full potential of bamboo as a powerful tool for carbon sequestration, climate resilience, and sustainable development can be unlocked.

Conclusion

When addressing environmental issues and climate change, bamboo is frequently the "forgotten answer." Its ability to store CO_2 has been well-documented and acknowledged globally. Bamboo has the potential to be highly effective in sequestering carbon due to its rapid growth and flexibility. As a fast-growing and sustainable resource, bamboo can function as a significant carbon sink, aiding efforts to mitigate and adapt to the consequences of climate change when managed strategically and scientifically. Additionally, bamboo can play a vital role in regreening degraded regions, thanks to its high growth rate and dense canopy. Its versatility extends beyond environmental benefits; bamboo is also a valuable resource in construction, offering a sustainable alternative to traditional building materials. As the world seeks solutions to climate change, recognizing and leveraging the full potential of bamboo could make a substantial difference in our global efforts to create a more sustainable and resilient future.

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STUDIES ON THE IMPACT OF EXOTIC FISH SPECIES ON THE INDIGENOUS FISH FAUNA OF HIMACHAL PRADESH, INDIA

Shivali Sharma, Harinder Singh Banyal, Neha Bains, Navneet Kaur, Rajender Pal

Department of Biosciences, Himachal Pradesh University, Summer Hill, Shimla (H.P.)
Corresponding Email: dr.harinderbanyal@gmail.com

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Abstract

The introduction of exotic fish species has significantly influenced aquaculture practices and aquatic ecosystems in Himachal Pradesh and across India. This review explores the ecological, economic, and management implications of introducing non-native fish species, focusing on their effects on native fish fauna and aquatic ecosystems. While exotic species have contributed to the growth of aquaculture and recreational fisheries, their ecological impacts, including habitat alteration, competition, and hybridization with native species, pose significant challenges to biodiversity conservation. Effective management strategies, including rigorous quarantine measures, stakeholder collaboration, and a focus on culturing native species, are imperative to mitigate these adverse effects. The review underscores the necessity of balancing aquaculture development with the preservation of local ecosystems and biodiversity.

Keywords: Exotic, Fish, Himachal Pradesh, Aquaculture, Sustainable.

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Introduction

The introduction of foreign species into an environment unit may pose a serious threat to the local fauna (Chattopadhyay et al., 2011), and it becomes a significant ecological concern worldwide, as these species often disrupt native ecosystems and alter the dynamics of local biodiversity. The introduction of exotic fish species, often for aquaculture, recreational fishing, or biological control, has posed serious threats to the indigenous ichthyofauna, leading to habitat alteration, competition for resources, and, in some cases, extinction of native species (Singh &Lakra, 2006; Gozlan, 2008). Additionally, predation by certain exotic species can cause significant declines in local fish populations, undermining the ecological balance of freshwater ecosystems (Moyle & Light, 1996). During the past few decades, exotic fish species have been introduced to India for variety of reasons, adding roughly 13.6% to the country’s diversity (Joshi et al., 2021). 31 aquaculture fish species, 600 ornamental fishes and 2 larvicidal fishes are exotic to Indian water bodies (Singh and Lakra, 2011; Singh, 2014). Increasing anthropogenic activities, coupled with the introduction of non-native species, have exacerbated the pressures on these fragile ecosystems (Kumar et al., 2021).

Himachal Pradesh, nestled in the Northwestern Himalayas, is endowed with a rich diversity of freshwater fish species, many of which are endemic to the region and contribute significantly to the stability of aquatic ecosystems. Exotic fish species such as *Cyprinus carpio* (common carp), *Salmo truttafario* (Brown trout),*Oncorhynchus mykiss* (rainbow trout) etc. have been extensively introduced into the cold-water streams and reservoirs of Himachal Pradesh. While these species provide economic benefits through fisheries, they are known to compete aggressively with native species, often outcompeting them for food and breeding grounds (Pawelec-Olesińska,2020).

The current article aims to assess the ecological impacts of exotic fish species on the native fish fauna of Himachal Pradesh analyzing key ecological parameters, including competition, predation, and habitat disruption. Furthermore, the research seeks to provide a comprehensive understanding of the challenges posed by exotic fish species and propose sustainable management strategies for conserving the region's aquatic biodiversity.

Area of Study

Himachal Pradesh is a state in Northwestern Himalayas, characterized by mountainous terrain, having an elevation of 350 meters to 6,975 meters. It lies in 30°22'40"N to 33°12'40"N latitude and 75°45'55"E to 79°04'20"E longitude, occupying an area of 55,673 sqkm and is bordered by Jammu and Kashmir to the north, Ladakh to the northeast, Tibet to the east, Uttarakhand to the southeast, Haryana to the south and Punjab to the west (Anonymous, 2024).The state encompasses four Himalayan ranges i.e., the Shivalik or the Outer Himalayas, the Lower and the Lesser Himalayas, the Higher or the Greater Himalayas, and the Trans-Himalayas, having abundant water resources in the form of rivers, streams, lakes, pond and reservoirs. These varied water resources serve as critical habitat to the native fish fauna of the state.

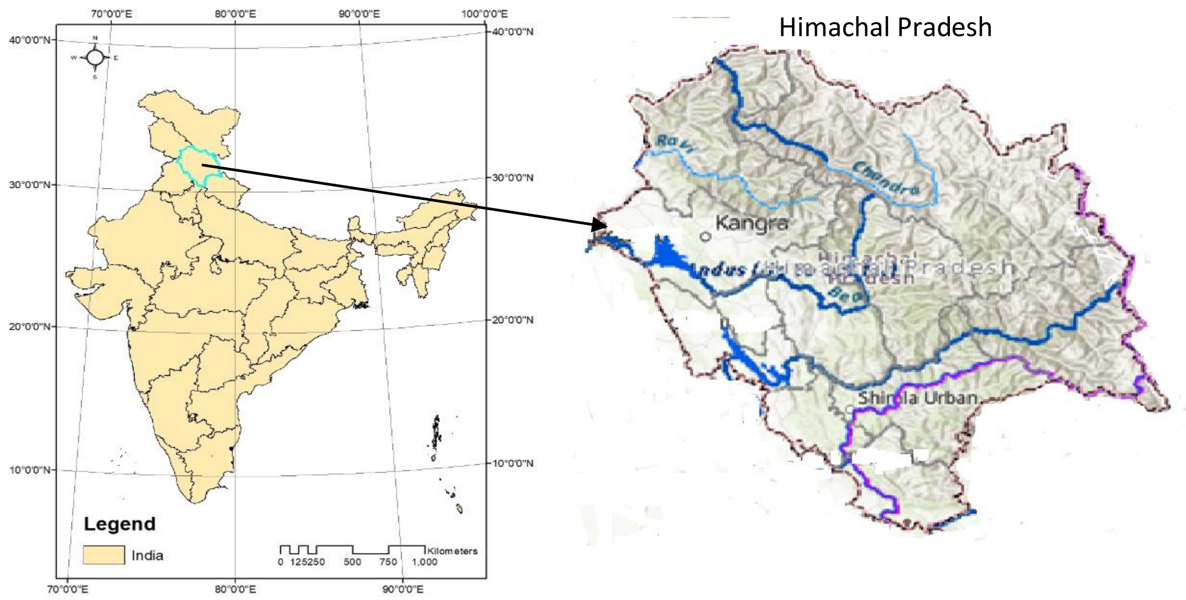

Fig 1: Map showing different water bodies of Himachal Pradesh (*Source: indiawris.gov.in*)

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Material and Methods

The methodology for secondary data collection focuses on systematically gathering and analyzing information from various credible sources including PubMed, Scopus, Web of Science, ResearchGate, and Google Scholar. Varied keywords such as exotic fish species, native fish fauna, aquatic ecosystems, Himachal Pradesh, fisheries and ecological impacts were used in search engines and databases. A comprehensive review of journals, books, technical reports and government publications was conducted.

Results and Discussion

A number of exotic fishes which are introduced in India for aquaculture and ornamental purposes (Table.1) have escaped from the aquaculture farms and formed a natural population in open waters of rivers and streams (Singh and Lakra, 2011). Due to their hardy, robust, omnivorous nature, strong adaptability and tolerance to wide range of temperature, these invasive species get established and alters the ecological condition of the natural water bodies (Joshi et al., 2021).

During the pre-independence (1870–1947), nine fish species were brought to India, *viz.*, temperate food fishes such *Tincatinca*, *Carassiuscarassius*, and *Cyprinus carpio*, salmonid game fishes like *Salmo truttafario* and *Salmo gairdnerii* (now *Onchorhynchus mykiss*), larvicidal *Gambusia affinis*, *Lebistesreticulatus*, and tropical osphronemids i.e., *Osphronemusgoramy* (Natarajan and Ramachandra, 1988). Furthermore, many ornamental and food fishes were introduced in India after independence, such as carps (Chinese strain of *C. carpio*, *Ctenopharyngodonidella*, *Hypophthalmichthys molitrix*, *Puntius javanicus*), cichlids (*Oreochromis mossambicus*, *O. niloticus*), and salmonids (*Salvelinus fontinalis*, *Salmo salar*, *Oncorhynchus mykiss*, *O. nerka*) etc. (Joshi et al., 2021).

Table 1: Major fish species introduced in Indian water bodies also invade into water bodies of Himachal Pradesh *(Joshi et al., 2021)*

Fish species	Common name	Year of Introduction in India	Source
Salmo truttafario	Brown trout	1863 - 1908	England, Japan
Onchorhynchus mykiss	Rainbow trout	1909	Sri Lanka, Germany, New Zealand
Ctenopharyngodonidella	Grass carp	1959	Japan, Hong Kong
Hypophthalmicthys molitrix	Silver carp	1959	Japan, Hong Kong
Cyprinus carpiocommunis	Scale carp	1939, 1957	Sri Lanka, Bangkok
Cyprinus carpiospecularis	Mirror carp	1939, 1957	Sri Lanka, Bangkok
Cyprinus carpionudus	Leather carp	1939, 1957	Sri Lanka, Bangkok
Carrasiuscarassius	Crucian carp	1974	England
Oreochromis niloticus	Nile tilapia	-	Thailand, Israel

A large number of exotic fish species also invade the local water bodies of Himachal Pradesh. Some of these are commercially important fish species and serves as a boon to the state pisciculture and economic growth. In-spite of this, they also outcompete local fauna of the state for food and shelter and also acts as carrier of large number of exotic pathogens. A total of 16 exotic ornamental fish species were recorded in Himachal Pradesh, out of which 6 species (*Carassiuscarrasius, C. auratus, Cyprinus carpiocommunis, C. carpiospecularis, C. carpionudus* and *Trichogasterfasciata*) invade into natural water bodies (Sharma and Dhanze, 2018).

Some of the Exotic Fish Species Found in Himachal Pradesh are (Fig. 2):

- *Cyprinus carpio* (European Carp or Common Carp)
- *Hypophthalmicthys molitrix* (Silver Carp)
- *Ctenopharyngodonidella* (Grass Carp)
- *Salmo truttafario* (Brown Trout)
- *Oncorhynchus mykiss* (Rainbow Trout)
- *Oreochromis niloticus* (Nile Tilapia)
- *Carassiuscarassius* (Crucian Carp)
- *Carrasius auratus* (Goldfish)
- *Trichogasterfasciata* (Banded gourami/ Striped Gourami/ Giant Gourami)

Cyprinus carpio (European Carp or Common Carp): Common carp was introduced in India in 1959 (Singh and Lakra, 2006), three varieties of common carp viz., *C. carpio var. communis* (Scale carp), *C. carpio var.specularis* (Mirror carp) and *C. carpio var. nudus* (Leather carp) were found in water bodies of Himachal Pradesh.*C. carpio var. communis*is widely used in plains for aquaculture, whereas, *C. carpio var. specularis* aqua cultured in hill state water bodies (Singh et al., 2010). In India, initially, German strain of Mirror carp was introduced from Ceylon in 1939, but the strain can't be able to breed freely in tropical water bodies so to overcome the problem Chinese stock of common carp i.e., scale carp was introduced in Uttarakhand (Kumaon lake). Later the species was also recorded in Dal lake (Kashmir), where it outcompetes local fish species, especially *Schizothorax* spp. It was also stocked in Govindsagar reservoir (H.P.), consequently, in-spite of dominant silver carp, it constitutes a profitable fishery. Due to bottom feeding habit, it competes with *Cirrhinusmrigala* and *Clariasmagur* for space and food (Swain et al., 2017). The species was also recorded in numerous natural water bodies of Himachal Pradesh (Sharma and Dhanze, 2018; Sharma and Chandra, 2021, Sharma and Banyal, 2023, 2024; Modeel et al., 2024).

Hypophthalmicthys molitrix (Silver Carp): The silver carp was first introduced in India, in Kulgarhi reservoir, Madhya Pradesh during 1959 (Swain et al., 2017). Later, in Himachal Pradesh silver carp was introduced in Govind Sagar reservoir, which have several negative consequences on native Indian major carps of the reservoir. Currently, the majority of the catch in the reservoir is made up of exotic silver carp (approximately 60–65%), followed by Indian major carps (20–25%), mahseer species (8–10%), and minor carps (8–10%) (Raman et al., 2013). The species also invade in various natural lentic and lotic water bodies of Himachal Pradesh.

Ctenopharyngodonidella (Grass Carp): This species was first introduced in India for controlling overgrowth of submerged vegetations. But later, due to its rapid growth rate it became an integral part of composite fish culture. It brings nutrients locked in weeds in circulation and produces valuable fish proteins. But, it adversely impacts the survival of fishes and other aquatic organisms which hide beneath these vegetations. Furthermore, the species only feed on selected macrophytes including *Hydrilla verticillata*, but others such as *Eichhorniacrassipes, Salvinia molesta*and *Pistia stratiotes* most threatening weeds in water are not fed by the fish (Swain et al., 2017). The species was widely distributed in Bilaspur, Kangra, Mandi, Kullu, Shimla, Solan, Sirmour, Chamba, Una and Hamirpurdistricts of Himachal Pradesh (Sharma and Chandra, 2021).

Salmo truttafario (Brown Trout) and ***Onchorhynchus mykiss*** (Rainbow trout): These two trout species have been introduced all over the world intentionally for commercial uses and recreational purposes (May, 2007). But, there is no systematic study has been conducted till now to evaluate the effects of trout introduction in open water. The mass mortality of rainbow trout in H.P. in 2002 has highlighted the necessity for quarantining and ecological concern among experts. It has been found that local cold-water species have reportedly been exterminated with the introduction of *Salmo truttafario* (Swain et al., 2017). *Onchorhynchus mykiss* was widely introduced in glacier fed water bodies of Kangra, Mandi, Kullu, Shimla and Sirmour, whereas *Salmo truttafario* was introduced in water bodies of Chamba, Kangra, Mandi, Kullu, Shimla and Kinnaur districts of Himachal Pradesh (Sharma and Chandra, 2021).

Oreochromis niloticus (Nile Tilapia): The species have been imported into more than 90 countries all over the world, with a global distribution second to common carp. Over the past few years, tilapias have contributed more to the world's aquaculture output. Because of their prolific breeding tendencies, tilapias have devastated local fish populations both in India and beyond. Recently, Nile Tilapia (*O. niloticus*) have been reported in Beas River basin in Himachal Pradesh (Sharma and Banyal, 2024; Modeel et al., 2024). The Nile tilapia affects the water body by changing native community composition, reduces water transparency, lowers planktonic microcrustaceans abundance, increases the concentration of microalgae (Okun et al., 2008; Simões Vituleet al., 2009).

Carrasius auratus (Goldfish): It is widely distributed ornamental fish found in India, but is also regarded as potential pest in natural water bodies. It causes mass mortality of fishes by resuspending of nutrients present at the bottom, which accelerates blue-green algal growth and causes large-scale aquatic destruction (Morgan, 2004; Sandilyan, 2016). Its bottom feeding behavior increases the turbidity of water, furthermore, the species also feed on eggs, larvae and adults of some native fish species (Richardson et al., 1995; Rowe and Smith, 2001). This fish species is widely distributed in Beas (Kangra, Mandi, Kullu), Sutlej (Bilaspur, Shimla), Ravi (Chamba) and Yamuna (Solan, Sirmour) River basins of Himachal Pradesh (Sharma and Dhanze, 2018).

Advantages of Introducing Exotic Fish Species

More than 300 species of exotic fishes have been brought to India along with Himachal Pradesh, during the past few decades for aquaculture, pleasure fishing, ornamental fish keeping, mosquito control and other purposes (Singh and Lakra, 2010), which offers various advantages to aquaculture.

- "Composite fish culture" of Indian Major Carps (IMCs) viz., *Labeorohita*(rohu), *Cirrhinusmrigala*(mrigal) and *Catlacatla* (catla) along with three exotic carps (*Hypophthalmichthys molitrix, Ctenopharyngodonidella* and *Cyprinus carpio*) have gained a popularity in pisciculture.

- Several fish species such as *Carrasiuscarrasius, Carrasius auratus, Trichogasterfasciata* have been introduced to meet the increasing demand of aquarium fishes (Singh and Welfare, 2017).
- Some exotic species can help control aquatic vegetation and maintain ecological balance, such as *Ctenopharyngodonidella* (grass carp), which is used for biological weed control in reservoirs.
- Furthermore, exotic fish species often serve as affordable protein sources for growing population, thus addressing food security issues in rural and urban areas (FAO, 2021).

Disadvantages of Introducing Exotic Fish Species

- Non-native/alien fish species, that are intentionally or non-intentionally transferred into natural water bodies can negatively impact local fauna by introduction of pathogens or parasites (Table.2) and spreading of diseases, genetic alterations, environmental modification and also acts as competitors or predators to native fauna (Lakra et al., 2008).
- Fish species such as *Ctenopharyngodonidella* introduced for biological control also have negative consequences on native fish fauna. As the fish feeds non-selectively on aquatic vegetation, changes the habitat quality and availability required by different aquatic organisms (Silva et al., 2014; Zonneveld and Van Zon, 2019).
- One example of a nuisance fish that has seriously harmed a number of aquatic habitats is the common carp. By grazing on submerged vegetation, it uproots plants that other aquatic species use for food and cover and depriving other fish of important resources required for survival (Lakra et al., 2008).
- A large number of ornamental fish species such as *Carassius auratus* (Goldfish) has frequently escaped into the wild and causes menace to local fish species (Erarto and Getahun, 2020).
- One of the most important ecological concern about the introduction of non-native fish species is hybridization between native and introduced species. One such example is hybridization between crucian carp (*Carassiuscarassius*) and Eastern native goldfish (*Carassius auratus*) or *Cyprinuscarpio* (Hanfling et al., 2005; Smartt, 2007).

Table 2: Common pathogenic parasites found in exotic fish species in Indian waters *(Abidi et al., 2011; Raman et al., 2013; Trujillo-González, 2018)*

Host fish species	**Pathogen or Parasite**
Cyprinus carpio	*Tripartiellacopiosa, Gyrodactylusmedius, Diplozoonnipponicum, Dactylogyrousachmerowi, D. anchoratus, D. crassus, D. extensus, D. minutus, D. mrazaki, D. vastator, D. yinwenyingae*
Hypophthalmichthys molitrix	*Tripartiella reticulata*
Ctenopharyngodonidella	*Tripartiellaobtusa, Neoergasilus japonicus*
*Carassius*sp.	*Pellucidhaptorkritskyia*
Carassius auratus	*Dactylogyrous*sp., *Gyrodactylusmedius, Schyzocotyleacheilognathi, Ichthyophthiriusmultifiliis, Argulus japonicus, Lernaeacyprinacea*

Management of Introduced Species:

Even though the introduction of exotic fish species can be seen as beneficial to aquaculture because of its maximum development potential, but we must have to carefully manage our own native ecology and biodiversity to prevent the negative effects of introducing exotic fishes.In order to avoid negative effects and entrance of exotic parasites and pathogens along with introduced species, rigorous quarantine measures are necessary (Lakra et al., 2006). It is the need of the today that the researchers should have to focus on culturing native species, rather than introducing new species, which will fulfill the increasing human demand for fish as food while still conserving local biodiversity. All stakeholders must be involved in the multifaceted management of introduction, in order to coordinate, monitor, and manage the transfer and introduction of species on an international level, it must be implemented at a number of scales, ranging from a homeowner working in their backyard to large government agencies including the Directorate of Fisheries of State Governments and central organizations like NBFGR (National Bureau of Fish Genetic Resources), ICAR (Indian Council of Agricultural research), NFDB (National Fisheries Development Board) etc., taking a state-wise and nationwide approach, respectively. Lastly, it must involve major intergovernmental agencies like FAO (Food and Agriculture Organization), NACA (Network of Aquaculture Centres), World Fish Center, ICES (International Council for Exploration of the Sea), EIFAC (European Inland Fisheries Advisory Commission) and others (Raman et al., 2013).

Oreochromis niloticus

Cyprinus carpio var. communis

Salmo trutta fario

Onchorhynchus mykiss

Fig 2: Depiction of some of the exotic fish species of Himachal Pradesh.

Conclusion

The introduction of exotic fish species has been a double-edged sword, benefiting aquaculture and fisheries while posing significant risks to native biodiversity and ecosystem stability. The findings of this review highlight the critical need for a systematic approach to manage exotic species. The ecological consequences, such as habitat degradation, competition, predation, and hybridization, threaten native fish populations and aquatic ecosystems. At the same time, the economic benefits from aquaculture and recreational fisheries cannot be overlooked. Moving forward, it is essential to prioritize native species in aquaculture practices, implement rigorous quarantine measures to prevent pathogen transmission, and foster coordinated management strategies involving local, national, and international stakeholders. By adopting sustainable practices and focusing on biodiversity conservation, we can ensure that the benefits of aquaculture development are achieved without compromising the health and stability of aquatic ecosystems.

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ROLE OF AGRICULTURE EXTENSION IN THE ADOPTION OF MICRO IRRIGATION IN INDIA

Pankaj Srivastava

Agronomist Division, Signet Industries Ltd., Indore
Corresponding Email: pankaj@groupsignet.com

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Abstract

India is running with water scarcity by holding 4 % world's water for 18 % of world's population. Water demand in agriculture sector in increasing because of increasing food demand and this sector has a pressure to produce more from less area. Irrigation is the major operation in agriculture which uses, rather wastes, a lot of water, therefore, the judicial use of water for irrigation is becoming very necessary now a day. Micro irrigation is the scientific method of irrigation which not only ensures the judicial use of water but also gives good yield and quality of produce to the farmers. Addressing the high initial cost of the system, National Bank for Rural and Agricultural Development (NABARD) was financing the system since 1985. In 2006, government launched a Centrally Sponsored Scheme for Micro Irrigation and given the subsidy to this technology. Nearly 2 million hectare area had been brought under micro irrigation through this scheme. National Mission on Micro Irrigation was launched in 2010 and it ensured the capacity building of farmers through training and extension. This resulted in the good coverage of area under micro irrigation and 7.73 million hectare area has been brought under micro irrigation till 2015. Presently the expansion of micro irrigation is going on under Pradhan Mantri Krishi Sinchai Yojana (PMKSY). One major guidelines of PMKSY is that the company will provide free services to the beneficiary for a period of at least three years from the date of installation of the system. The company Signet Industries Ltd. is also working under this guideline and providing the effective agriculture extension services, in addition to supplying quality irrigation system to the farmers.

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Introduction

India has 4 % world's water resource which is available to the 18 % of the world's population present in the country. India has 1123 billion cubic meter (BCM) of fresh water available for use every year. Being an agrarian country, major amount of water, 85 %, is used by agriculture followed by industry which uses 10 % and then the domestic purpose uses 5 % of the fresh water (Gulati, 2023). With the increasing population of the country water demand for all sectors are increasing. Water demand in agriculture is increasing because of increasing food demand also as this sector has the pressure to produce more from less area. Irrigation is the major operation in agriculture which uses, rather wastes, a lot of water, therefore, the judicial use of water for irrigation is becoming very necessary now a days.

Micro irrigation is the scientific method of irrigation which ensures the judicial use of water, hence known as water saving technology. It comprises drip irrigation, sprinkler irrigation, mini sprinkler irrigation, and rain pipe irrigation. Drip irrigation is the modern method of irrigation which applies water drop by drop directly to the root zone of the plant in low volume and at frequent interval through a pressurized pipe network. It minimizes water wastage by providing precise amount of water to the root zone, reducing evaporation, deep percolation and weed growth. Drip irrigation ensures consistent moisture level in root zone at near field capacity level throughout the life cycle of the plant promoting healthier and fast plant growth. It results good yield to the farmers and higher production for the increasing population and thus helpful in meeting the increasing food demand. It also fetches the higher return to the farmers and increases their income.

Adoption of Micro Irrigation in India

The modern drip irrigation technology was introduced in India in mid 1980s. National Committee on use of Plastics in Agriculture (NCPA) was formed in 1981 under the Department of Chemicals and Petrochemicals to promote the use of plastics in agriculture and in irrigation. In 1983, NCPA started to work under Department of Agriculture and Cooperation. Initially the adoption of drip irrigation was slow in India but later on NCPA was reconstituted in 1996 to boost its adoption considering its importance in horticulture. It is named as NCPAH, i.e. National Committee on Plastics Application in Horticulture in 2001. Again in 2016, it is reconstituted as National Committee on Precision Agriculture and Horticulture. One of the major roles of NCPAH is to facilitate increased adoption of various plasticulture applications like drip and sprinkler irrigation systems, plastic mulch and protected cultivation in India.

Constraints in Adoption of Micro Irrigation

Micro irrigation techniques are beneficial in all respect as it not only save the water, which is precious input in agriculture, but also increase the yield and the quality of the produce. It also eases the farming operations for the farmers. In spite of having such the benefits, its adoption is slow among farmers due to the several reasons (Pandya and Dwivedi, 2016).

- High initial investment required to install drip irrigation system on the field.
- More maintenance required as compared to conventional irrigation.
- Damage to the system due to rats and other animals.
- Problems in farming operation due to lack of knowledge.
- Problem of clogging of drippers due to salt or impurity in water.
- Irrigation is to be done more frequently.
- Lack of technical knowledge and information about operation of drip irrigation for different crops.
- Unsatisfied after sale services.
- Laying and removing the drip irrigation system is problematic or difficult.
- Less availability of spare parts at local level.
- Difficult to understand and to maintain head and pressure.
- Negative feedback of careless farmers about drip irrigation.
- Non availability of skilled person for repairing the system.

- Difficulties about timely availability of electricity.
- Unawareness of drip irrigation technology if sufficient water is available.
- Use to practice as habit of farmers towards conventional irrigation method.

The task force on micro irrigation identified the constraints involved in adoption of micro irrigation and reasons for its low adoption in his report in January 2004.

- High initial cost.
- Lack of credit facilities.
- Technology intensiveness.
- Lack of training and information.
- Micro irrigation viewed more different than farm irrigation.

Extension Helps in Adoption of Micro Irrigation

Agriculture extension plays an important role in the adoption of drip and sprinkler irrigation in India by providing awareness and training on efficient irrigation technique at several levels. In addition to the extension services, government subsidy is the major support to address the issue of high initial cost in the adoption of drip irrigation system in India. National Bank for Agriculture and Rural Development (NABARD) has been financing micro irrigation system since 1985. Maharashtra was the first state to introduce subsidy on drip irrigation in 1986-87 (Bhamoriya and Mathew, 2014). Since ever, subsidy has become a regular government support in the spread of drip irrigation. Realizing the importance of micro irrigation, first time central government specially mentioned it in 8th five year plan in 1992. The Government of India has constituted a task force in June 2003 headed by N. Chandrababu Naidu, the then Chief Minister of Andhra Pradesh to look into the issues of micro irrigation in India and to suggest the strategies to expand micro irrigation, advise on technological support for crops, region specific interventions and to suggest measures to reach the benefits for the target groups. The task force submitted the report on January 2004. It estimated the micro irrigation potential in the country as 69.5 million hectare with 27 million hectare under drip irrigation and 42.5 million hectare under sprinkler irrigation. The team has recommended Rs. 10500 crore programme to cover about 3 million hectare under hi-tech irrigation system during the 10th plan (Narayanamoorthy, 2009).

However, the first real thrust came in 2006 when the government launched a Centrally Sponsored Scheme for Micro Irrigation with the objective to enhance water use efficiency in the agriculture sector by promoting appropriate technological interventions like drip and sprinkler irrigation techniques and to encourage the farmers to use it (Kumar and Eswaran, 2018). Nearly 2 million hectare area had been brought under micro irrigation by this scheme which is extremely miniscule when compare with the potential of 69.5 million hectare. Government of India has, therefore, decided to impart further thrust to this scheme by implementing it in a mission mode and upscaled the Centrally Sponsored Scheme to National Mission on Micro Irrigation (NMMI) in 2010, during 11th plan. NMMI addressed the three issues, i.e. area coverage under micro irrigation, transfer of technology through demonstrations, and human resource development through training, awareness programmes, exhibitions, publications and quality control. State Micro Irrigation Committees and District Micro Irrigation Committees were constituted under this mission. The mission ensured the good supply of good quality micro irrigation system to the farmers through BIS mark enforcement. Capacities building of farmers have been taken up through training and demonstrations with the active participation of state agricultural universities (SAUs), precision farming development centers (PDFCs) and the industries (DAC, 2010). NCPAH has been involved in monitoring and reviewing the progress of the scheme. NMMI had also formed the technical support group which helped in monitoring the scheme including the technical guidance on irrigation system and on crop specific matters. NCPAH had strengthened the technical support group by developing the experts in various fields of agriculture, horticulture, water management, information technology, and human resources. By working under mission mode, 2.79 million more area had been covered under micro irrigation in India till 2014-15 (Global AgriSystem, 2014).

Presently, extensive extension work is going on to expand the area under micro irrigation in India under the currently running scheme Pradhan Mantri Krishi Sinchai Yojana (PMKSY) with the motto *har khet ko paani*. During 2014-15, the NMMI was subsumed as On Farm Water Management component of National Mission for Sustainable Agriculture (NMSA) and further subsumed Per Drop More Crop component of PMKSY. Pradhan Mantri Krishi Sinchai Yojana (PMKSY) was launched on 1st July 2015 with the objective achieve convergence of investments in irrigation sector at field level (DA & FW, 2021). The scheme aims at proving end to end solutions in irrigation supply chain from water resource to farm level application through distribution network and improving water use efficiency. Some key features of the scheme are emphasizing the importance of agriculture extension in the success of scheme. The operation guideline of PMKSY also provide the detail methodology of its implementation, assistance and monitoring. Some features of PMKSY are given below:

- District irrigation plan is the cornerstone for planning and implementing the scheme which identifies the gaps in irrigation chain after taking into consideration the currently available resources that would be added from ongoing schemes.
- The Annual Action plan is to be drawn from District Irrigation Plans.
- State irrigation plan focuses on cluster based approach and integrated development of different components in the irrigation chain.
- The scheme is to be implemented through the mechanism of Direct Benefit Transfer (DBT).
- The scheme will be monitored through web-portal of PDMC. Physical and Financial progress achieved during the preceding month is required to be up- loaded by states on the web-portal of PDMC.
- More focus be given on promotion of micro irrigation in rainfed areas and also for water intensive/guzzling crops to minimize water requirement.
- The pattern of assistance payable to the beneficiary under the micro irrigation scheme will be 55% for small and marginal farmers and 45% for other farmers which will be met by both Central Government and State Government in the ratio of 60:40 for all states except the North Eastern and Himalayan States.
- Only BIS marked systems/components can be supplied under the scheme.
- The registration of manufacturers/companies under the scheme will be for a period of 5 years.
- The company will provide free service after sales to the beneficiary for a period of at least three years from the date of installation of the system.

The company Signet Industries Ltd. is also working under guideline of Pradhan Mantri Krishi Sinchai Yojana (PMKSY) and providing the effective agriculture extension services to the farmers, in addition to supplying quality irrigation system to the farmers' filed. The extension services are becoming the key in expanding the adopting of micro irrigation by the farmers in India.

Status of Micro Irrigation in India

Only 3.09 million hectare area was under micro irrigation in India till 2005 after the introduction of this technology in the country. It was due to subsidy given by state government and NABARD. Centrally Sponsored Scheme for Micro Irrigation, which was launched in 2006, could add 1.85 million hectare more area under micro irrigation in the country. The adopting of micro irrigation was slow at farmers' level till 2010 because the schemes were focusing only on giving the subsidy to the farmers on micro irrigation. National Mission on Micro Irrigation launched in 2010 was the scheme which focused on agriculture extension and thus adopting also increased. NMMI added 2.79 million hectare more area under micro irrigation. An area of 8.35 million hectare has been covered under micro irrigation (PIB, 2024) in the country till March 2024 in last 10 years, i.e. after the extensive extension services under Pradhan Mantri Krishi Sinchai Yojana (PMKSY).

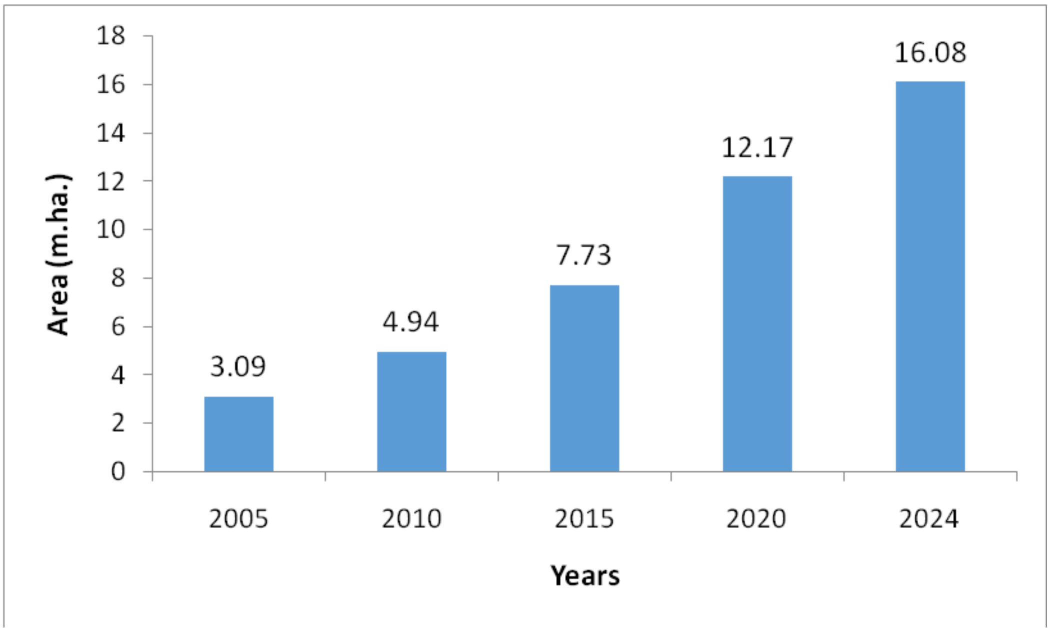

Fig 1: Year Wise Total Area Covered under Micro Irrigation In India

Conclusion

India has 69.5 million hectare potential area that can be brought into micro irrigation, but only 16.08 million hectare area has been covered under it so far. Though the progress is good in last decay but more work is required to increase the expansion of micro irrigation at farmers' field. As population and food demand are increasing fast, agriculture will have to produce more from less. Micro irrigation is the technology that not only save water but also ensures the better plant growth, high productivity and good quality of produce. But this can be achieved if farmers use the drip irrigation technology in correct manner. It is observed that farmers are not aware about system pressure, fertigation, and maintenance of irrigation system. More farmers' trainings are required so that farmers can not only adopt the micro irrigation system but also get its full advantages, maintain the system and take its services for long time, get good productivity and higher income for their family and ultimately, ensure the food security for the country.

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ECOLOGICAL SIGNIFICANCE OF RECALCITRANT SEEDS

Vinay Chamoli[1], Shailendra Tiwari[1], J S Chauhan[1], Anoop Badoni[2] and Chandan Kumar[2]

[1]Department of Seed Science and Technology, HNB Garhwal University, Srinagar
[2]Plantica – Indian Academy of Rural Development, Dehradun
Corresponding Email: chamolivinay.44@gmail.com

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Abstract

Recalcitrant seeds, characterized by their sensitivity to desiccation and inability to withstand freezing temperatures, play a critical role in maintaining biodiversity and ecosystem functionality. Unlike orthodox seeds, recalcitrant seeds germinate rapidly after dispersal, allowing them to adapt to specific environmental conditions, particularly in tropical and subtropical ecosystems. These seeds contribute to ecosystem dynamics through specialized dispersal strategies, nutrient cycling, and fostering microhabitats that support diverse plant and animal life. They also enhance ecosystem resilience by promoting rapid regeneration following disturbances. This paper explores the ecological significance of recalcitrant seeds, emphasizing their evolutionary adaptations, role in biodiversity maintenance, and implications for ecosystem stability amidst climate change. The article highlight the need for targeted conservation strategies to protect recalcitrant-seeded species and ensure the sustainability of the ecosystems they support.

Keywords: Recalcitrant seeds, Desiccation, Orthodox seeds, Biodiversity

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Introduction

Recalcitrant seeds are a unique category of seeds characterized by their sensitivity to desiccation. Unlike orthodox seeds, which can withstand drying and remain viable for extended periods, recalcitrant seeds are unable to tolerate significant loss of moisture. This makes them highly vulnerable to drying conditions. These seeds are typically shed at relatively high moisture content, a feature that is essential for their survival and germination. Due to this requirement, they are incapable of forming a soil seed bank, as they cannot endure prolonged periods of dormancy in dry conditions. However, an interesting adaptation seen in recalcitrant seeds is their ability to form a seedling bank. This allows the seedlings to persist in their environment and germinate successfully even in conditions with limited light availability, an important ecological strategy for their propagation.

Despite their slower germination rates compared to orthodox seeds, recalcitrant seeds share similar temperature optima and maxima for germination. This indicates that while they may be slower to initiate growth, they are adapted to germinate within a specific temperature range that supports their development. The slow germination process and their sensitivity to drying pose significant challenges for the regeneration and sustainability of plant species producing recalcitrant seeds, particularly under conditions of climate change. With changing environmental conditions, such as increasing droughts and fluctuating temperatures, the vulnerability of these seeds to regeneration failure becomes pronounced. This sensitivity to drought conditions highlights the precarious position of species dependent on recalcitrant seeds for reproduction. The moisture content of recalcitrant seeds is a critical factor influencing their germination. Studies have shown a positive correlation between seed moisture content and the rate of germination. High moisture levels are essential to maintain cellular integrity and support the metabolic processes required for seed development and germination. When recalcitrant seeds experience desiccation, they undergo cellular damage, particularly to the cell membranes. This damage is often irreversible and leads to significant issues such as electrolyte leakage. The loss of cellular stability not only hampers the viability of the seed but also reduces its capacity to germinate and develop into a healthy seedling.

Abscisic acid (ABA), a plant growth regulator, plays a pivotal role in determining the behavior of recalcitrant seeds. ABA is known to influence various physiological and developmental processes in seeds, including dormancy, germination, and stress responses. In recalcitrant seeds, ABA may regulate the balance between dormancy and germination, ensuring that seeds only germinate under favorable conditions. However, the high sensitivity of these seeds to environmental changes can complicate this balance, making them more susceptible to adverse conditions.

Recalcitrant seeds are found in a wide range of tree species, many of which are ecologically and economically significant. These seeds have been part of the evolutionary history of plants for millions of years, with evidence suggesting their presence since the late Cretaceous period. This long-standing evolutionary adaptation demonstrates their resilience and the ecological strategies that have allowed them to persist through various climatic and environmental changes. However, the current challenges posed by climate change, habitat loss, and other anthropogenic factors threaten the survival of species relying on recalcitrant seeds.

The characteristics of recalcitrant seeds present both opportunities and challenges for conservation and agricultural practices. Their inability to withstand desiccation complicates their storage and preservation, making ex situ conservation efforts more complex. Traditional seed storage methods, such as drying and freezing, are unsuitable for recalcitrant seeds, necessitating alternative approaches such as cryopreservation. Moreover, the ecological dependence of these seeds on specific environmental conditions underscores the need for habitat conservation and the development of strategies to mitigate the impacts of climate change on their survival.

Recalcitrant seeds also offer insights into plant physiology and adaptation. Their behavior highlights the intricate mechanisms plants use to survive and reproduce under varying environmental conditions. By studying these seeds, researchers can gain a deeper understanding of plant responses to stress, the role of growth regulators like ABA, and the evolutionary strategies that have shaped plant diversity over time. Such knowledge is invaluable for developing innovative solutions to address the challenges faced by plant species in a rapidly changing world.

Overall, recalcitrant seeds represent a fascinating aspect of plant biology, characterized by their desiccation sensitivity and unique germination strategies. While their ecological significance and evolutionary history underscore their resilience, the challenges posed by their vulnerability to drying and climate change highlight the need for targeted conservation efforts. By understanding the complex mechanism between moisture content, cellular integrity, and environmental conditions, scientific community can work towards preserving the diversity and ecological contributions of species dependent on recalcitrant seeds.

Table 1: List of Some notable species of Recalcitrant seeds

Botanical Name	Common Name	Family	Seed Type
Rhizophora mangle (Red Mangrove)	Red Mangrove	Rhizophoraceae	Recalcitrant
Avicennia marina (Gray Mangrove)	Gray Mangrove	Acanthaceae	Recalcitrant
Castanea spp.	Chestnut	Fagaceae	Recalcitrant
Hevea brasiliensis	Rubber tree	Euphorbiaceae	Recalcitrant
Theobroma cacao	Cacao, Cocoa	Malvaceae	Recalcitrant
Persea americana	Avocado	Lauraceae	Recalcitrant
Durio spp.	Durian	Malvaceae	Recalcitrant
Mangifera indica	Mango	Anacardiaceae	Recalcitrant
Dimocarpus longan	Longan	Sapindaceae	Recalcitrant
Litchi chinensis	Lychee	Sapindaceae	Recalcitrant
Artocarpus heterophyllus	Jackfruit	Moraceae	Recalcitrant
Psidium guajava	Guava	Myrtaceae	Recalcitrant
Olea europaea	Olive	Oleaceae	Recalcitrant
Castanea sativa	Sweet chestnut	Fagaceae	Recalcitrant
Duguetia spp.	Duguetia	Annonaceae	Recalcitrant
Tamarindus indica	Tamarind	Fabaceae	Recalcitrant
Ochroma pyramidale	Balsa	Malvaceae	Recalcitrant
Rhizophora mangle (Red Mangrove)	Red Mangrove	Rhizophoraceae	Recalcitrant

Role of Recalcitrant Seeds in Natural Ecosystems

Recalcitrant seeds hold a vital position in natural ecosystems, particularly in tropical and subtropical regions where they are more commonly found. Their ecological significance is profound, contributing to biodiversity conservation and the maintenance of ecosystem balance. Exploring their role offers valuable insights into their importance in sustaining diverse and dynamic ecosystems. One of the primary contributions of recalcitrant seeds is their role in supporting biodiversity. Many tree species in tropical and subtropical forests rely on recalcitrant seeds for reproduction, making these seeds essential for the survival and propagation of numerous plant species. The plants that grow from recalcitrant seeds often serve as keystone species, providing habitat and food for various animals, insects, and microorganisms. By facilitating the growth of these plants, recalcitrant seeds indirectly support a wide array of species, contributing to intricate ecological networks. Recalcitrant seeds are particularly adapted to environments with high humidity and consistent rainfall. Unlike orthodox seeds, which can remain dormant for extended periods, recalcitrant seeds germinate quickly and rely on moist conditions to survive. This characteristic enables them to establish seedlings rapidly in suitable conditions, playing a critical role in the regeneration of forests. Their ability to germinate in shaded or low-light conditions further enhances their contribution to forest dynamics, as they can thrive beneath dense canopies, aiding in forest stratification and maintaining diverse plant layers. The rapid germination and growth of plants from recalcitrant seeds also contribute to soil health and erosion control. As these plants establish themselves, they stabilize the soil with their roots, preventing erosion and enhancing soil fertility through organic matter deposition. This process is particularly beneficial in tropical ecosystems, where heavy rainfall can lead to significant soil loss without adequate vegetation cover.

Recalcitrant seeds also play a role in carbon sequestration. The plants that grow from these seeds often include large trees with significant biomass, which act as carbon sinks. By supporting the growth of these trees, recalcitrant seeds contribute to mitigating climate change by absorbing atmospheric carbon dioxide. Furthermore, the presence of recalcitrant seeds in ecosystems supports the survival of wildlife species that depend on them as a food source. Animals such as birds, mammals, and insects feed on these seeds and their seedlings, facilitating seed dispersal and enhancing genetic diversity within plant populations. This symbiotic relationship ensures the perpetuation of both plant and animal species, highlighting the interconnectedness of natural ecosystems.

Despite their ecological importance, recalcitrant seeds face threats from habitat destruction and climate change. Their sensitivity to desiccation and reliance on specific environmental conditions make them vulnerable to changing climates and deforestation. Conservation efforts aimed at protecting habitats and understanding the physiology of recalcitrant seeds are essential to ensure their continued role in ecosystem stability. Recalcitrant seeds are indispensable to natural ecosystems, supporting biodiversity, forest regeneration, soil health, and climate regulation. Their unique adaptations and ecological contributions underscore the need for targeted conservation strategies to preserve their role in maintaining the balance and resilience of natural habitats. Here are several key aspects of their role:

Diversity and Adaptation

Recalcitrant seeds are often associated with species that inhabit diverse and dynamic environments, such as tropical rainforests. These environments experience fluctuating moisture levels, temperature variations, and rapid changes in light availability. Recalcitrant seeds, which are desiccation-sensitive, are found in many woody species of tropical forests. These seeds are shed at a high moisture content, do not form a soil seed bank, and are dependent on regeneration under low light levels. The ability of large recalcitrant seeds to germinate in low light is an important adaptation associated with the formation of a seedling bank. Recalcitrant seeds have been found in 721 species, 297 genera, and 84 families, with the trait appearing in numerous lineages since the late Cretaceous. The transition from orthodox to recalcitrant seeds is less frequent than vice versa, and recalcitrant seeds spend less time in the recalcitrant state compared to orthodox seeds in the orthodox state[2]. Climate change, particularly increases in temperature and drought, can negatively affect the success of ex situ conservation and cryopreservation of recalcitrant-seeded species. However, some recalcitrant-seeded species may benefit from increased temperatures and water stress, leading to better adaptation to drying and increased success in propagation and cryopreservation. Recalcitrance is associated with certain ovule/seed characters, such as bitegmic and crassinucellate ovules, nuclear endosperm development, and extensive vascularization of the integument/seed coat, which are considered ancestral character states in dicotyledons. The presence of recalcitrant seeds in such ecosystems reflects the adaptation of plants to these conditions. These seeds germinate quickly after dispersal, taking advantage of favourable conditions for growth and establishment.

Seed Dispersal and Succession

Seed dispersal and succession play pivotal roles in the ecological functioning of recalcitrant seeds, influencing their distribution, establishment, and contribution to ecosystem dynamics. These seeds, sensitive to desiccation and reliant on moist environments, exhibit unique adaptations and ecological behaviors that impact how they are dispersed and how they contribute to ecological succession.

Recalcitrant seeds often rely on biotic agents for dispersal, as their high moisture content and relatively large size limit their ability to be dispersed by wind or other abiotic means. Animals such as birds, mammals, and rodents play a critical role in transporting these seeds to suitable germination sites. In many cases, the seeds are consumed as a food source, with undigested or partially digested seeds deposited elsewhere via animal feces. This process not only aids in dispersal but also enhances germination by exposing the seed to optimal conditions, such as nutrient-rich soil.

Some species of recalcitrant seeds have evolved mutualistic relationships with specific dispersers. For instance, certain large-seeded tropical plants depend on large mammals like elephants for effective seed dispersal over long distances. These dispersers are essential in maintaining the genetic diversity and spatial distribution of plant populations. However, the decline of key disperser species due to habitat loss or hunting poses significant challenges for the dispersal and survival of plants producing recalcitrant seeds.

Recalcitrant seeds are integral to various stages of ecological succession, particularly in forested ecosystems. Their ability to germinate rapidly under favorable conditions allows them to establish seedlings in newly disturbed or regenerating areas. For example, after natural disturbances such as storms, landslides, or human activities like logging, recalcitrant seeds contribute to the initial wave of vegetation that stabilizes the soil and creates a microenvironment conducive to further plant colonization.

These seeds often give rise to species that play a foundational role in forest structure. By forming a dense understorey or canopy layer, plants germinated from recalcitrant seeds provide shade, regulate microclimatic conditions, and create habitats for other organisms. Over time, this facilitates the establishment of more diverse and complex plant communities, driving succession toward a mature ecosystem.

Despite their ecological significance, the dispersal and succession processes involving recalcitrant seeds face several challenges. Habitat fragmentation and climate change disrupt the availability of suitable dispersal agents and germination sites, reducing the effectiveness of natural dispersal mechanisms. Furthermore, the sensitivity of recalcitrant seeds to desiccation makes them particularly vulnerable in changing climates, where increased droughts and temperature fluctuations can hinder their germination and establishment.

To support the role of recalcitrant seeds in seed dispersal and succession, targeted conservation efforts are crucial. Protecting natural habitats and ensuring the survival of key disperser species are essential steps. Additionally, understanding the physiological requirements and ecological interactions of recalcitrant seeds can inform restoration efforts, particularly in degraded landscapes where these seeds can play a transformative role in re-establishing vegetation cover and biodiversity.

Overall, seed dispersal and succession are central to the ecological success of recalcitrant seeds. Their reliance on biotic dispersers and their contribution to forest regeneration highlight their importance in maintaining ecosystem dynamics and biodiversity, underscoring the need for their conservation in the face of environmental challenges.

Microhabitat Creation

Recalcitrant seeds play a significant role in microhabitat creation, contributing to the establishment and maintenance of localized environmental conditions that support diverse plant and animal communities. Their unique traits, such as sensitivity to desiccation and rapid germination, enable them to influence their immediate surroundings in ways that promote ecological balance and biodiversity.

When recalcitrant seeds germinate, the resulting seedlings often form dense clusters that modify the microenvironment. These clusters provide shade, reduce soil temperature, and retain moisture, creating a more favorable environment for other organisms. The shading effect is particularly beneficial in tropical and subtropical forests, where intense sunlight can hinder the growth of shade-intolerant species. By moderating light availability, plants grown from recalcitrant seeds help maintain the layered structure of forest ecosystems, supporting diverse plant life at various strata.

The establishment of seedlings from recalcitrant seeds also contributes to soil stabilization and fertility. Their roots bind the soil, reducing erosion and enhancing water retention. Additionally, organic matter from fallen leaves and decaying plant material enriches the soil, creating nutrient-rich microhabitats that support the growth of other plants and microorganisms. These localized improvements in soil quality foster a cycle of regeneration and growth, facilitating the development of a stable ecosystem.

Plants originating from recalcitrant seeds often provide critical resources for wildlife. Their presence can create small habitats that shelter insects, birds, and small mammals. The seeds themselves, as well as the plants they grow into, serve as food sources, supporting the survival of these organisms. In turn, these animals contribute to seed dispersal and pollination, reinforcing the ecological interdependence within these microhabitats.

In disturbed or regenerating areas, recalcitrant seeds play a crucial role in initiating the recovery process. By germinating quickly and establishing vegetation cover, they create microhabitats that allow other species to colonize the area. This process not only aids in restoring the ecosystem but also ensures the survival of species dependent on the microhabitats created by these plants. The capacity of recalcitrant seeds to influence their surroundings underscores their ecological importance. Their role in creating and sustaining microhabitats highlights the intricate relationships between plants, soil, and organisms within an ecosystem. However, the challenges posed by habitat loss and climate change threaten their ability to perform these functions, making conservation efforts essential for preserving their ecological contributions.

Ecosystem Resilience

Recalcitrant seeds contribute significantly to ecosystem resilience by supporting biodiversity, facilitating regeneration, and maintaining ecosystem processes. Their unique characteristics, such as desiccation sensitivity and rapid germination, allow them to play a critical role in ensuring the stability and adaptability of ecosystems, particularly in tropical and subtropical regions.

By germinating quickly under favorable conditions, recalcitrant seeds enable the rapid establishment of vegetation, which is essential in recovering from natural disturbances such as storms, floods, or human-induced activities like deforestation. The plants that arise from these seeds often act as pioneer species, stabilizing the soil, reducing erosion, and creating a microenvironment that promotes the growth of other plants. This regenerative capacity enhances the ecosystem's ability to bounce back after disturbances, contributing to long-term stability.

Recalcitrant seeds also support species diversity, which is a key component of ecosystem resilience. Many of the plants that grow from these seeds serve as keystone species, providing habitats and food resources for a wide range of organisms. This interconnectedness fosters ecological redundancy, where multiple species perform similar roles, ensuring that ecosystem functions continue even if some species are lost. For example, plants from recalcitrant seeds may sustain populations of pollinators and seed dispersers, whose activities are essential for maintaining plant diversity and ecosystem productivity.

The ability of recalcitrant seeds to germinate in shaded or low-light conditions further strengthens ecosystem resilience by enabling forest regeneration beneath existing canopies. This characteristic supports the development of stratified forests, which are more resistant to environmental stressors such as drought or temperature fluctuations. The diverse plant layers created by these seeds enhance ecosystem functions, including carbon sequestration, nutrient cycling, and water regulation, all of which are crucial for maintaining resilience in the face of climate change.

In addition, plants grown from recalcitrant seeds contribute to long-term ecosystem health by enriching the soil with organic matter and improving its structure. The nutrient-rich environment they create supports the growth of other plant species and microorganisms, fostering a dynamic and self-sustaining system. This process ensures the ecosystem's capacity to adapt to changing conditions and continue providing essential services.

However, the sensitivity of recalcitrant seeds to desiccation and their dependence on specific environmental conditions make them vulnerable to climate change and habitat degradation. Their decline could compromise the resilience of ecosystems that rely on them. Conservation efforts, including habitat protection and research into the ecological requirements of recalcitrant seeds, are critical to preserving their role in maintaining ecosystem stability and adaptability.

Recalcitrant seeds exemplify the intricate relationships within ecosystems, where their growth and survival are intertwined with broader ecological processes. Their ability to promote biodiversity, facilitate recovery, and enhance ecological functions underscores their importance in building and maintaining resilient ecosystems.

Adaptation strategies of Recalcitrant Seeds in Ecosystems

Genetic Diversity and Evolutionary Strategies

Plants with recalcitrant seeds often exhibit high genetic diversity within populations. This diversity allows them to respond to environmental changes and adapt to varying conditions over time. The presence of recalcitrant seeds in ecosystems represents an evolutionary strategy that balances risks associated with seedling establishment in challenging environments and opportunities for rapid growth and reproduction under favourable conditions.

a) Adaptation to Moist Environments

Recalcitrant seeds are predominantly found in species inhabiting moist tropical and subtropical environments. Their sensitivity to drying is an evolutionary adaptation to these humid climates where the risk of desiccation is minimal. This adaptation ensures that seeds remain viable and ready for

Fig. 1: *Shorea robusta* seeds (Sal) *(Source: Indiamart)*

germination when environmental conditions are favourable, particularly moisture availability. For instance, species such as the tropical tree *Shorea robusta* produce recalcitrant seeds that thrive in the consistent humidity of tropical rainforests.

b) Rapid Germination and Seedling Establishment

One of the most notable ecological features of recalcitrant seeds is their propensity for rapid germination. Unlike orthodox seeds, which may remain dormant until conditions are suitable, recalcitrant seeds often germinate soon after dispersal. This rapid germination is advantageous in stable environments where the conditions for seedling establishment, such as adequate moisture and temperature, are consistently met . For example, the seeds of the mangrove species *Avicennia marina* exhibit immediate germination, allowing seedlings to establish quickly in the dynamic intertidal zones they inhabit .

Fig. 2: *Avicennia marina*

(Source of Fig.-2: https://www.asergeev.com/pictures/archives/compress/2015/1645/12.htm)

c) Contribution to Continuous Reproduction

Recalcitrant seeds support continuous reproductive cycles in ecosystems where seasonal changes are minimal. In tropical rainforests, where environmental conditions remain relatively constant throughout the year, the ability of recalcitrant seeds to germinate without a dormancy period enables ongoing regeneration and maintenance of forest structure and biodiversity. This continuous reproduction is crucial for sustaining the dense and diverse vegetation typical of these ecosystems.

4. Maintenance of Biodiversity

The unique germination requirements and characteristics of recalcitrant seeds contribute significantly to the maintenance of plant biodiversity. These seeds support species that might not survive if their seeds required dormancy and desiccation tolerance. This promotes a variety of plant life, which in turn supports diverse animal and insect populations, creating a complex and interdependent web of life . For instance, the African oil palm (*Elaeis guineensis*) produces recalcitrant seeds that contribute to the rich biodiversity of tropical African forests.

Fig. 3: African oil palm (*Elaeis guineensis*)

(Source of Fig. 3: Franz Eugen Köhler, Köhler's Medizinal-Pflanzen)

5. Specialized Seed Dispersal Strategies

Plants producing recalcitrant seeds often rely on specific dispersal mechanisms, frequently involving animal dispersers. The mutualistic relationships between these plants and their dispersers are critical for seed propagation. Animals such as birds, mammals, and insects that feed on these seeds play a crucial role in transporting them to suitable germination sites. This dispersal strategy not only aids in plant propagation but also enhances genetic diversity by spreading seeds across wider areas. The Brazil nut tree (*Bertholletia excelsa*), for instance, relies on agoutis to disperse its large, recalcitrant seeds.

Fig. 4: The Brazil nut tree (*Bertholletia excelsa*) *(Source: wikipedia)*

6. Role in Nutrient Cycling

Recalcitrant seeds contribute to nutrient cycling within their ecosystems. Since they are not adapted for long-term dormancy, recalcitrant seeds that do not germinate decompose relatively quickly. This decomposition process returns valuable nutrients to the soil, supporting the overall health and fertility of the ecosystem. The rapid breakdown of these seeds helps maintain soil quality and promotes the growth of other plant species.

7. Implications for Climate Change Resilience

Understanding the ecological significance of recalcitrant seeds is increasingly important in the context of climate change. As global temperatures rise and precipitation patterns shift, the habitats of many recalcitrant seed-bearing plants are under threat. Conservation efforts targeting these species are critical for maintaining the resilience and functionality of ecosystems that rely on them. Preserving the genetic diversity and adaptive potential of these plants is essential for ensuring ecosystem stability in the face of environmental changes.

Conclusion

Recalcitrant seeds play a vital role in their ecosystems through rapid germination, support of continuous reproduction, maintenance of biodiversity, specialized dispersal strategies, and contribution to nutrient cycling. Their ecological significance underscores the need for targeted conservation strategies to ensure the survival of these sensitive species amidst the challenges posed by climate change. By appreciating and protecting the unique characteristics of recalcitrant seeds, we can help sustain the complex and dynamic ecosystems that depend on them.

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MONITORING OF LAND DEGRADATION AND DESERTIFICATION USING STATE-OF-THE-ART METHODS AND REMOTE SENSING DATA

Venus Mahant[1] and Pradeepto Pal[2]

[1]School of Applied and Life Sciences, Uttaranchal University Dehradun, Uttarakhand India
[2]College of Horticulture, Central Agricultural University (Imphal) Thenzawl, Mizoram, India
Corresponding E-mail: pradeeptopal03@gmail.com

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Abstract

Managing soil health is critical for sustainable agricultural growth and ecological balance, as well as for delivering many essential ecosystem services. Soils are a huge and valuable natural resource. Due to anthropogenic activity and climate change, land degradation has emerged as a significant worldwide problem that is hazardous to ecological and food security. Accurate and exact reporting of land cover changes is crucial for enhancing the study of the nature of the landscape and for reducing the consequences of desertification. Due to desertification and other related activities (such as the reduction of forests), it is challenging to identify. Due to its great efficiency and time-saving benefits, remote sensing technology is often and widely employed for researching land degradation occurrences. This article analyses contemporary advancements and technologies that have been employed in various studies at various locations to investigate land/soil degradation, including the introduction of a deep learning/AI techniques and some models to address desertification detection using Landsat imaging, etc. In order to produce findings&judge the techniques to improve&enhance the technology where improvement is required so that it could be incorporated for more efficiency&accuracy for precision in the remote sensing technologies, we conducted this study at the end we provided results of this study&some recommendations.

Keywords: Landsat imaging, desertification, soil health, land degradation, remote sensing, salinization

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Introduction

Soil bridges Earth's four spheres—lithosphere, biosphere, hydrosphere, and atmosphere—through its support of life alongside sustainable development. The natural environment achieves regulatory functions along with providing ecosystem services which together generate cultural advantages while handling worldwide threats like biodiversity loss and food and water supply assurance and climate management systems and human wellness maintenance. Earth functions become threatened because expanding land use for human needs results in soil degradation. Life and development needs, and resource conflicts require immediate sustainable soil management to receive protection[1],[2],[3],[4],[5],[6].

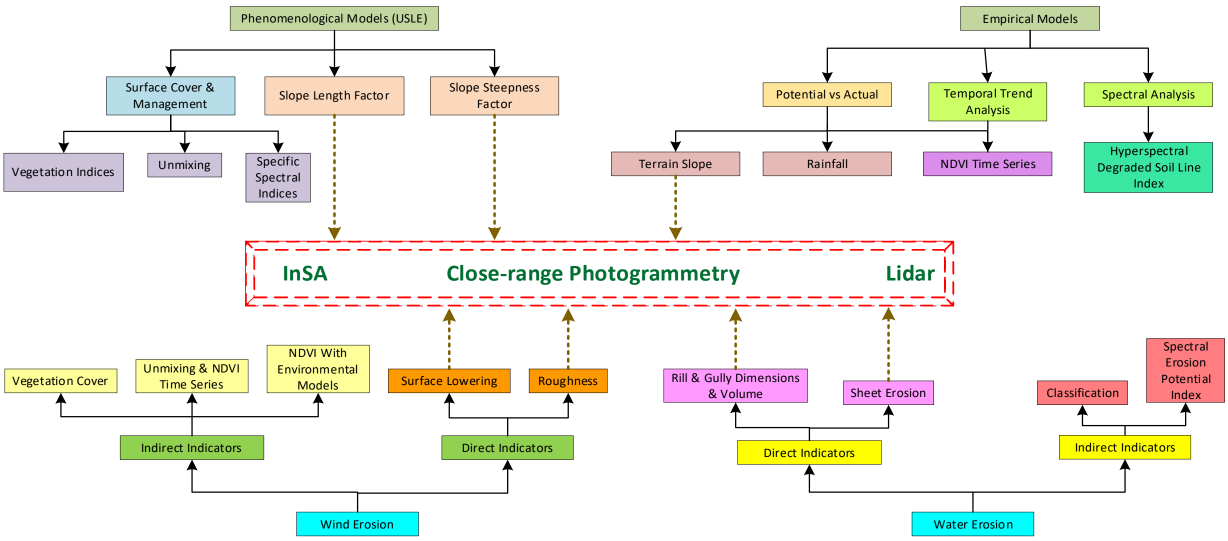

Fig. 1: Models Used for Monitoring of Soil Losses

Soil quality deterioration causes a reduced ability of the soil to generate ecosystem products alongside losing its regulatory functions. Loss of physical chemical and biological properties occurs through natural and human activities thus reducing soil ability to conduct land use operations and maintain environmental regulation. Soil degradation exists as a dynamic complex process that shows past present and future damage and serves as a vital sign for land degradation. The FAO established its definition of degradation through the GLASOD initiative and divided it into three degradation types: biological, chemical and physical processes. Erosion along with compaction and four additional issues including salinization constitutes the main signs of degradation. This occurs in combination with acidification and heavy metal pollution and depletion of nutrients. Academic institutions and governments alike focus on soil degradation solutions through proper assessment, prevention and restoration programs [7],[8],[9].The 2015 UN Sustainable Development Summit established the Sustainable Development Goals (SDGs) at this occasion. Soil management sustainability plays an essential role in accomplishing SDG1 for no poverty along with SDG2 for zero hunger as well as SDG6 for clean water and SDG13 for climate action and SDG15 for life on land. The condition of soil provides benefits for both agricultural systems that resist climate changes and aid in carbon storage and promote human welfare. Traditional field methodologies cover essential soil degradation patterns and cause analysis yet remain slow and expensive and suffer from accessibility constraints. The advancement of sustainable management strategies and soil degradation research both require modern and detailed soil data collection at improved spatial resolution. [13],[14],[15]. RS technology provides several beneficial features which outperform standard field research methods in soil degradation investigation. This methodology provides wide perspective views along with excellent efficiency along with affordable costs that enable real-time data acquisition together with repetitive surface data acquisition capabilities. Remote sensing-based data receives categorization through energy type together with site and spectral bands as well as range area definitions. The advancement of earth observation technologies together with imaging technology has led to improved accessibility of satellites with high spatial resolution and time resolution. RS investigation of soil degradation has become crucial because it offers improved spatial and temporal advantages. Computer technology and algorithm development advances have substantially improved how RS can be used to study soil degradation through monitoring processes. Scientists currently focus on developing RS-based systems to track and forecast soil deterioration because of recent technological advancements [19],[20],[21]. To evaluate the forms, contributing causes, and model techniques of soil degradation, these studies, however, mostly concentrate on a particular nation or region. Within this framework, the current review will map the worldwide landscape of soil degradation research in great detail, Explain the broad knowledge base for study on soil deterioration using remote sensing, and examine the mechanics of this field's development. Inspired, in part, by the recent and swift advancements in radio science technologies, in addition to the important benefits of modelling algorithms to comprehend soil deterioration and consequences from a number of angles, in this study, we want to give a summary of the function of RS in filling in information gaps and promoting advancements in studies on soil deterioration. This has some reference relevance for soil science investigations in different domains in addition to helping to objectively show the state of the study on soil degradation. Additionally, it provides a scientific resource for RS technology-based soil degradation study in the future.It also offers a scientific resource for future research on soil deterioration using RS technology. Next, we talk about how RS may be used to discover significant occurrences linked to soil deterioration, including erosion of soil (Section 3.1), salinization of the soil (Section 3.2), desertification of the soil(Section 3.3), and heavy metal pollution in soil (Section 3.4). Next, the section number 4 (Section 4) we have discussed result and Section 5 we have discussed some recommendations and discussions.

Characterization of Soil Characteristics by Remote Sensing

As a multi-phase substance soil possesses distinctive electromagnetic behavior through transmission and emissivity and absorbance and reflectance modes. RS technology enables the gathering of radiation and reflection data from objects which makes possible their identification and classification methods. The technology provides both temporal as well as spatial information about soil properties which allows scientists to assess soil qualities. Soil degradation occurs from physical, chemical and biological factors resulting in two types of damage: direct and indirect. Surface roughness, soil water content, organic matter content and mineral composition make up the direct indicators in addition to land cover/use and vegetation features which serve as indirect measures. The use of RS technology for soil parameters observation delivers extensive insights into the nature of soil degradation conditions along with their environmental consequences.[27],[28],[29].

Direct

Mineral Makeup of Soil

The chemical properties of soil along with its degradation patterns depend heavily on the mineral content that comes from parent materials. Primary minerals continue to show features from their natural parent materials yet secondary minerals particularly clay help demonstrate both soil fertility patterns and mineral transformation and soil development processes. Soil minerals work with organic compounds and microorganisms to influence nutrient contents together with pollution responses and total soil functioning. The visible and near-infrared (VNIR) regions (400–2500 nm) allow remote detection of spectrally active soil minerals such as clay and silicate as well as carbonate, sulphate, and iron compounds.

Remote sensing devices that include VNIR spectrometers with satellite multispectral systems and hyperspectral imaging play an essential role in studying soil mineral structure and degradation. The combination of peculiarities in hyperspectral imaging technology has enabled scientists to develop comprehensive maps showing iron concentrations alongside organic matter contents and clay measurements thus facilitating studies of soil degradation. Multiple recent advancements utilize the time series data from satellites including Landsat TM, ETM, OLI, and Sentinel-2 for precise mapping of clay content and soil degradation assessment. Scientists have proven that average spectral reflectance captured from satellite images produces accurate clay content maps (R^2 = 0.75 with RMSE = 188 g/kg). This technique applies an effective mechanism to monitor soil mineral properties together with degradation processes over extended time periods and geographic areas. The technique utilises globally accessible VNIR/SWIR satellite imagery to provide substantial capabilities for worldwide soil degradation assessment and sustainable soil management support. [2],[34],[35],[36],[37],[38],[39],[40].

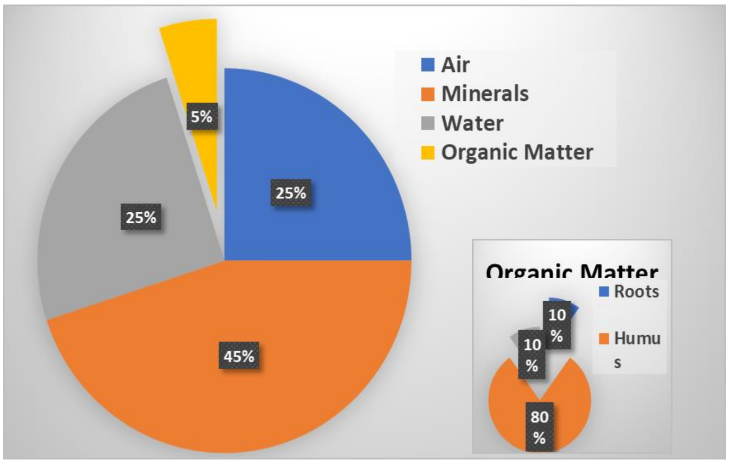

Fig. 2: Showing soil composition

Organic Matter in Soil

Soil organic matter describes all organic materials found in soil which comprise microbial substances and decaying remains of plants and animals together with microbial-produced chemicals. The presence of SOM works to sustain soil water content and physical form while ensuring climatic stability. Soil organic matter regulates CO2 uptake in the atmosphere as it simultaneously enhances water-retention ability and soil productivity alongside decreasing soil degradation. The organic matter level in soil serves as a valid meter for evaluating quality along with degradation status where increased SOM amounts appear through darker colour tones[2],[42],[15],[43],[29],[18]. The determination of soil SOM through NH, CH and CO functional group analysis needs precise monitoring by near-sensing technologies and remote sensing identification. Researchers use multispectral RS images to measure regional patterns of SOM along with its scales and types[29].SOM distributions can be successfully predicted through multispectral optical RS data acquisitions from GF-1 as well as Landsat, CBERS, ASTER, and IKONOS systems. Cloudy conditions together with low spectral resolution keep these methods from being effective. The accuracy of SOM estimations increased through researcher-developed portable VNIR spectrometers and hyperspectral RS systems[29],[45],[46],[47].The combination of Hyperion spectra and VNIR methods enables SOM content calculation to serve as a substitute for tracking soil degradation in desert areas and predicting sample soil concentration values[48], [18],[49].A global investigation of VNIR spectra conducted an analysis to predict soil properties including SOM. The spectra offer complete measurements of soil variations while also providing descriptions of worldwide VNIR spectral libraries for soil variations. Soil properties particularly SOM show spatial variation that impedes the process of spatial pattern description. The research design uses 20 g/kg SOM content as its specific threshold value [45],[50]. A combination of NIR spectroscopy and EPO has become valuable to reduce SOM measurement interferences so salt-affected areas can determine their soil organic matter content by minimizing both water content and iron oxide effects [51],[52].

Surface Roughness of Soil

The physical feature of soil surface roughness developed from a combination of mineral and rock fragments as well as micromorphological features and particle distribution patterns. Surface roughness plays a major role in soil erosion mechanisms because it alters flow pattern movements and hydrodynamic actions and sediment transport patterns. The Pisha sandstone region serves as an "Earth Cancer" example of erosion since it features steep slopes attached to loose rock configurations and diverse ground topography. Soil degradation studies require knowledge of surface roughness because the condition controls how fast erosion occurs and how sediments move. Research shows that higher surface roughness decreases soil erosion operations by 31% which simultaneously enhances soil quality while advancing biological systems and developing plants and animals. Remote sensors use detected soil shadows to provide essential information through optical RS reflectance readings. The Bi-directional Reflectance Distribution Function (BRDF) determines directional reflectance by using physical, semi-empirical, and empirical models. The broad investigation of surface roughness across large regions is possible with Microwave Remote Sensing which supports studies about soil degradation. Single models that analyse surface roughness serve analysts to examine soil characteristics and erosion methods while supporting preservation research by focusing on roughness measurements. [53],[54],[55],[56],[33],[57],[58], [59],[60].

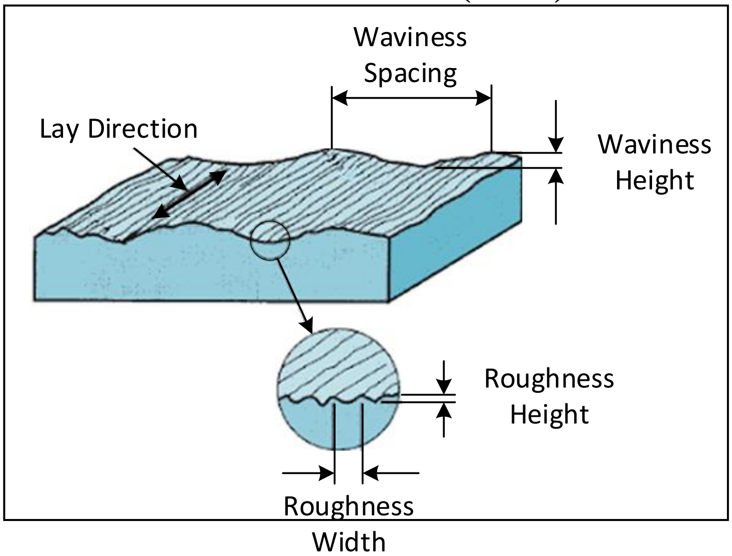

Fig. 3: Engineering Properties of Soil Surface Roughness

Moisture of Soil

Various soil qualities undergo perpetual change because of human activities and weather factors and maintain an ongoing adaptive process with regional ecosystems. Excessive dryness in the soil leads to structural degradation which diminishes biodiversity and decreases productivity and causes desertification. Soil moisture content detection from a distance would aid scientists in studying soil degradation processes. Soil moisture regulates temperature and nutrition and aeration conditions but elevated moisture decreases aeration functions while opposing effects occur from reduced soil moisture. Soil erosion becomes inevitable as both strong winds increase evaporation rates and the absence of soil water leads to destructive erosion processes [65],[66],[2],[67],[68].The vital function of Microwave remote sensing (RS) enhances macrofaunal transportation which strengthens both soil carbon cycling performance and structure-fertility characteristics. This technology provides capabilities for measuring time series and soil moisture content as well as estimating evaporation and drought status. The technique functions with specific boundaries because plants obstruct visibility and rugged land surfaces become a factor but it proves effective for broad-scale research [69],[70]. Each of the RS dataset-based techniques for retrieving soil moisture has benefits and features of its own (Table 1)[71],[72]. The analysis of soil moisture content through microwave technology employs multi-source RS data fusion-based collaborative inversion along with artificial intelligence techniques such as Convolution Neural Networks, semi-empirical and physical model improvements and inverted algo development for recently deployed sensors. Soil deterioration and drought characteristics along with multi-scale soil moisture information have been evaluated through extensive use of these models.[73],[74],[73],[52]. Additionally, a great deal of study has been done on the effectiveness of remotely sensed soil moisture products in comparing and evaluating the characteristics of drought&soil deterioration (Table 2) [75],[76].

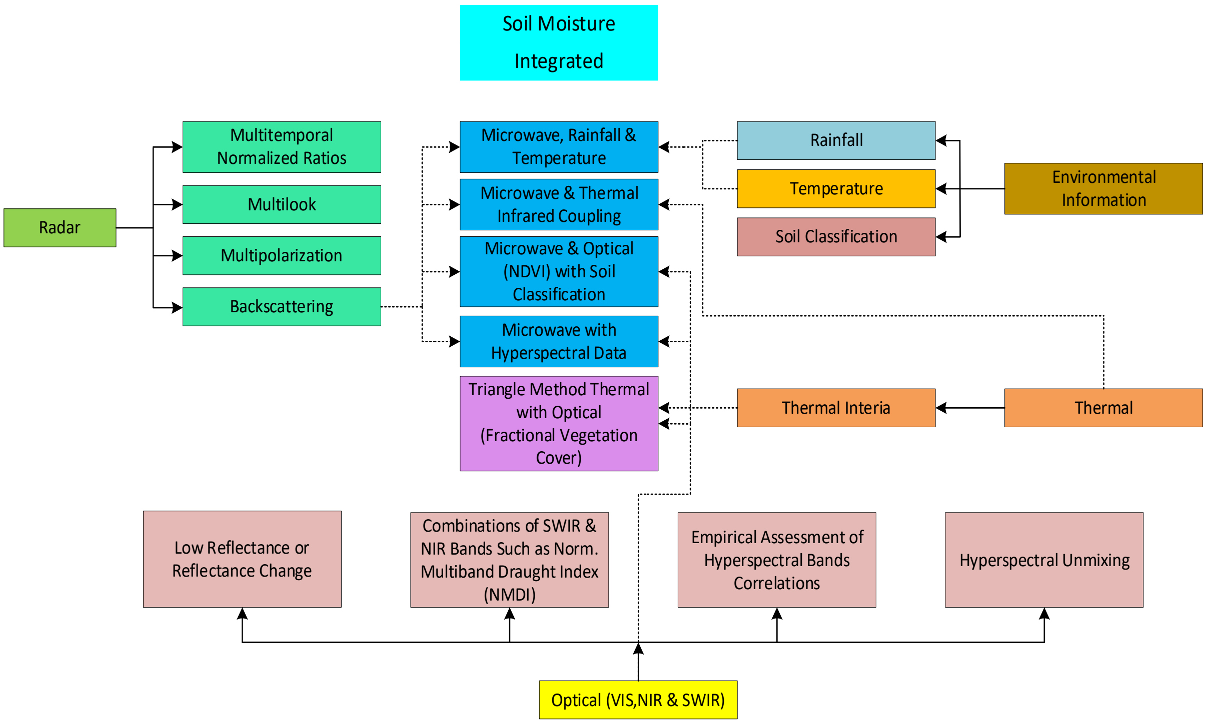

Fig. 4: The diagram illustrates the Architecture of Optical, Thermal & Radar Indicators and how they are integrated with Environmental Data to Track Soil Moisture.

Indirect

State of the Vegetation

Soil deterioration prevents itself through the protective actions of vegetation. The underground plant anatomy supports soil stabilizing properties to reduce direct scouring from runoff and the foliage protects the soil from precipitation erosion. The connection between soil quality and vegetation operates as a two-way system where the physical-chemical properties of soil directly affect vegetation health but vegetation deterioration produces negative effects on soil properties that cause reductions in biomass quantity and biodiversity together with soil porosity and infiltration rates. Soil restoration receives support from proper vegetation management since it enhances water efficiency along with fertilizer and heat utilization. Fast-wood plantation systems in dry regions worsen soil drought by producing high levels of water evaporation which reduces water supply to shallow-rooted vegetation. The evaluation of soil health usually relies on land use surveillance which focuses on monitoring changes in vegetation coverage. The decrease in tropical African vegetation cover resulted in reduced rainfall and worsened soil conditions of the region. The connection between vegetation and soil organic carbon reserves makes vegetation loss responsible for enhancing soil erosion along with carbon depletion. Programs by remote sensing involving vegetation indices (VIs) and fractional vegetation cover (FVC) along with net primary productivity (NPP) serve as key tools for tracking vegetation changes and environmental stresses. Wind erosion models require these indices to function properly while soil degradation assessment occurs indirectly through their usage. However, vegetation-based assessments have limitations. The remote sensing method does not account for litter layers although these layers play an essential role in protecting the soil surface. The effects of climate change and human activities on vegetation states create challenges when attempting to analyse particular environmental impacts. The usage of VIs as proxy elements means they cannot reveal exact details about soil degradation types or extent. The evaluation of soil degradation becomes more accurate when remote sensing combines with on-site observations while resolving its limitations[77],[78],[32],[79],[80],[81],[82],[67],[83],[84],[85],[86],[87].

Table 1: Merits and Demerits of Distinct Spectral Data to Map the Moisture Content of Soil

Electromagnetic Range	Observation Range	Advantages	Limitations
Visible and nearinfrared	Spectral reflectance	Broad sweep range&fine spatial resolution	Weak penetration, cloud cover interference,&daytime only
Thermal infrared	temperature at the land's surface	Broad sweep range, distinct physical processes,&fine spatial resolution	Weak noise penetration, cloud cover,&plant interference
Passive microwave	Dielectric characteristics & brightness temperature	robust penetration, constant&all-weather situations,&obvious physical mechanisms	Poor spatial resolution, as well as vegetation&uneven terrain
Active microwave	Backscattering coefficient&dielectric characteristics		

Land use/cover Change

Human activities drive global change causing important modifications in land use patterns across Earth (LUCC). LUCC serves as a direct connection between human impacts and Earth surface system processes which produces diverse land-use patterns that deliver reflection of human social-economic activities. A quick natural environment response serves as the fundamental method to study and combat global change[85],[88],[89],[90]. The world experiences rising demands for land resources while its population grows at the same time that land production rates decrease. The environmental change indicator called LUCC or optical remote sensing affects ecological processes while modifying both biodiversity and bio-geo-chemical cycles and sustainable resource use. The collection of optical remote sensing data has exceeded 50 years through the use of Landsat and SPOT and MODIS satellite systems in analysis. The Sentinel-2 mission joined by the Planet Dove satellite constellation delivery in 2015 enables space and time resolution enhancement which enhances modern land resource management practices[91],[89], [88],[92]. The LUCC (Land Use and Conservation) technology enables research into land degradation effects on soil. Extensive LUCC practices lead to severe soil degradation because changes in soil redistribution rates result in deteriorating soil quality. Three main factors that trigger soil degradation include alterations to the land surface combined with overuse of fertilizer and excessive animal grazing. LUCC methods allow scientists to properly study the combination of degradation impacts along with their linked soil erosion patterns [93],[94],[95],[81],[96],[85],[81].As a vital determinant of soil attributes LUCC serves as a critical factor in soil characteristics throughout riparian areas of the middle Heihe River basin. The soil moisture content depends on modifications of land cover combined with salt crust formation due to lake reduction and operations used to manage soil. A lack of nitrogen elements blocks the growth of understory plants thus reducing organic matter delivery to the soil. The accurate assessment of soil degradation proves difficult through GIS and RS technologies because remote sensing data has known limitations as well as availability constraints for RS data [68],[97].

Table-2: An Explanation of the Vegetation Indices that are Frequently Used to Measure Soil Deterioration.

Indexes	**Descriptions**	**Refences**
Conventional spectral indices		
NDVI	Normalized difference vegetation index	[98]
GNDVI	Green normalized difference vegetation index	[99]
RDVI	Renormalized difference vegetation index Linearizes relationships with surface parameters	[100]
EVI2	Two-band enhanced vegetation index	[101]
MTVI2	Modified triangular vegetation index2	[102]
Red-edge spectral indices		
NDVIre1	Red-edge normalized difference vegetation index1	[103]
NDVIre2	Red-edge normalized difference vegetation index2	
NDVIre3	Red-edge normalized difference vegetation index3	
CIre1	Chlorophyll index- Red-edge1	[104]
CIre2	Chlorophyll index- Red-edge2	
CIre3	Chlorophyll index- Red-edge1	

Evaluations of Soil Deterioration Based on Data from Remote Sensing

The analysis of soil deterioration depends heavily on remotely sensed data because these tools offer high geographical and temporal capabilities. The extraction of soil degradation data makes use of sensors including multispectral and hyperspectral and SAR alongside ground-based VNIR devices. The monitoring ability of traditional satellites remains restricted for studying soil deterioration because they operate with poor temporal resolution and available sensors are sparsely distributed. The space-time advantages of UAVs surpass satellite systems because these vehicles can release from traditional altitude limits and avoid some cloud-cover interference. Research focusing on current advancements in RS technology for modelling soil deterioration and its characterization and prediction remains systematically sparse. This paper presents an organized space-time analysis of soil deterioration research through root cause analysis (RS) by summarizing multiple techniques and indicators[31],[19],[58],[105].

Erosion of Soil

The worldwide problem of soil erosion leads to degradation through the equilibrium state of soils. The process advances methodically without major indications to degrade top soil resources of ecosystems. The state of soil and fertility depends on flood irrigation and agricultural work as well as weather conditions[106],[107],[108],[16],[108].The investigation of soil erosion together with wind erosion in Central Asia reveals the necessity to develop restoration programs. The combination of RS technology with physical models including WEQ and RWEQ through technology enables prediction of erosion rates[109],[60],[110],[111],[84],[112].Soil scientists widely adopt the RUSLE tool as a modelling system but researchers identified weaknesses to enhance its functionality. RUSLE evaluates four soil factors including rainfall, runoff erosivity and slope length and erodibility to enhance system precision and efficiency[6],[113],[23].The advancement of rainfall satellite technology now provides real-time precipitation data which solves the problem of lacking weather station observational data. The Climate Prediction Centre Morphing among other reanalysis tools including PERSIANN-CDR, TRMM, GMP, NCEP-CSFR and ERA5 underwent validation studies and comparison which may prove useful to calculate the R-factor in place of weather station observations [114],[115]. Soil structure evaluation and organic material measurement along with erodibility factors become possible through combining the RUSLE model with remote sensing and GIS. Soil erosion detection gets improved through FVC assessment together with spectral indices analysis. Scientists applied inversion models to LS factors based on RS data together with field tests which allowed for watershed area mapping [116],[113].During the last ten years both academics and society members perceived digital soil mapping (DSM) as key for evaluating soil erosion. The implementation of multi-temporal data alongside RS by researchers produced a soil deterioration assessment index which signifies DSM together with RS represents a usable approach to monitor soil deterioration from erosion processes[117],[40],[94].

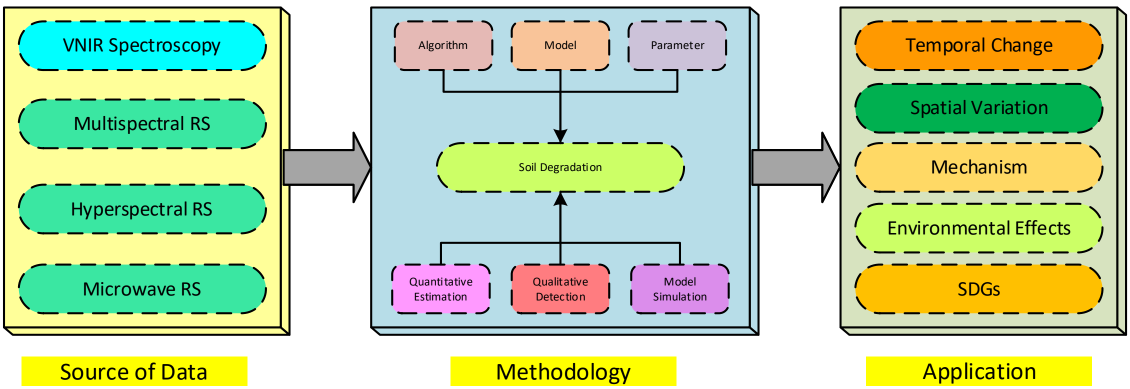

Fig. 5: Framework for Using Remote Sensing Technologies in Research of Soil Deterioration.

Soil Salinization

Soil salinization consists of two types: primary and secondary salinization which describes when salt dissolves in water. The agricultural yield suffers from primary salinization while the food security faces risks along with secondary salinization causing harm to local eco-systems and biomass production levels. The process results in desertification and leads to erosion and multiple ecological problems including degradation [118],[119],[120]. Worldwide soil salinization has exceeded 1 x 108 hectares while exceeding 100 countries in total number of affected regions. Soil salinity detection through MODIS technology depends on electromagnetic properties to interpret precise spectral reflectance patterns thus solving environmental issues [121],[122],[68]. Soil salinity monitoring relies on hyperspectral sensors as well as ground-based VNIR devices along with synthetic aperture radar (SAR). The technologies build long-term database systems to explore related processes. The current data systems have both spatial limitations and unclear resolution capabilities. The combination of land surface data and RS imagery with historical soil characteristics maps and AI algorithms enables producers to generate soil salinity maps. The combined techniques stretch research duration and enhance precision to forecast worldwide salt-induced soil changes and identify all salt-affected soil areas globally [95],[119],[21],[17],[121].

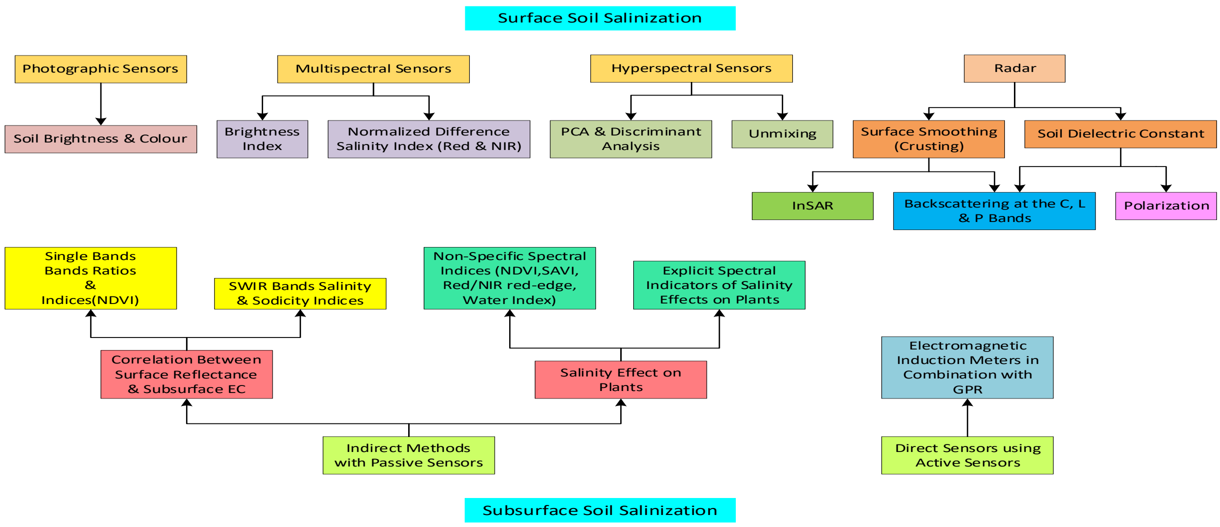

Fig. 6: Diagrammatic Topology of the Many Sensors Used to Track the Salinization of Both Surface and Subterranean Soil.

Soil Desertification

Dry subhumid regions presently experience land degradation because of human activities and environmental change which affects 1.5 billion people and destroys 2 million hectares of cultivated land each year. Soil degradation occurs as a result of human activities which disrupts environmental equilibrium while making environmental problems worse and wind erosion becomes a main contributor to these issues [123],[106],[124],[125],[126].International organizations require desertification monitoring through RS-based satellite data from Sentinel-2 and Landsat series because these platforms allow detailed local inspections. Surface data provided through SAR extends across twenty-four hours while enabling weather analysis which helps researchers study soil moisture together with surface roughness conditions. The desertification indicators of plant coverage along with biomass and soil moisture are measurable through hyperspectral remote sensing data. The degradation indicator of topsoil grain size becomes measurable through remote sensing methods based on the desertification difference index (DDI)[127],[17],[128]. Remote sensing technology should work with ground surveys to identify desertification regions along with their classification levels. Several procedures including soil identification and vegetation recognition and multi-temporal image classification processes need to be followed. A thorough evaluation of indicator biological as well as physical meanings needs to take place during the assessment process[127],[97]. The monitoring of decertified territories proves difficult because different indicator methods do not align across geographical and time-based domains. The strategic development framework allows scientists to combine field research and remote sensors for studying desertification effects in a scientific manner[131].

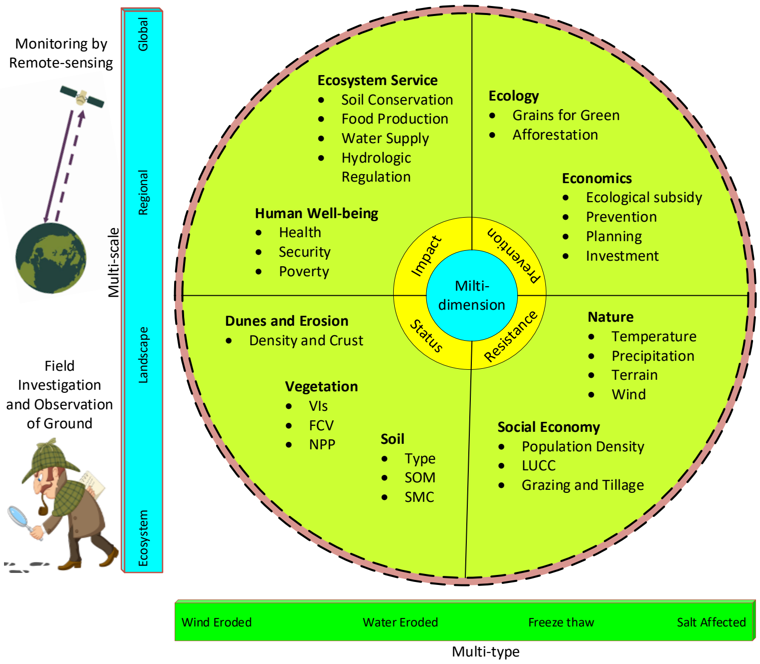

Fig. 7: The Indicator Framework for Monitoring Soil Desertification from the Perspectives of Zero Multi-Dimension (Ring Part) Multi-Scale (Y-Axis) & Multi-Type (X-Axis).

Contamination of Soil with Heavy Metals

Soil degradation occurs because of industrial operations and agricultural procedures that affect soil systems critically. Spectral analysis of soil structures represents an essential approach to identify pollutants along with their dispersion patterns which aids in resolving these problems for food security [132],[133],[134].The identification of chemical soil contaminants involves using spectroradiometers for both visible and near-infrared substances according to spectroscopy methodology. The heavy metal contents in samples can be computed through VNIR spectroscopy although researchers mainly concentrate on developing inversion methods and identifying responsive spectral parameters [137]. Soil spectroscopy stands as an essential methodology for measuring heavy metals in soil because it detects hard to identify spectral characteristics in the process. The methods benefit from improvements in pXRF instruments as well as gamma-ray machines and advanced proximal soil detection technology. [139],[133],[140]. RS technology demonstrates potential as a tool for measuring heavy metals in soil although researchers primarily use DSM technology to map hazardous metal spatial distributions in soil. Analysis of soil degradation processes along with environmental changes are currently studied from an earth systems science point of view. Sustainable development needs the combination of remotely sensed data with geographical data to understand the environment as well as human relationships due to its influence on social cohesion and economic development alongside health[135],[141],[142],[143]. AI has revolutionized current political understanding of soil degradation through its capability to analyze bio-physical, social and political factors and their combined effect.

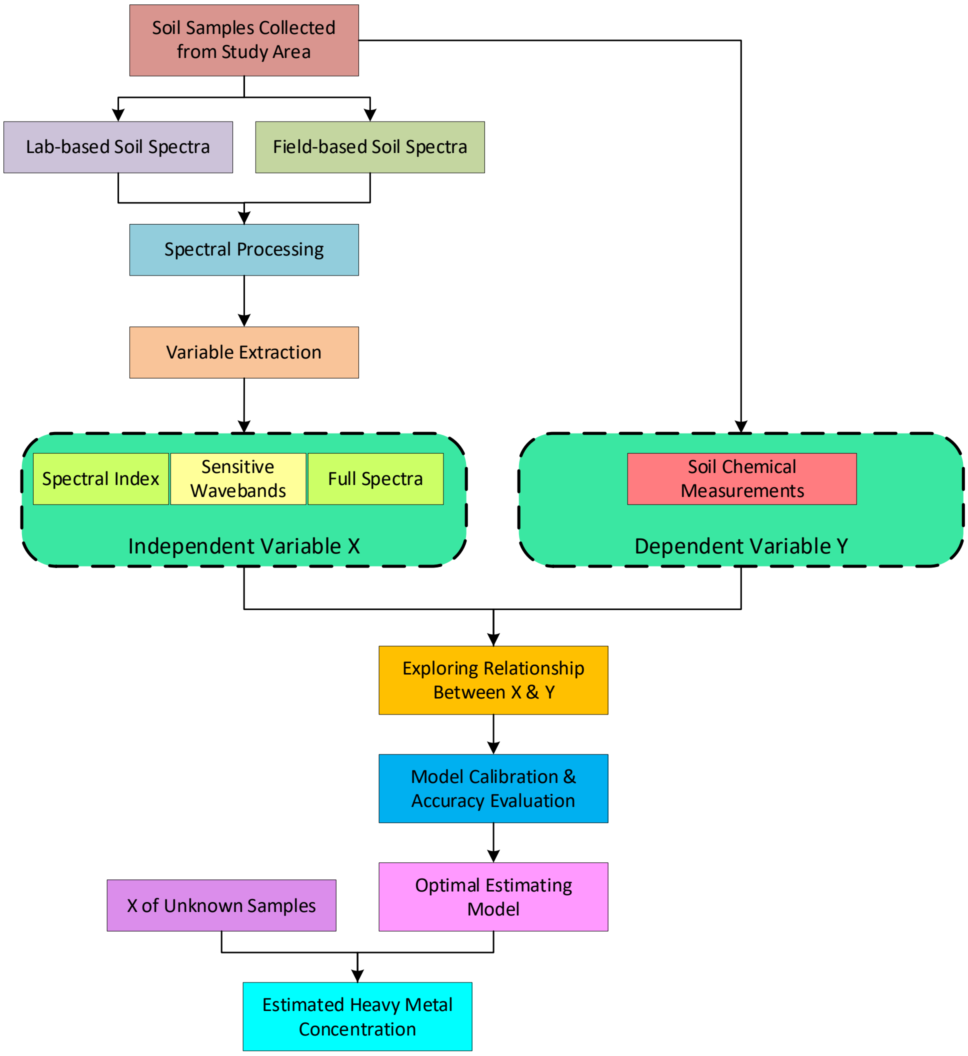

Fig. 8: Methodological Flowchart Illustrating the Primary Stages of Spectral-Based Heavy Metal Concentration Estimate

Result

Soil degradation has affected more than 30% of landmasses worldwide with special focus on dry and semi-arid regions. Determining how soil deteriorates coupled with knowledge about soil resource availability enables better prevention of worsening degradation. Soil processes are influenced by the simultaneous presence of chemical along with biological and physical characteristics[145],[8]. The application of RS systems by researchers involves using technology to restore affected land areas and monitoring environmental modifications and soil degradation while creating public awareness initiatives.[146]. The preservation of soil resources requires research about degradation alongside effective data collection and soil restoration training to support sustainable development of civilization.

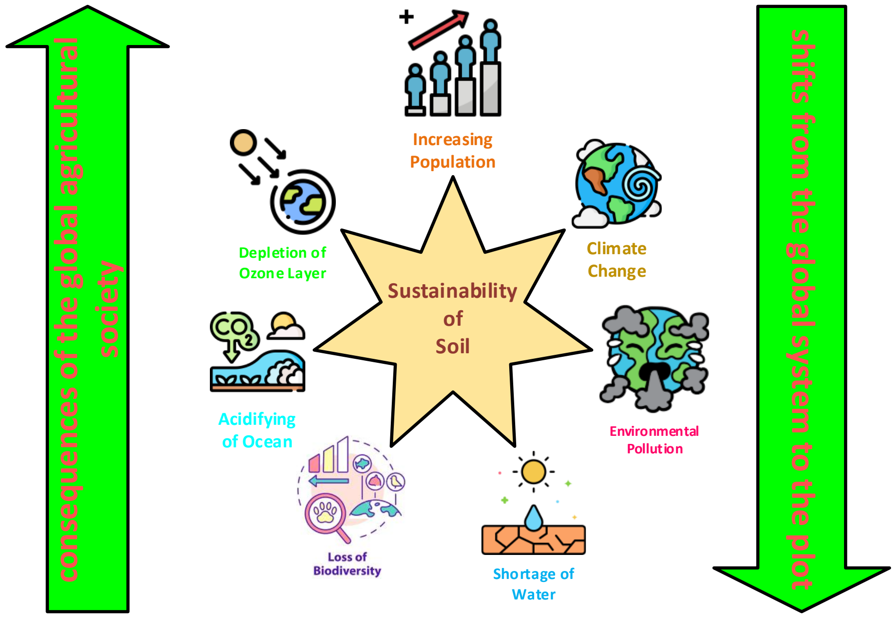

Fig. 9: Possible Connections between Variations in the Global Environment and Soil.

Conclusion

The research details about soil detergent progression presents the primary RS applications for different scenarios of soil degradation. The monitoring of soil deterioration through RS requires direct indicators combined with indirect proxies which yield crucial information for building better conceptual models and processing frameworks. Large data information spans across multiple domains including time, space and spectrum due to the emerging RS technology era. The use of independent observational data comes from devices operating in satellite mode and drone mode and from ground-based devices. Studying soil deterioration requires extensive utilization of big data information together with RS-CCP and heterogenous multisource remote sensing. A standardized worldwide method for earth observation and decision support initiatives proposes uniform datasets for quantifying soil deterioration patterns and economic implications across regions and periods. A goal exists to restore ecosystems while protecting environmental and ecological systems while blocking ongoing soil degradation processes.

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STORED GRAIN INSECT PEST AND THEIR MANAGEMENT IN THE KUMAUN REGION OF UTTARAKHAND: A REVIEW

Himanshu Pande, Divya Pangtey, Akanksha Singh and Isha Chandra

Kumaun University, Nainital, 263001, Uttarakhand, India
Corresponding E-mail: divyapangtey810@gmail.com

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Abstract

This study provides an in-depth review of the life cycle, characteristics, and impact of insect pests on stored grains. These pests, primarily from the orders Lepidoptera and Coleoptera, cause significant damage to grain quality, leading to substantial economic losses globally. Insects are categorized into various feeding groups based on their behaviour: External Feeders, which feed on the surface of grains; Internal Feeders, which infest the grains; and Primary and Secondary Feeders, depending on whether they directly damage the grain or exploit previously damaged material. The presence of these pests leads to a range of issues, including reduced nutritional value, contamination, and the promotion of mould growth, which further compromises grain safety for consumption. Given the severe consequences of pest infestations, effective pest control is critical. Management strategies to control these pests include microbial, cultural, chemical, and physical methods, each targeting specific aspects of pest behaviour and grain preservation. Microbial control utilizes natural enemies such as bacteria, fungi, and viruses; cultural methods focus on environmental modifications to discourage pest survival; chemical controls involve insecticides and fumigants; and physical methods include techniques like temperature regulation, sealing, and storage structure modifications. A comprehensive understanding of these strategies and their effective implementation is essential for minimizing the adverse impact of insect pests on stored grains, ensuring food security, and reducing economic losses in the agricultural sector.

Keywords: Stored grains, Insect pests, Pest Management, Food preservation, Lepidoptera, Coleoptera

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Introduction

The Kumaun region of Uttarakhand, located in the northern part of India, is home to a variety of agro-climatic zones conducive to the cultivation of staple grains such as wheat, rice, and maize. Indeed, agriculture forms the backbone of livelihoods for millions globally, with India's dependence on it even more pronounced, given that over 70% of its population relies on this sector (Negi and Solanki, 2016). The issue of stored grain pests, especially prevalent in regions like India with conducive climates, highlights the critical need for implementing proper grain storage techniques. Post-harvest losses resulting from unscientific storage not only threaten food security but also present economic hurdles (Daglish et al., 2018).

These pests infest grains to satisfy their need for sustenance and shelter, leading to both quantitative and qualitative losses (Bhargava & Kumawat, 2010). Interestingly, the economic impact isn't solely attributed to the actual consumption of grain by these pests but also to the contamination they introduce, including their excretions, rendering food unsuitable for human consumption. Addressing this issue requires a multifaceted approach, including the implementation of scientifically sound storage methods, the use of pest management techniques, and perhaps even innovations in storage technology to minimize losses and ensure food security for India's large population. The worldwide annual loss of food grains, estimated to be between 10-40%, (Stejskal et al., 2014) is largely attributed to insect pests, with a significant portion belonging to the orders Lepidoptera and Coleoptera. Stored grain pests are categorized as major or minor pests based on the severity of damage they cause. Further classification is based on their feeding habits (Deshwal et al., 2020).

Primary Pests

These pests directly feed on undamaged grains. They include species like the larger grain borer (*Prostephanus truncatus*) and the rice weevil (*Sitophilus oryzae*) (Deshwal et al., 2020).

a) External Feeder: Both the larval and adult stages of external feeders consume grains from outside. These pests typically access the grains through openings or weak points in the storage containers. Examples include certain species of beetles and moths that feed on the surface of stored grains or infest grain heaps (Bhargava & Kumawat, 2010).

b) Internal Feeder: Larvae of internal feeders feed entirely within the kernels or stored material. They penetrate the outer layer of the grain and consume the interior, often causing significant damage that may not be immediately visible from the outside. Common examples of internal feeders include certain types of weevils and borers (Bhargava & Kumawat, 2010).

Secondary Pests

These pests infest grains that have already been damaged or cracked, accelerating spoilage. Species like the red flour beetle (*Tribolium castaneum*) and the lesser grain borer (*Rhyzopertha dominica*) fall into this category (Deshwal et al., 2020).

Each category of pest requires specific management strategies tailored to their feeding habits and lifecycle. Integrated pest management techniques, including sanitation, temperature control, and the use of chemical or biological controls, are often employed to mitigate losses caused by these pests and ensure the security of stored grains.

Primary Pest of Stored Grains

1. Rice weevil - *Sitophilus oryzae*

Distribution

The rice weevil, scientifically known as *Sitophilus oryzae*, is a significant pest worldwide, particularly in India, where it inflicts severe damage to stored grains (Bhargava & Kumawat, 2010).

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Host

It affects a variety of grains, including paddy, wheat, millet, maize, sorghum, and barley (Kumar, 2017).

Bionomics

1. The full-grown larvae are around 5mm in length, plump, fleshy, and legless.
2. The adult beetle is reddish-brown, approximately 3mm in length, with a cylindrical body and a long, slender, curved rostrum. Its elytra bear four light reddish or yellow spots.
3. Breeding occurs from April to October, with adults hibernating during winter inside cracks, crevices, or under wheat bags in storage facilities.
4. During the active season, females lay approximately 400 eggs on grains, sealing the hole with a gelatinous secretion (Bhargava& Kumawat, 2010).
5. Eggs hatch in 6 to 7 days, and the young larvae bore directly into the grain, where they feed and grow to maturity. Pupation also occurs inside the grain, lasting 6-7 days. (Deshwal et al., 2020).

Damage Symptoms

1. Both the larvae and adults cause damage to grains. They hollow out the grains, reducing them to powder.
2. Damage can start in the field itself, and adults cut circular holes in the grains, causing more destruction than consumption.
3. Developing larvae live and feed inside the grains, causing irregular holes approximately 1.5 mm in diameter (Kumar, 2017).

Table 1: Primary Pest of Stored Grains

Common name	Scientific name	Order	Family
Internal feeders			
Rice weevil	*Sitophilus oryzae*	Coleoptera	Curculionidae
Lesser grain borer	*Rhyzopertha dominica*	Coleoptera	Bostychidae
Angoumois grain moth	*Sitotroga cerealella*	Lepidoptera	Gelechiidae
External feeders			
Red flour beetle	*Tribolium castaneum*	Coleoptera	Tenebrionidae
Indian meal moth	*Plodia interpunctella*	Lepidoptera	Phycitidae
Fig moth or Almond moth	*Ephestia cautella*	Lepidoptera	Phycitidae
Rice moth	*Corcyra cephalonica*	Lepidoptera	Galleriidae
Khapra beetle	*Trogoderma granarium*	Coleoptera	Dermestidae

Table 2: Secondary Pest of Stored Grains

Common name	Scientific name	Order	Family
Saw-toothed grain beetle	*Oryzaephillis surinamensis*	Coleoptera	Silvanidae
Long-headed flour beetle	*Latheticus oryzae*	Coleoptera	Tenebrionidae
Flat grain beetle	*Cryptolestus minutas*	Coleoptera	Cucujidae
Grain lice	*Liposcelis divinitorius*	Psocoptera	Liposcelidae

2. Lesser grain borer - *Rhyzopertha dominica*

Distribution

The lesser grain borer is found in several regions, including India, Algeria, Greece, the United States, New South Wales (Australia), Japan, and China (Bhargava& Kumawat, 2010).

Hosts

It attacks a wide range of stored grains and commodities, including wheat, rice, maize, sorghum, barley, lentils, army biscuits, ship biscuits, stored and dried potatoes, corn flour, beans, pumpkin seeds, tamarind seeds, and millets. (Kumar, 2017).

Bionomics

1. The larva is about 3mm long, dirty white, with a light-brown head and a constricted elongated body.
2. The adult is a small cylindrical beetle measuring about 3mm in length and less than 1mm in width. It is shining dark brown with a deflexed head, covered by a crenulated hood-shaped pronotum. There's no morphological difference between the two sexes.
3. Breeding occurs from March to November, with hibernation in December either as an adult or as a larva.
4. A single female can lay 300-400 eggs in 23-60 days at a rate of 4-23 eggs per day. Eggs are laid singly among the frass or glued to the grain in batches (Bhargava & Kumawat, 2010).
5. The incubation period is about 5-9 days. Larvae cut a circular hole in the pedicel end of the eggs to emerge.
6. Larval period lasts 23-50 days, pupal period 4-6 days, and adults live for about 40-80 days. There are typically 5-6 generations in a year (Deshwal et al.,2020).

Damage Symptoms

1. Both adults and larvae are voracious feeders, boring into grains and reducing them to mere shells with irregular holes.
2. Adults are capable of migrating from one storage facility to another, causing fresh infestations.
3. They produce a considerable amount of frass, spoiling more than what they eat.

4. Larvae eat their way into the grain or feed on the grain dust and can also attack grain externally (Kumar, 2017).

3. Angoumois grain moth - *Sitotroga cerealella*

Distribution

The Angoumois grain moth is found worldwide. In the Indian subcontinent, it is more abundant in mountainous areas or regions with mild climates (Ahmad et.al., 2021).

Hosts

It infests a variety of grains, including paddy, wheat, maize, sorghum, barley, oats, etc. (Kumar, 2017).

Bionomics

1. A full-grown larva is about 5 mm long, with a white body and a yellow-brown head.
2. The adult is a buff, grey-yellow, brown, or straw-colored moth with a wing expanse measuring about 10-12 mm. It has narrow, pointed wings fringed with long hair.
3. Breeding typically occurs from April to October. The insect overwinters as a hibernating larva and pupates in early spring as the season warms up.
4. Females lay eggs singly or in batches on or near the grain. The eggs are initially small and white, turning reddish later on. A single female lays, on average, 150 eggs, usually within a week after mating. The egg period is 4-8 days (Ahmad et.al., 2021).
5. The larval stage may last about 3 weeks. Before pupation, the larva constructs a silken cocoon in a cavity. The pupal period is 9-12 days, and the adult lives for about 4-10 days. During the active season, the life cycle is completed in about 50 days. Several generations are completed in a year (Deshwal et al., 2020).

Damage Symptoms

1. The damage is most severe during the monsoon season.
2. Only the larvae cause damage by feeding on grain kernels before harvest and in storage. They bore into the grain and feed on its contents.
3. Exit holes of about 1 mm in diameter, with or without a trap door, are observed on affected cereal grains. As the larva grows, it extends the hole, which partly gets filled with pellets of excreta.
4. Infested grains exhibit an unhealthy appearance and smell. In a heap of grain, the upper layers are most severely affected (Kumar, 2017).

4. Red flour beetle - *Tribolium castaneum*

Distribution

Worldwide (Ahmad et.al., 2021).

Hosts

Wheat flour, broken grains, mechanically damaged grains, dry fruits, pulses, and prepared cereal foods such as cornflakes (Kumar, 2017).

Bionomics

1. Eggs: Laid by females, typically about 25 in number, and take around 2 weeks to hatch.
2. Larvae: Initially yellowish-white and about 1 mm in length, mature into reddish-yellow larvae. They feed and develop for about 26-30 days in summer.
3. Pupae: Yellowish and hairy, pupation occurs in the flour, lasting 5-9 days.
4. Adults: Active during the breeding season from April to October (Deshwal et al.,2020).

Damage Symptoms

1. Larvae: Cause damage by feeding on stored food products. They are usually concealed within the food.
2. Adults: Construct tunnels as they move through flour and other granular food products. They are mostly found hidden in flour.
3. Infestation Signs: Flour may turn greyish, moldy, and develop a pungent odor, rendering it unfit for human consumption (Ahmad et.al., 2021).
4. Affected Products: Damaged processed food, flour, Suji, meda (Kumar, 2017).

5. Indian meal moth- *Plodia interpunctella*

Distribution

The Indian meal moth is indeed found worldwide, infesting various stored food products across different regions (Ahmad et.al., 2021).

Host Range

It infests a wide range of stored food products, including grains, meals, breakfast foods, soybeans, dried fruits, nuts, dried roots, herbs, and even dead insects.

Bionomics

1. The larva of the Indian meal moth is typically white, sometimes tinged with green or pink, with a light-brown head.
2. When mature, the larva can reach a length of 8-13 mm.
3. The adult moth has a wingspan of about 13-20 mm and exhibits a coppery lustre.
4. Breeding can occur throughout the year.
5. The female moth lays 30-350 whitish ovate eggs, singly or in clusters, on or near suitable food sources.
6. The egg period lasts 2 days to 2 weeks, depending on environmental conditions.
7. Larvae reach maturity in about 30-35 days, after which they pupate within a thin silken
8. The pupal stage can last from 4-35 days. In summer, the life cycle is completed in 5 or 6 weeks, with about 4-6 generations per year (Deshwal et al.,2020).

Damage Symptoms

1. Damage is primarily caused by the larval stage. Larvae crawl over the surface of stored grains and other food materials, webbing them together with silken threads.
2. Adult moths fly from one storage bin to another, spreading infestations (Kumar, 2017).

6. Fig moth or Almond moth or Warehouse moth - *Ephestia cautella*

Distribution

Widely spread in tropical and subtropical regions (Ahmad et.al., 2021).

Host

Wheat, rice, maize, jowar, barley, sorghum, Groundnut, soybean, Spices, dry fruits, oilseeds (Kumar, 2017).

Bionomics

1. Adult Moth: Greyish wings with transverse stripes, approximately 12 mm in wing expanse.
2. Egg Laying: Females lay whitish eggs indiscriminately in cracks and crevices of grain receptacles or on foodstuff.
3. Larval Stage: Larvae spin tubes within the food material while feeding. Full-grown larvae are white with a pinkish tinge, measuring about 1.5 cm, and take around 40-50 days to mature (Ahmad et.al., 2021).
4. Pupal Stage: Larvae pupate inside cocoons, with the pupal stage lasting about 12 days.
5. Life Cycle: Completed in about two months, with 5-6 generations in a year (Deshwal et al.,2020).

Damage Symptoms

1. Feeding Habits: Larvae primarily feed on the germ portion of grains, leaving the rest of the kernel undamaged.
2. Infestation Patterns: In bulk infestations, damage is typically limited to the peripheral top layer of stored grains.
3. Web Formation: Larvae may create webs that cover bags, floor space, and milling machinery, leading to clogging issues in mills (Kumar, 2017).

7. Rice moth -*Corcyra cephalonica*

Distribution

Widely distributed in Asia, Africa, North America, and Europe. It is an important stored-grain pest in both India and Pakistan, particularly in rice-growing areas (Ahmad et.al., 2021).

Hosts

Primary Host: Rice and stored paddy. Other Hosts: Sorghum, wheat, maize, gram, groundnut, cotton-seed, milled products, cocoa beans, and raisins (Kumar, 2017).

Bionomics

1. Activity Period: Active from March to November, overwintering in the larval stage.

2. Egg Laying: Females lay eggs singly or in groups of 3-5 on grains, bags, and other objects in storage facilities. Each female can lay 62-150 eggs during its 24-day lifespan (Ahmad et.al., 2021).
3. Larval Stage: Larvae hatch from eggs in 4-7 days and feed under silken web-like shelters, preferring partially damaged grains. They reach full size in 21-41 days, then make silken cocoons among infested grains.
4. Pupal Stage: Lasts 9-14 days, and adults live for about one week.
5. Life Cycle: Completed in 33-52 days, with approximately six generations in a year (Deshwal et al., 2020).

Damage Symptoms

1. Feeding Habits: Larvae damage grains of rice and maize by feeding under silken webs. High infestations can convert entire grain stocks into a webbed mass.
2. Odor: Characteristic foul odor develops in heavily infested grains, rendering them unfit for human consumption (Kumar, 2017)

8. Khapra beetle- *Trogoderma granarium*

Distribution

The khapra beetle's origin in India and its spread to various regions, including Europe, Australia, North America, and other parts of the Indian subcontinent, highlights its adaptability. Its preference for extremely dry climates in regions like Punjab, Haryana, UP, and Rajasthan, with less prevalence in coastal areas, reflects its ecological niche (Bhargava & Kumawat, 2010).

Host

The Khapra beetle targets a wide range of dried materials, including grain and cereal products, wheat, barley, oats, rye, maize, rice, flour, malt, noodles and animal products like dead mice, dried blood, dried insects (Kumar, 2017).

Bionomics

1. Breeding: The insect breeds from April to October.
2. Egg Stage: Females lay white translucent eggs, usually singly or in clusters of 2-5, on grains. A female can lay 13-35 eggs in 1-7 days.
3. Egg Period: 3-10 days.
4. Larval Period: 20-40 days.
5. Pupal Period: 4-6 days.
6. Hibernation: Larvae hibernate from November to March in cracks and crevices.
7. Generations: Typically, there are 4-5 generations in a year.
8. Larva: Fresh larva is yellowish-white, about 4mm long, turning brown as it grows.
9. Adult: A small dark-brown beetle, 2-3 mm long, with a retractile head and clubbed antennae. The body is covered in fine hairs.
10. Flight: Adults are incapable of flying (Deshwal et al., 2020).

Damage Symptoms

1. Seasonality: The greatest damage occurs in summer, from July to October.
2. Feeding Habits: Larvae consume grain near the embryo or weak points, progressing inwards. They primarily target the upper 50 cm layer of grains in a heap or the periphery in a sack.
3. Extent of Damage: Infestation can lead to substantial loss, reducing the grain to mere frass.
4. Collection: Larvae can be collected by placing gunny bags on a grain heap due to their positive thigmotactic behavior (Kumar, 2017).

Secondary Pest of Stored Grains

1. **Saw-toothed grain beetle - *Oryzaephillis surinamensis***

Distribution

It is a common stored product pest found worldwide, particularly in temperate regions but can also survive in tropical and subtropical climates (Ahmad et.al., 2021).

Host

Saw-toothed beetles are commonly found infesting grains, including wheat, rice, oats, barley, corn, and other cereal grains (Kumar, 2017).

Bionomics

1. The saw-toothed grain beetle is characterized by its slender, dark, narrow, and flattened body shape.
2. Notably, it possesses a distinctive feature: a row of saw-like sharp teeth on each side of the prothorax, which gives it its name.
3. Its antenna is clubbed, and the elytra (hardened forewings) completely cover the abdomen, offering protection.
4. The female saw-toothed grain beetle lays approximately 300 whitish eggs, depositing them loosely in cracks or crevices of storage receptacles in places like warehouses or godowns.
5. The egg period ranges from 3 to 17 days, depending on environmental conditions.
6. After hatching, the larva emerges. It is slender, pale, and cream in color with slightly darker patches on each segment.
7. The larval period typically lasts from 14 to 20 days.
8. Following the larval stage, the beetle enters the pupal stage. It constructs a protective cocoon-like covering with sticky secretions (Ahmad et.al., 2021).
9. The pupal period varies from 7 to 21 days before the adult beetle emerges (Deshwal et al., 2020).

Damage Symptoms

1. Saw-toothed grain beetles primarily feed on grains, dried fruits, and other stored food products.

2. They cause damage by either scavenging the surface of grains or burrowing holes into them.
3. Common targets include rice, wheat, maize, cereal products, oil seeds, and dry fruits.
4. Their feeding activity can contaminate food products and reduce their quality, making them unfit for consumption and leading to economic losses for farmers, food processors, and distributors (Kumar, 2017).

2. Long-headed flour beetle - *Latheticus oryzae*

Distribution

It is a common pest found worldwide, particularly in regions where grains are stored. Originally native to Asia, it has spread globally due to trade and transportation (Ahmad et.al., 2021).

Host

These beetles infest stored grains such as rice, wheat, barley, oats, corn, and various processed foods. They can be found in homes, food storage facilities, warehouses, and even grocery stores. They are particularly prevalent in warm and humid environments, but they can survive in a wide range of climates (Kumar, 2017).

Bionomics

1. Physical Description: The beetle is light brown in color with an elongated body, measuring 2-3 mm in length. Its appearance resembles that of *Tribolium castaneum*, commonly known as the red flour beetle (Ahmad et.al., 2021).
2. Reproduction: Female beetles lay approximately 400 white eggs individually on grains and seams of bags where grains are stored. The incubation period for these egg ranges from 7 to 12 days.
3. Larval Stage: The larvae, which are small, white, and highly active, feed voraciously on the inner portions of grains. The larval period lasts from 15 to 80 days, during which they undergo significant growth and development.
4. Pupal Stage: After the larval stage, the beetle pupates for 5 to 10 days, undergoing metamorphosis within a cocoon-like structure before emerging as an adult beetle.
5. Under optimal conditions of 35°C and 70% relative humidity, the entire life cycle of the long-headed flour beetle can be completed in approximately 25 days *(Deshwal et al., 2020).*

Damage Symptoms

1. Both larvae and adult beetles feed on milled products, causing damage to stored grains and packaged food and occur as secondary pests in stored grains (Kumar, 2017).

3. Flat grain beetle -*Cryptolestus minutas*

Distribution

The flat grain beetle, *Cryptolestus minutas*, is found globally, particularly in regions where grains are stored. It can be encountered in homes, food storage facilities, warehouses, and agricultural settings (Bhargava& Kumawat, 2010).

Host

This beetle infests a variety of grains and grain products. Its hosts include rice, maize (corn), wheat, various flours, groundnuts (peanuts), and other stored grains susceptible to infestation (Ahmad et.al., 2021).

Bionomics

1. Physical Description: *Cryptolestus minutas* is the smallest among stored grain insect pests, measuring 1.5 mm to 2.0 mm. It ranges in color from light to dark reddish-brown.
2. Reproduction: The female beetle lays white eggs loosely in flour, grains, or crevices. The egg period lasts approximately 5 days.
3. Larval Stage: The larva of *Cryptolestus minutas* is cigar-like and yellowish-white, with two reddish-brown spots at the anal segment. The larval period extends for about 21 days.
4. Pupal Stage: After the larval stage, the beetle pupates within a gelatinous cocoon *(Ahmad et.al., 2021).*
5. Life Cycle: The complete life cycle of *Cryptolestus minutas* spans approximately 42 days under favorable conditions.

Damage Symptoms

1. Both larvae and adults feed on broken grains or milled products, causing damage to stored grains and processed foods.
2. Heavy infestations can lead to heating in grain and flour, which can result in spoilage and reduced quality.

4. Grain lice -*Liposcelis divinitorius*

Distribution

Grain lice are found worldwide, particularly in regions where grains are stored. They are commonly encountered in homes, food storage facilities, warehouses, and agricultural settings.

Host

Liposcelis divinatorius infests a wide range of starchy materials. Its hosts include various grains such as rice, wheat, maize (corn), barley, and oats, as well as processed grain products like flour and cereals.

Bionomics

1. Physical Description: Liposcelis divinatorius is pale grey or yellowish-white in color, small in size, resembling pinheads, with filiform (thread-like) antennae.
2. Reproduction: Females of Liposcelis divinatorius can lay approximately 7 to 60 eggs during their lifespan.
3. Metamorphosis: The metamorphosis of Liposcelis divinatorius is incomplete, meaning they undergo gradual development without distinct larval, pupal, and adult stages (Bhargava et. al., 2007).

Damage Symptoms

1. Grain lice primarily act as scavengers, affecting the germ portion of grains in heavy infestations. They feed on insect fragments, broken grains, and other organic matter present in stored grains.
2. They can thrive on a variety of starchy materials, including grains and processed grain products.
3. Damage symptoms caused by grain lice may include reduced grain quality, contamination of stored products, and economic losses due to spoilage.

Management of Stored Grain Pest

The management of stored grains refers to the various practices and techniques employed to ensure the safe storage, preservation, and quality maintenance of harvested grains over an extended period. It involves controlling environmental conditions, minimizing pest infestations, and preventing spoilage to maximize the economic value of the stored grains. Effective management of stored grains is essential for sustaining food security, minimizing post-harvest losses, and supporting agricultural livelihoods. It requires a combination of knowledge, resources, and ongoing monitoring and adaptation to mitigate risks and optimize storage outcomes.

With the vulnerability of stored grains to pest attacks and the reliance on chemical pesticides for control (Stejskal et.al., 2014), there's a pressing need to explore alternative and sustainable pest management strategies. While organophosphorus and pyrethroid insecticides, as well as fumigants like methyl bromide and phosphine (Yadav & Tiwari, 2018), have been effective in controlling pests, their continued use raises concerns about human health, environmental impact, and the development of pesticide resistance among pests. Key aspects of grain management include:

1. Traditional pest management approaches
2. Modern pest management approaches

Traditional Pest Management Approaches

Traditional pest management practices for stored grains involve a range of cultural, physical, and chemical methods that have been used for generations (Hajam & Kumar, 2022). These traditional pest management practices are often low-cost, accessible, and suitable for small-scale farmers (Manish et.al., 2011), but they require careful planning and implementation to be effective. Here are some key strategies:

1. Storage in Sealed Containers

Using containers that are sealed tightly helps prevent insect pests from accessing stored grains. Materials such as triple-layer plastic bags with airtight seals or containers treated to resist pests can effectively suffocate pests by depriving them of oxygen (Negi, & Solanki, 2016).

2. Sand/Ash

Mixing inert materials like sand or ash with stored grains acts as a physical barrier to insects and can suffocate them. Fine ash or powders can be particularly effective at preventing adult insects from laying eggs on grains (Negi & Solanki, 2016).

3. Harvesting Time

Harvesting grains at the right time, when they are fully matured and developed, can reduce the risk of pest infestations (Manish et.al., 2011). Delaying harvesting can deter adult insects from laying eggs on uncovered seeds, thus lowering infestation rates.

4. Alternate Hosts

Eliminating alternate host plants that pests can use when the primary crop is not available helps reduce pest populations. This can involve removing wild plants that serve as hosts for pests (Hajam & Kumar,2022).

5. Intercropping

Growing compatible crops together can help reduce pest infestations. For example, intercropping beans with maize has been shown to decrease infestations of bean pests in some regions (Yadav and Tiwari, 2018).

6. Cleanliness

Keeping storage areas and equipment clean helps prevent pest infestations (Manish et al., 2011). Proper cleaning of sheds, vehicles, and storage containers reduces the risk of introducing pests to stored grains.

7. Smoking

Using smoke from materials like cow dung (Ahmad et.al., 2021) can repel insects and reduce infestations without harming the grains. Smoke has been found to be effective in controlling pulse beetles and can be a low-cost alternative to chemical insecticides (Yadav and Tiwari, 2018).

8. Gaseous Effects

Manipulating the storage environment to alter gas concentrations, such as increasing carbon dioxide levels, can be lethal to insect pests (Yadav and Tiwari, 2018). High carbon dioxide levels can kill adult beetles and inhibit the development of pest larvae (Manish et.al., 2011).

9. Vegetable Oils

Coating grains with vegetable oils can deter pests by inhibiting egg laying and causing high mortality rates in larvae and adults. Crude and non-edible oils are often more effective and have ovicidal properties without affecting the quality of the grains (Hajam & Kumar,2022).

Modern Pest Management Approaches

1. Chemical control

Stored grain pest infestation can be effectively managed through various methods, with fumigation being one of the most commonly employed techniques. Fumigation exposes insect pests to toxic gases generated by applying grain fumigants, effectively eliminating them from buildings, warehouses, small bags, soil, seeds, and stored products (Upadhyay & Ahmad, 2011). These fumigants enter the insect's body through their spiracles and spread to their trachea and tracheoles, ultimately binding to components of their hemolymph.

Historically, synthetic fumigants have been widely used to eliminate stored grain insect pests. Pyrethrins (Rajendran, 2016), for instance, are utilized to control specific pests like *Corcyra cephalonica*, while natural and synthetic cyanohydrins have shown effectiveness against various stored product pests.

A range of fumigants, including ethylene dichloride, carbon tetrachloride, ethane dinitrile, and others (Rajendran, 2016), are employed to combat pests like termites, cockroaches, mites, and stored grain insects. Phosphine gas, generated by metal phosphide preparations, is commonly used to fumigate public storehouses and inhibit the development of eggs in stored product pests. Additionally, fumigation with HCN gas, produced by metal phosphide preparations (Rajendran, 2016), effectively controls stored insect pests.

2. Physical Control

Physical control methods such as temperature, heat, and pressure play crucial roles in managing stored grain pest infestations.

Temperature treatment is a highly effective physical method that can kill various life stages of insects in stored grains. Extreme temperatures, both high and low, can cause heavy mortality in stored product insects. Superheating grains to temperatures between 55-65°C for 10 to 12 hours (Upadhyay & Ahmad, 2011) can effectively eliminate all life stages of stored grain pests in warehouses. Similarly, maintaining low temperatures can provide long-term protection against insect infestation, as it reduces insect development and eventually leads to insect mortality. Insects become inactive and die below 12°C (Stejskal, 2014), making long-term storage feasible and economical. Temperature also influences the reproductive performance of stored grain pests. For example, *Tribolium castaneum* exhibits reduced fecundity (Stejskal, 2014), egg-to-adult survival, and adult progeny production at lower temperatures. Additionally, moderate temperatures, up to 25°C (Upadhyay & Ahmad,2011), can accelerate the rate of increase of stored product mite populations.

Low pressure represents a nonchemical alternative to fumigants like methyl bromide and phosphines for controlling pests such as bruchids (Hajam & Kumar, 2022). Eggs and young larvae are particularly susceptible to high temperatures, while adults of certain species, like the rusty grain beetle, respond faster to higher temperature gradients.

The movement and distribution of adult insects within grain provide valuable information for pest detection and simulation of their distribution in grain bins (Hajam & Kumar, 2022). Acoustic techniques are effective in detecting hidden infestations of stored-product insect larvae, especially when larvae are highly active. Heat treatment can increase larval activity, enhancing the speed and reliability of acoustic detection under adverse conditions.

3. Microbial Control

Microbial control offers an effective alternative to synthetic pesticides, utilizing microbial insecticides in the form of spores and toxins. This approach is safer and more specific, with highly targeted toxins that can effectively control stored grain pests. One of the most effective microbial strains is *Bacillus thuringiensis* (Rajendran, 2016), which produces toxins that are lethal to stored grain insects. Entomopathogens, such as various fungi and viruses, are commonly used for controlling stored grain pests. These organisms infect and kill pests, providing a natural and sustainable method of pest control. For example, mustard oil combined with fungi like *Paecilomyces formosoroseus* or *Nomuraea rileyi* has been shown to reduce oviposition and adult emergence in *Bruchidius incarnatus*. Similarly, fungal species like *Beauveri abassiana, and Lecanicillium lecanii*, (Rajendran, 2016) are used to control the Indian meal moth.

4. Biological Control

Biological control methods employ various living organisms or their products to suppress populations of stored grain insects. These strategies have become widely accepted as effective means of managing stored grain pests. Several types of biological agents, including parasitoids, predators, and pathogens, are utilized in natural conditions to control insect populations.

Hymenopterans are commonly employed to reduce infestations and damage caused by stored grain insects. Parasitoids like *Bracon hebetor* and *Venturia canescens* are used to suppress populations of pests like *Ephestia cautella.* Additionally, predators such as hemipteran bugs, like *Xylocoris flavipes*, (Rajendran, 2016) and anthocorid bugs are frequently used to control stored grain pests in warehouses. These predators prey on various stages of insects and can significantly reduce populations, particularly of Coleoptera and Lepidoptera insects. Parasitoids play a crucial role in biological control by relying on other parasites to maintain low population levels of stored grain insects.

For controlling specific pests like the Indian meal moth, egg and larval parasitoids such as *Trichogramma deion* and *Habrobracon hebetor* are employed. Similarly, parasitoids like *Apanteles flavipes* (Rajendran, 2016) are used to control pests like the bean weevil. These parasitoids complete their life cycles inside the bodies of their hosts, effectively suppressing pest populations.

5. Cultural Control

Ensuring the cleanliness and proper maintenance of food grain storage facilities is crucial for preserving the quality and safety of the stored grains. Regular cleaning is essential to remove dirt, eggshells, dead larvae, and any other debris from the storage area. Broken and infested grains should be promptly removed and destroyed by burning before new grains are stored to prevent the spread of pests. All cracks and crevices in the walls and ceiling of the storage facility should be sealed with cement to prevent pests from entering or escaping. Proper labelling ensures these areas are identified for maintenance. The storage area should be whitewashed or painted with repellent paint to further deter pests. Coal tar can be used for painting purposes. Superheating the godowns with burning charcoal can effectively disinfect the area by raising the temperature to about 150°F (Upadhyay & Ahmad,2011). This process helps kill pests and their eggs. During this treatment, doors should be tightly closed for 48 hours, after which the godowns should be allowed to cool and cleaned before storage. Sulfur can be burned on charcoal to fumigate the godowns, releasing sulfur dioxide gas, which acts as a fumigant. Before supplying food grains, disinfestation measures should be carried out to ensure the grains are free from pests. Proper storage methods should be adopted in warehouses, including dusting the walls, floors, and ceiling with insecticidal specks of dust like BHC or DDT to disinfect the storage space. Commercial smoke generators can also be used for disinfection if the area can be made reasonably airtight (Upadhyay & Ahmad,2011).

6. Behavioral Control by Using Pheromones

Behavioral control using insect pheromones is a promising strategy for managing stored grain pests. Pheromones, which are chemical signals emitted by insects to communicate with each other, can be used in various ways to disrupt mating, monitor populations, and trap insects (Ahmad et.al., 2021). Disruption of mating with pheromones can lead to suppression of insect populations. For example, pheromones of insects like *Trogoderma* and the black carpet beetle (Hajam & Kumar, 2022) are used in bait traps to capture large numbers of these pests. Synthetic pheromones have also been developed for monitoring populations of stored grain insects, including species like Tribolium and Sitophilus (Upadhyay & Ahmad,2011).

Pheromones are also used in combination with entomopathogens, such as *Bacillus thuringiensis*, (Upadhyay & Ahmad,2011) for more effective pest control. Pheromone-baited traps containing insect pathogens can distribute the pathogen among stored-product insects, leading to increased mortality. This method is particularly promising for long-term control of insect pests, as it can suppress subsequent generations of pests through spore transfer and pathogen transmission.

Conclusion

The study highlights the practices of hill farmers who rely on traditional knowledge to construct eco-friendly grain storage structures. These farmers utilize indigenous methods for pest management, incorporating Integrated Pest Management (IMP) techniques. Effective control measures can significantly reduce the degree of infestation. Understanding the life cycle of pests, monitoring their activity, and assessing the damage they cause is crucial for better pest management in stored grains. External feeders, pests that consume grain from the outside, are easily noticeable. However, internal feeders, which damage grains from within, may not be apparent until significant damage has occurred. To prevent further infestation, heavily infested grain should not be stored in the godowns (storage facility). If infested material does enter the godowns, it should be kept separate until it can be fumigated. These practices aim to preserve grain quality and minimize losses due to pests.

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ADVANCES IN ENVIRONMENTAL TOXICOLOGY: EXPLORING EMERGING CHALLENGES AND SOLUTIONS

Jyoti Sharma[1], Vishal B. Jare[2], Pooja Sao[3] and Dhale D.A.[4]

[1]Department of Zoology, Sant Gahira Guru Rameshwar Collège, Lailunga, Raigarh, Chhattisgarh
[2]Department of Biochemistry, Ahmednagar College, Ahmednagar, Maharashtra
[3]Department of Zoology, Govt. Arts, Science and Commerce College Dharamjaigarh, Raigarh, Chhattisgarh
[4]Post - Graduate Department of Botany, SSVP Santha's L. K. Dr. P. R. Ghogrey Science College, Dhule, MS
Corresponding E-mail: drdattadhale@gmail.com

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Abstract

Environmental toxicology is a multidisciplinary field that investigates the adverse effects of various contaminants on living organisms and ecosystems. This review aims to provide a comprehensive overview of recent advancements and key findings in environmental toxicology research. The primary focus is on assessing the impacts of pollutants such as heavy metals, pesticides, industrial chemicals, and emerging contaminants on environmental health and biodiversity. Key themes explored in this review include the mechanisms of toxicity, bioaccumulation, biomonitoring techniques, and risk assessment methodologies. The review discusses how these pollutants enter the environment, their pathways of exposure, and the subsequent biological responses at the molecular, cellular, organismal, and population levels. Additionally, the review highlights the importance of understanding the interactions between pollutants and environmental factors such as temperature, pH, and salinity in modulating toxicity outcomes. Furthermore, the review examines the role of advanced analytical techniques, such as omics technologies and computational modeling, in elucidating the complex interactions between contaminants and biological systems. It also addresses the challenges associated with extrapolating laboratory-based findings to real-world scenarios and proposes strategies for improving the ecological relevance of toxicological studies. Overall, this review synthesizes recent research findings to provide insights into the current state of environmental toxicology, identifies knowledge gaps, and suggests future research directions to mitigate the adverse effects of environmental contaminants on human health and ecosystems.

Keywords: Environmental toxicology, Pollutants, Mechanisms of toxicity, Biomonitoring, Risk assessment, Ecological relevance.

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Introduction to Environmental Toxicology

Environmental toxicology plays a critical role in protecting the health of the planet and its people by investigating the adverse effects of various chemicals, biological agents, and physical substances on living systems and ecosystems. Environmental toxicology thrives as an interdisciplinary discipline, drawing on a broad range of disciplines such as chemistry and biology, ecology and even physics, to address complex environmental issues. This network of understanding allows environmental toxicologists to explore the complex interactions between contaminants and living systems, uncovering the multi-layered chance of damage across biological systems. At its core environmental toxicology is concerned with understanding the interactions of pollutants with the environment i.e. pollutant, organisms, and humans. It examines the pathways by which contaminants enter an ecosystem, the fate and transport of contaminants within an environment compartment, and their impact on vegetation as a whole. One of the key differences between environmental toxicology and other fields of science is its multidisciplinary approach. Environmental toxicologists draw on a wide range of disciplines, including ecology and toxicology, as well as chemistry, biology and epidemiology, as well as risk assessment. A multidisciplinary approach allows researchers to address complex environmental challenges in a holistic manner. It allows them to bring together insights from different fields and consider how interconnected environmental systems are. By bringing together expertise from different fields of science, environmental toxicology can gain a better understanding of the behavior of pollutants and their impact on ecosystems and human health. Environmental toxicology plays a critical role in environmental policy, regulation and management strategies. Environmental toxicologists provide scientific evidence on the hazards associated with various pollutants, thereby helping to create effective policies to protect environmental quality and human health. In addition, their research findings inform decision-making on pollution control and remediation efforts, as well as sustainable resource management practices. [1] [2] Environmental toxicology plays a vital role in the investigation and understanding of the harmful effects of contaminants on organisms and ecosystems, as well as on human health. Environmental toxicologists conduct rigorous research and analysis to understand the complex interactions between pollutants and the environment. By understanding the potential risks of human activities on the environment, environmental toxicologists provide valuable information that informs decision-making and policy development to protect ecosystems and human health. Environmental toxicology is essential in determining the sources, pathways and mechanisms by which contaminants cause harm to organisms and ecosystems. This information is needed to evaluate the extent of environmental pollution and the impact it has on ecological integrity. Experimental studies, field surveys and modeling approaches are used by environmental toxicologists to measure the concentration of pollutants in different environmental compartments and to evaluate their toxicity to various organisms. By characterizing their toxicological profiles, researchers can evaluate the potential risks of contaminants on individual organisms, populations and entire ecosystems. Environmental toxicology is the study of the effects of pollutants on the functioning of ecosystems and biodiversity over a long period of time. Environmental toxicologists study the effects of contaminants on a wide range of ecological processes, including nutrient cycling and energy flow, as well as species interactions. This knowledge is important as it allows for the prediction and mitigation of the downstream effects of environmental pollution on the resilience and stability of ecosystems.[1] [3]

Impacts of Pollutants on Environmental Health and Biodiversity

Environmental toxicology is concerned about the effects of heavy metals on the health and biodiversity of the environment. Heavy metals are persistent pollutants that accumulate in ecosystems and pose serious threats to organisms and environmental processes. Heavy metals include lead, mercury and cadmium, as well as arsenic and chromium. Heavy metals are released into the environment through a variety of anthropogenic sources, including mining, industrial discharges, agricultural runoff, and natural sources such as weathering of rock and volcanic activity. The toxic effects of heavy metals affect organisms at several levels of biological structure. At the cellular level, heavy metals bind to proteins and enzymes that interfere with important biochemical processes. This results in cell dysfunction and oxidative stress, resulting in DNA damage and protein denaturation. Lipid peroxidation also results in cell death and impaired tissue integrity. At the organism level, heavy metals can lead to developmental and reproductive defects, immune disorders, and neurological disorders. Heavy metals can affect both land and aquatic organisms and can affect species diversity and population dynamics, as well as community structure. Ecosystem health and biodiversity are at risk due to heavy metal pollution. Heavy metals disrupt ecological processes and disrupt ecosystem services, such as nutrient cycling, soil microbial communities and plant growth. As a result, ecosystems become less productive and resilient. In aquatic systems, heavy metals build-up in sediments. Heavy metals can also build-up in food chains, leading to increased risks for fish, birds and mammals. Heavy metal pollution affects ecosystems beyond individual organisms. It can cause habitat degradation, biodiversity loss and ecosystem dysfunction. [4] [5] [6]

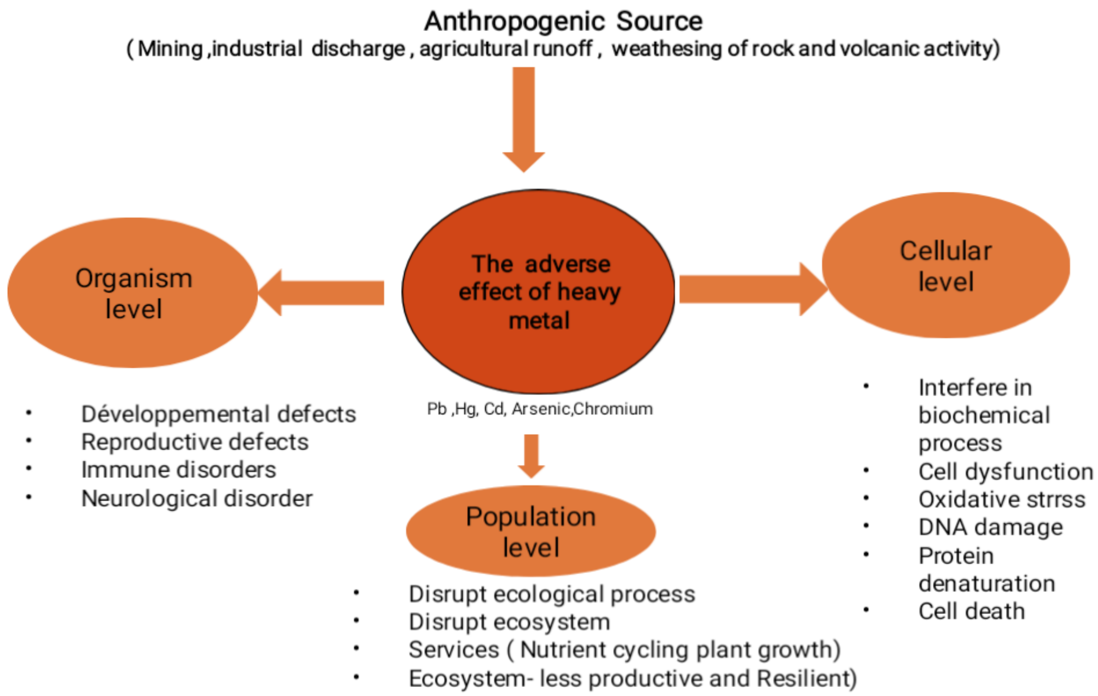

Fig.1: Effects of heavy metals pollution on cellular, organism & population level.

Pesticides are a class of pollutants that have a significant impact on human health and biodiversity. Pesticides are chemical compounds that are used to control pests and improve agricultural productivity. However, they can unintentionally cause harm to non-target organisms (NTOs) and ecosystems. Pesticides are released into the environment through a variety of sources, including agricultural runoff and spray drift. They also leach into soil and water, where they remain and build up over time. Pesticides have a wide range of biological effects on the environment and biodiversity. They can affect organisms at trophic level and at the molecular level. Pesticides can interfere with the functioning of neurotransmitters, enzymes, and hormones in organisms. Organophosphate (PPA) and carbamate (PFOA) pesticides inhibit the activity of acetylcholine synthases, which can lead to neurotoxicity in insect, bird, and mammalian species. Other pesticides can cause oxidative stress and genotoxicity in organisms exposed to pesticides, as well as immune suppression, which can harm the organism's general health and fitness. Pesticides can cause direct mortality and sublethal effects, as well as indirect ecological consequences. In acute exposure to high pesticide levels, non-target organisms such as beneficial insects, birds and aquatic species can be subject to mass mortality events. In chronic exposure to sublethal pesticides, reproductive success is impaired, behavior is altered and ecosystem functioning is impaired. Pesticides can also play a cascading role in food webs and in the dynamics of ecosystems by decreasing prey availability, changing predator-prey relationships, and disrupting the trophic cascade.[7] [8] [9]

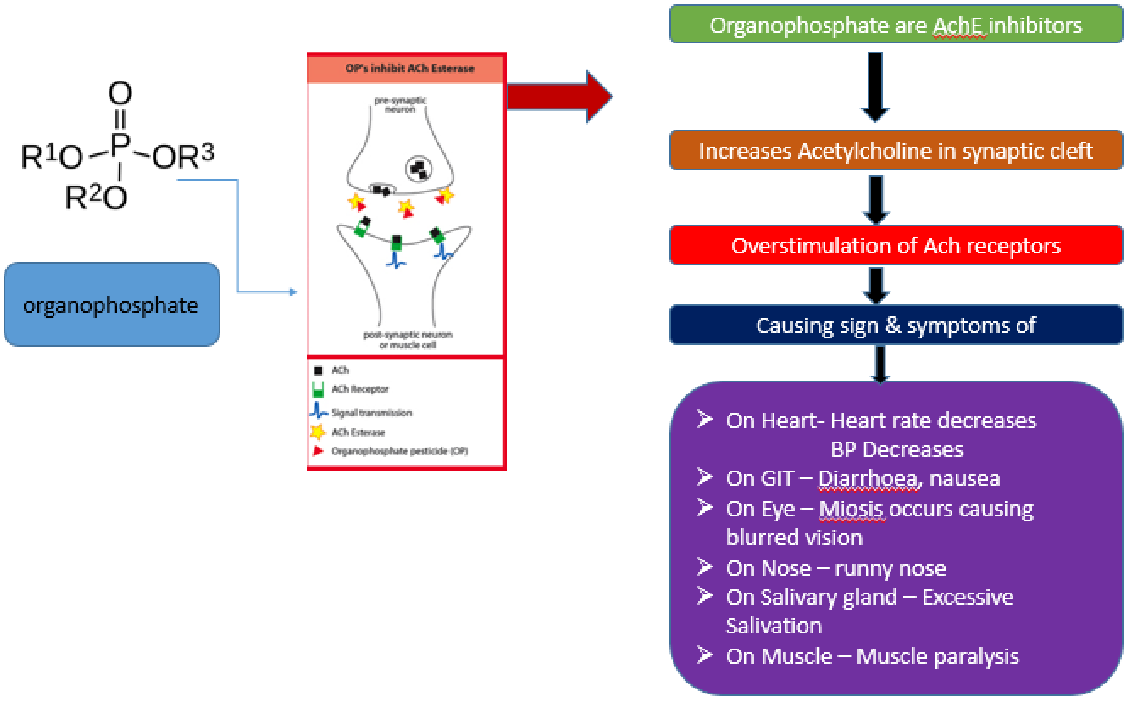

Fig.2: Effect of pesticide application in agriculture, contrasting with the negative impacts on non-target organisms.

Industrial chemicals are a broad category of pollutants that have a significant impact on human health and biodiversity. Industrial chemicals are used in a variety of industrial processes, such as manufacturing, mining and energy production. Industrial chemicals can be released into the environment through a variety of sources, including emissions into air and water, accidental releases, and improper disposal. Industrial chemicals include heavy metals, organo solvents, POPs, and VOCs, each with its own toxicological profile and environmental fate. Industrial chemicals have a wide range of effects on environment health and biodiversity, both at the cellular and molecular levels. PCBs, dioxins and other industrial chemicals are well-known for their long-lived and bioaccumulating nature, as well as their toxicity to organisms. Industrial chemicals have been linked to endocrine disrupters, reproductive failure, and developmental abnormalities in organisms exposed to them. Other industrial chemicals such as benzene and toluene have been linked to inhalation exposure to human and wildlife, which can lead to respiratory diseases, neurotoxicity and carcinogenicity. Industrial chemicals can contaminate soil, water, sediments, and disrupt the structure and function of ecosystems. Heavy metals released from industrial processes can accumulate in aquatic systems, where they can be harmful to fish, aquatic invertebrates and aquatic plants, resulting in a decrease in population and species abundance. Organic pollutants can persist in soils and sediments, changing microbial communities, reducing plant growth, and affecting terrestrial ecosystems productivity. [10] [11]

Contaminants are a broad and ever-changing group of pollutants that threaten the health of the environment and biodiversity. Contaminants range from pharmaceuticals and personal care products to industrial chemicals and microplastics. Many of these contaminants have only recently been identified as a threat to the environment. Contaminants enter the environment through a variety of sources, including wastewater discharges, agricultural runoff, and atmospheric deposition, as well as through improper disposal practices. The persistence of contaminants in ecosystems, their bioaccumulation potential, and their unknown ecological effects are just some of the reasons why contaminants are causing concern. The effects of new contaminants on the health and biodiversity of the environment are complex and multi-faceted. This is due to the variety of pollutants and how they interact with different environments and organisms. Pharmaceuticals or personal care products are designed to have specific biological effects on humans. However, their use and incomplete elimination during wastewater treatment process can result in them accumulating in aquatic environments where they can interfere with endocrine functions, change behavior, and reduce the reproductive success of aquatic organisms. Another emerging contaminant is microplastics. Microplastics are found in almost every marine and freshwater ecosystem and pose a threat to human health and biodiversity. The synthetic polymer particles that microplastics are made of are ingested by a variety of organisms, ranging from small fish and crustaceans to marine mammals. Microplastics can cause physical damage, intestinal blockage, and the accumulation of toxic chemicals related to plastic debris. In addition, they can be vectors for the transportation of other contaminants such as POPs and heavy metals. [12] [13] [14]

Mechanisms of Toxicity and Bioaccumulation

Toxicity mechanisms are a complex interaction between pollutants and bio-systems at various organizational levels. Pollutants can induce toxicity at the molecular level by disrupting essential biochemical processes such as enzyme functioning and DNA replication. This can lead to oxidative stress and genotoxicity. It can also disrupt cell homeostasis by activating detoxification pathways. Depending on the contaminant and its nature, cellular responses may include inflammatory responses, apoptosis, or necrosis. Depending on the organism, the organ system's responses to a pollutant can range from physiological impairments to developmental abnormalities to reproductive dysfunction to compromised immune function. The cumulative effects of pollutants at the population level can lead to population decline, community structure changes, and biodiversity loss, resulting in cascading ecosystem functions and resilience. These mechanisms are essential for anticipating the ecological consequences of contaminants and for developing effective risk assessments and management strategies. [6] [15]

Molecular Responses

Molecular reactions to toxicants are an important part of understanding how toxicants interact with each other and how they accumulate in the body. When an organism is exposed to a pollutant, it sets in motion a series of molecules designed to protect against or reduce the effects of the pollutant. One of the most common molecular responses is to activate the detoxification pathway, which involves the metabolism and biotransformation of the pollutant into a less toxic or less excretable form. In addition, organisms may also upregulate their antioxidant defenses to counter oxidative stress caused by the reactive oxygen species produced by the pollutant. For example, the formation of antioxidant enzymes and protect cells from oxidative damage is a common molecular response to toxicants. Stress-responsive genes are often activated, as well as stress-regulated signaling pathways (MAPK, Nrf2, etc.), which control cell stress responses and support cell survival. All of these molecular mechanisms play a critical role in regulating the cell fate of a toxicant, whether it undergoes repair, undergoes apoptosis or adapts to chronic exposure. Different species and populations have different molecular responses to different toxicants. This is due to differences in susceptibility, as well as in adaptive capacity. Some organisms may have genetic polymorphisms i.e. allelic variants that make them more resistant or sensitive to a particular pollutant. Other factors such as exposure history and environmental conditions, as well as life stage, can also affect molecular responses to a toxicant. For example, developmental stages that are characterized by rapidly dividing and dividing cells may be more sensitive to the mutagenic effects of a toxicant. On the other hand, chronic exposure to a low level of a pollutant may cause molecular damage that accumulates over time, leading to long-term health effects. Interactions between pollutants and environmental stressors that are temperature, pH levels and dissolved oxygen levels can also modify molecular responses and worsen or improve the effects of the toxicant on organisms. Therefore, a well-understood molecular response to a toxicant requires consideration of several factors, including genetics, physiological factors, and environmental factors. [16] [17] [18] [19] [20] [21]

Cellular Responses

Toxicant responses play an important role in determining exposure and toxicity. When exposed to pollutants, cells respond in a variety of ways to maintain cell homeostasis and repair damage and eliminate harmful substances. For example, one of the most common cellular responses to a toxicant is heat shock. Another is the induced stress-responsive pathway. These pathways help cells manage the stress caused by a misfolded protein or protein aggregate that has been exposed to a toxicant. They help to fold, degrade, and repair proteins to minimize cellular damage and promote cell survival. When DNA is damaged by a genotoxic pollutant, DNA repair mechanisms may be activated to repair the DNA damage. This helps to maintain genomic integrity and prevents the accumulation of tumour-causing mutations that could cause cell death or carcinogenesis. Apoptosis, also known as programmed cell death (PCD), is the process of programmed cell death. Apoptosis involves the controlled dismantling of cells by the body’s immune system. Apoptosis occurs when cells are killed by the immune system and the immune system rejects the damaged cells. Necrosis is a type of uncontrolled cell death that results in cell swelling and membrane rupture. Necrosis usually occurs in response to acute or chronic toxicity and can cause inflammatory reactions and tissue damage. These cellular responses to toxins are highly regulated processes that control the fate of the exposed cells and affect the overall toxicity of the pollutants to organisms. Cellular responses to toxicants show complex cross talks with other biological processes. For example, inflammation, oxidative stress and immune regulation all modulate the fate of the cells exposed to the pollutants and contribute to their overall toxicity. For example, exposure to Pro-inflammatory cytokines produced as a by-product of cellular stress can aggravate cellular damage and promote necrotic or apoptotic cell death pathways. Activation of antioxidant defenses and antiretroviral pathways can also mitigate cellular damage and improve cell survival when exposed to toxicants. Cell responses to toxicants vary depending on the cell type, tissue type and organismal context. This highlights the importance of cellular heterogeneousness as well as intercellular communication for assessing the toxicity of pollutants. [22] [23] [24] [25] [26] [27]

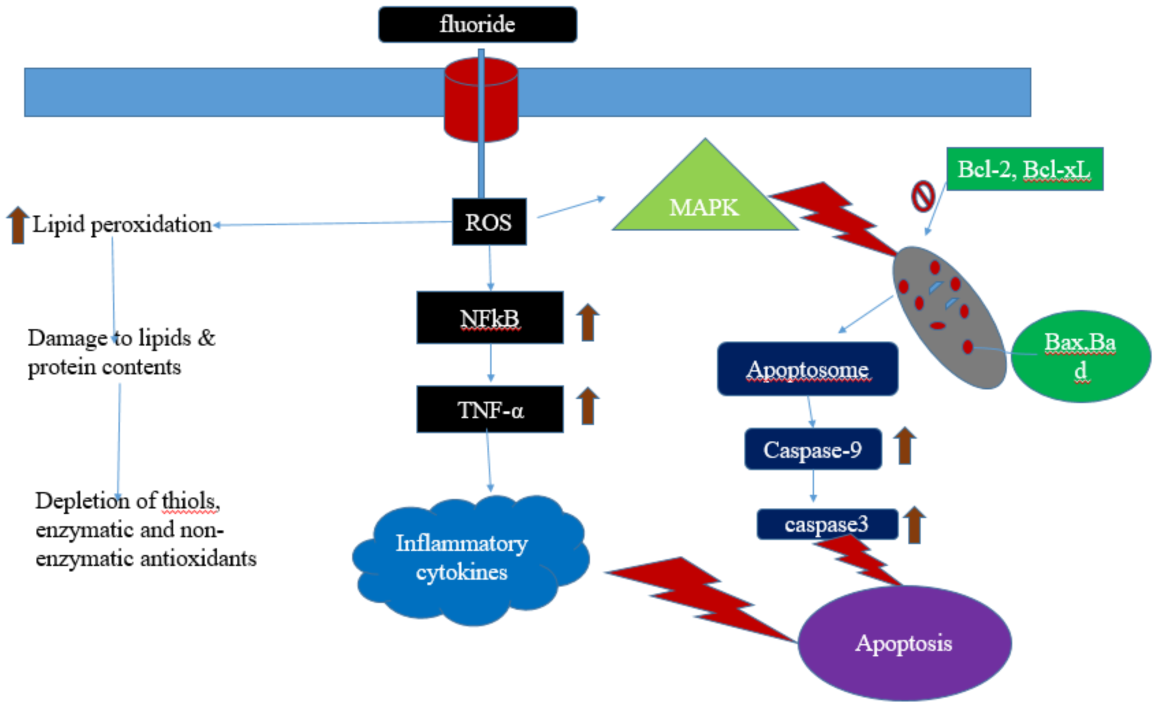

Fig. 3: Diagram illustrating the molecular mechanism of toxicity

Organismal reactions to toxicants include a variety of physiological, behavioral and morphological alterations that take place at the organism level after exposure to pollutants. These alterations play a critical role in the organism's survival and adaptation to its environment in response to chemical stressors. For example, physiological responses may include changes in metabolism rate, energy utilization and hormonal regulation to meet the metabolic demands of toxicant exposure. Behavioral responses such as changes in feed behavior, locomotion and reproductive activities may be adaptive strategies to reduce exposure to pollutants or reduce their adverse effects. Organisms may also exhibit morphological changes, such as body size, morphology or coloration, to respond to selective pressures from toxicants or to increase their ability to withstand environmental stressors. All of these responses reflect a complex interplay between environment factors, genetic predisposition and physiological processes, emphasizing the importance of a holistic organismal perspective to understand the mechanisms of toxicity/bioaccumulation. [28] [29]

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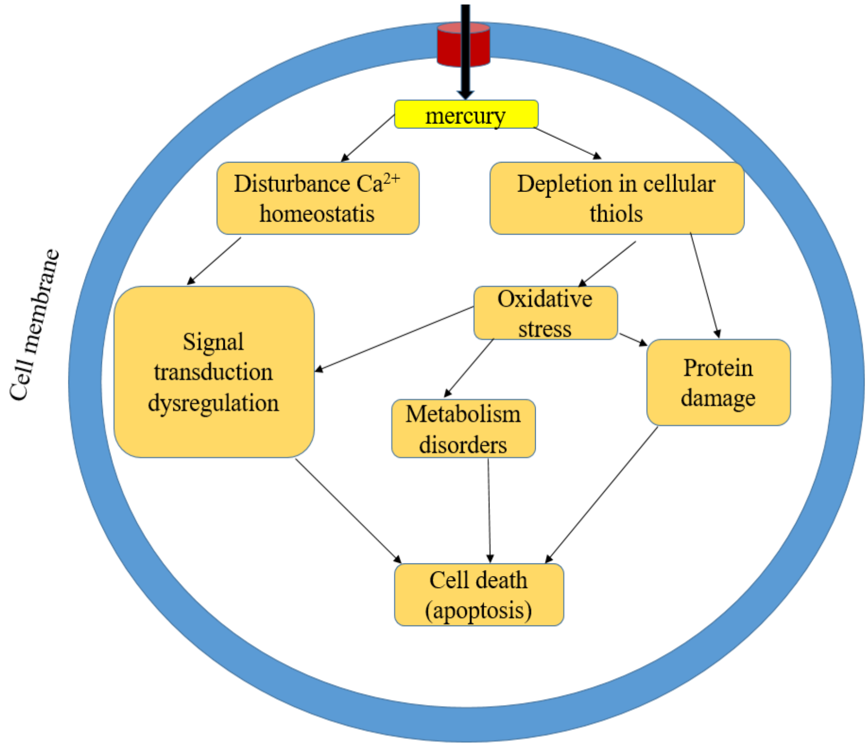

Fig. 4: Diagram illustrating the cellular mechanism of toxicity.

A population-level effect is a change in the size, structure and dynamics of a population, reflecting the cumulative response of individuals within the population to a chemical stressor. One of the most common population-level effects of exposure to a pollutant is a decrease in population abundance. This can be due to increased mortality, decreased reproductive success, or decreased recruitment into the population. A pollutant can also change the age structure of a population by selectively impacting certain age classes (e.g. young or adults), resulting in changes in population size and age distribution. A toxicant can also affect population dynamics (e.g. birth rate, death rate, migration patterns) by disrupting essential life processes like growth, development and reproduction. All of these effects can have a cascading effect on the structure and function of the ecosystem, changing trophic interactions and community composition, as well as changing the biodiversity of the ecosystem. A population-level response to a pollutant provides valuable insights into the environmental consequences of the pollutant and serves as a key indicator of the health and resilience of the ecosystem. Understanding the mechanisms that underlie population-level responses to toxicants is important for predicting the long-term ecological consequences of the pollution and for developing conservation and management strategies. [30] [31] [32]

Assessment Techniques and Methodologies

Biomonitoring plays an essential role in evaluating environmental toxicity by detecting and quantifying the presence and impact of pollutants on living organisms. These methods use biological indicators of organisms or their tissues to track the bioavailability of contaminants and their bioaccumulation in the environment. Biomonitoring can take place at different levels of biological organization from single organisms to entire ecosystems and can provide valuable insights into the spatial and time-scale distribution of pollutants and their potential effects on ecological health. Common biomonitoring methods include the selection of sentinel species (organisms selected based on their susceptibility to particular pollutants or their ecological importance within an ecosystem). Sentinel species can act as early warning systems for environmental contamination and can be used to identify pollution hotspots and areas of concern. Biological analysis may include analysis of biomarkers i.e. enzyme activity, gene expression patterns or physiological responses, which can provide insight into mechanisms of toxicity and overall health status of exposed organisms. A biomonitoring approach is often combined with other environmental monitoring methods e.g. water or sediment analysis, chemical analysis, etc. to provide a full picture of environmental quality and pollutant levels. [33] [34] [35]

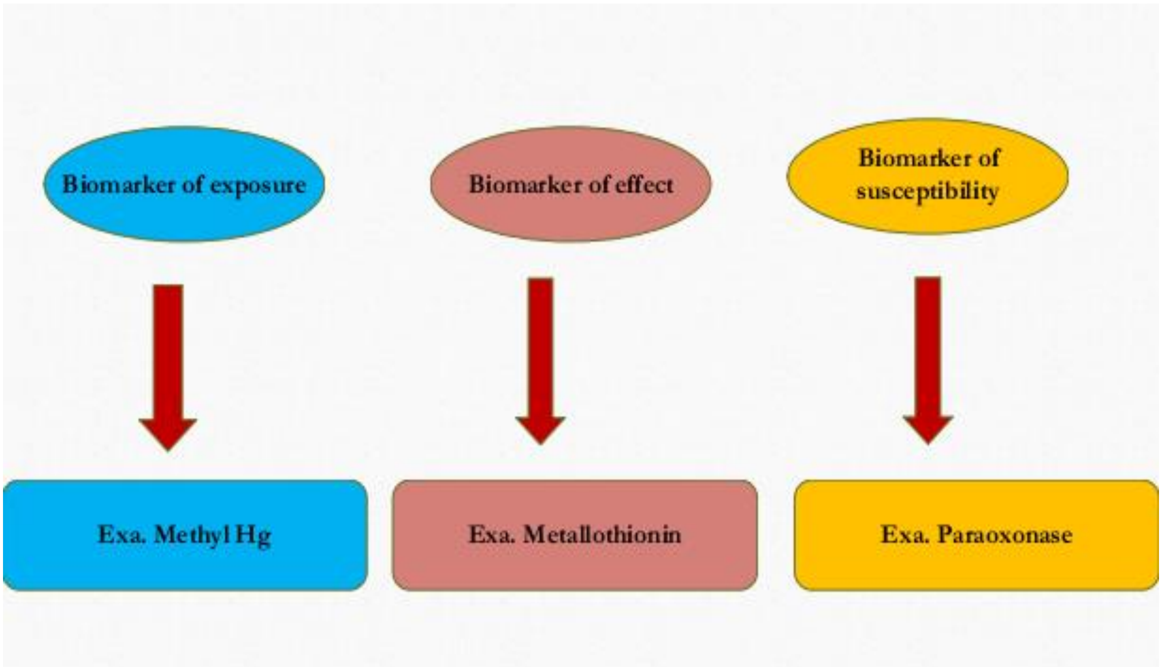

Fig. 5: Visual representation of 3 biomarkers used in environmental toxicology research.

Risk assessment methodology is the systematic analysis of hazards caused by pollutants, the assessment of exposure pathways and concentrations, and the quantification of the probability and magnitude of the associated risks.

Risk assessment typically includes several steps: Hazard identification is the identification of the type of adverse effects pollutants can cause in exposed organisms based on toxicologic studies and empirical data. Exposure assessment is the estimation of the extent and time of exposure to a pollutant. It takes into account emission sources and environmental fate, as well as human (or ecological) receptor characteristics. Dose response assessment is the measurement of the relationship between a pollutant's exposure level and the likelihood (or severity) of adverse effects. This is often done by dose-response modelling or by extrapolating data from experimental studies. Risk characterization is the integration of hazard identification (HID), exposure assessment (EX), and dose response assessment (DRE) to estimate the total risk posed by a pollutant. Risk assessment methodologies can range from qualitative to quantitative models depending on how complex the system is and what data is available. Deterministic and probabilistic risk assessments, Scenario-based risk assessments, Cumulative risk assessments, Multiple pathways, Exposure pathways, Ecosystem services, Socio-economic factors, Risk assessment frameworks. Risk assessment methodology provides valuable information on the potential effects of environmental toxicity on human health and the environment. This information is used to inform regulatory decisions and management strategies as well as public health interventions to mitigate risks and protect both the environment and human health. [36] [37] [38] [39] [40]

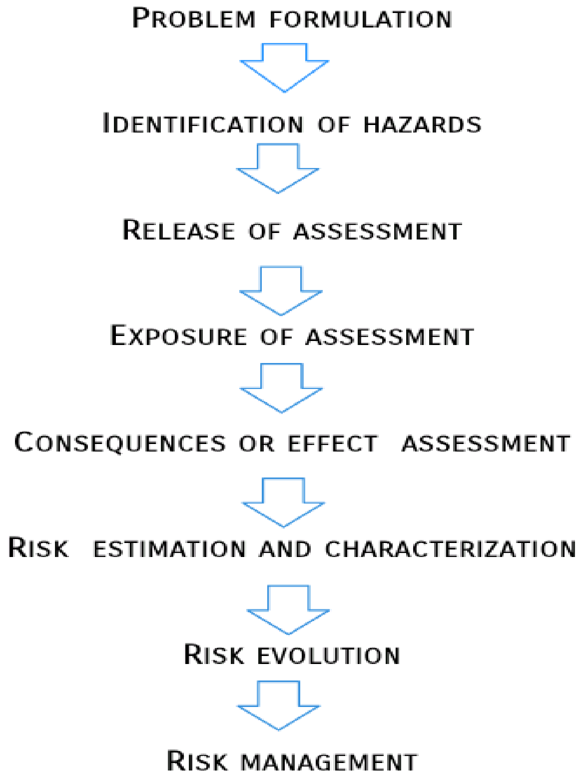

Fig. 6: Illustrations explaining the steps of risk assessment methodology

Influence of Environmental Factors

The most affecting environmental factors are Temperature, pH and salinity these factors influence the environmental toxicity by changing the metabolic reactions, absorption of ions etc. and effect on the osmoregulation respectively.

Temperature: Temperature plays a major role in the toxicity of a pollutant in an aquatic or terrestrial ecosystem. Temperature affects chemical reactions, metabolism rates, and bioavailability of a pollutant. In general, higher temperatures speed up chemical reactions and metabolism, resulting in increased toxicity of pollutants. For instance, higher temperatures increase bioavailability and bioavailability of heavy metals, making them more soluble and easier to absorb by organisms. Temperature also affects the susceptibility of organisms to a pollutant. Many species are more sensitive to pollution at high temperatures due to higher metabolic demands and increased physiological stress. On the other hand, cold temperatures slow down metabolism and reduce toxicity, although some cold adapted species may be more sensitive to certain contaminants. pH : pH plays an important role in the speciation and solubility of pollutants in an aquatic and soil environment. As pH changes, so does the chemical form of the pollutant. For instance, changes in pH can cause a pollutant to dissociate metals from complexes or ligands, resulting in changes in bioavailability and toxicological effects for aquatic organisms. In addition, pH changes can also affect the absorption of nutrients and key ions, making organisms less likely to be exposed to pollutants. Salinity : Salinity refers to the amount of dissolved salt in water. Salinity plays an important role in the health of aquatic ecosystems and can affect the toxic effects of pollutants on aquatic organisms. High levels of salinity can increase the bioavailability and bioavailability of pollutants by aquatic organisms. For instance, metals like copper and zinc become more toxic for aquatic organisms in saltwater environments due to increased metal ion activity that interferes with ion regulation systems. Salinity changes can also affect aquatic organisms osmoregulatory, ion balance and metabolic processes, which can affect their tolerance to pollutants. [41] [42] [43] [44]

Advanced Analytical Techniques in Toxicology Research

Omics technologies, particularly genomics technologies, have advanced toxicological research by providing a comprehensive understanding of the molecular mechanisms that underlie toxicological responses to environmental pollutants. Omics technologies include a wide range of highly-accurate analytical approaches, such as genomics and transcriptomics, as well as those for metabolomics, metabolism, and epizootiology. Together, these analytical approaches allow for the systematic elucidation of biological molecules, and their interactions in biological systems. Genomics techniques, including next-gen sequencing, allow for the identification of polymorphic genetic variations and polymorphic gene expression profiles related to pollutant exposure. This allows researchers to gain a better understanding of the genetic basis for susceptibility to environmental toxins. Transcriptomics studies provide important information on the alteration of gene expression patterns associated with toxicant exposure. These studies reveal key molecular pathways as well as signaling networks that are involved in the cell's response to contaminants. Proteomics approaches provide insights into the alteration of protein expression as well as the metabolic pathways that are induced by the toxicants. This provides a deeper understanding into the biochemical mechanisms that underlie toxicity. Along with epigenomics techniques look at DNA methylation changes, histone changes, and noncoding RNA expression patterns related to environmental exposures to determine how environmental pollutants regulate gene expression. Integrating omics data with bioinformatic and systems biology techniques allows researchers to build robust molecular networks and predict toxicity models. This allows for the discovery of biomarkers for exposure, effect and susceptibility, and the development of personalized therapeutic interventions and prevention strategies to reduce the negative impacts of environmental pollutants. [45] [46] [47]

One of the most important applications of computational modeling is in toxicology. Computational modeling is a powerful tool for predicting, simulating, and interpreting complex biological systems and toxicological events. It leverages mathematical algorithms and statistical methods, as well as computer simulations, to integrate disparate data sources, understand underlying mechanisms, predict environmental pollutants effects on biological systems, and more. One of the most common uses of computational modeling for toxicology is in QSAR modeling. Quantitative structure-activity relationships are models that link a pollutant's chemical structure to its bioavailability or toxicity. These models can be used to quickly screen large chemical libraries, prioritizing compounds for further analysis based on their hazard or risk profiles. Another common use of computational modeling is for the simulation of ADME (Absorption, Distribution, Metabolism, and Excretion) of chemical substances in the body. This model allows researchers to predict the internal dose and tissue concentration of pollutants after exposure and to evaluate their potential health consequences. Systems biology approaches combine computational modeling with observational data to create mechanistic toxicological models that capture the interactions of genes, proteins and metabolites under environmental stressor conditions. These models allow for the simulation of cell and molecular pathways that play a role in toxicant induced toxicity, providing insight into the underlying mechanisms and potential target areas for intervention. Computational modeling provides a cost-efficient, high-performance, and ethical alternative to conventional experimental toxicology approaches, allowing for prioritization of chemical candidates for testing, design of focused experiments, and interpretation of large datasets. [48] [49] [50] [51] [52] [53]

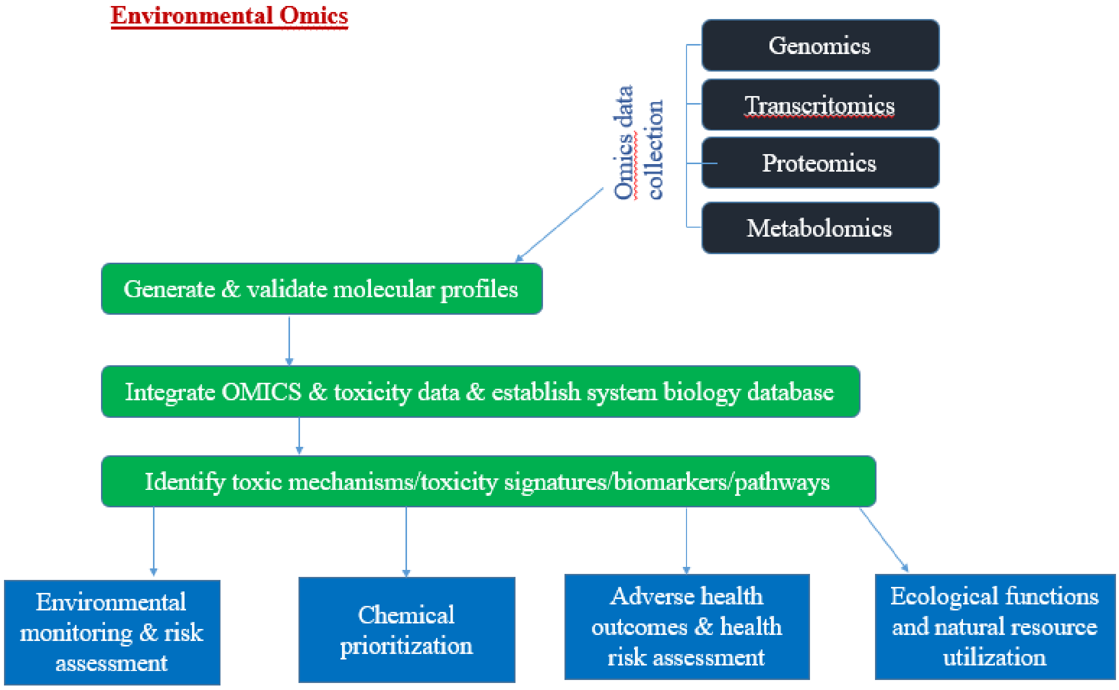

Fig.7: Visual representation of omics technologies such as DNA sequencing or metabolomics

Challenges and Future Directions

Environmental toxicology has many challenges as it attempts to evaluate and reduce the effects of pollutants on the environment and on human health. A major challenge is the ever-increasing complexity and variety of contaminants that enter the environment. Technology and industrialization are leading to the rapid introduction of new chemicals into ecosystems. Many of these new chemicals have toxicological profiles that are not immediately known. New contaminants such as pharmaceuticals and microplastics as well as nano-materials present unique challenges in that they are persistent in nature, have bioaccumulation potential, and have the potential to interact in unexpected ways with biological systems. Interactions between multiple stressors are a major challenge for risk assessment and management. Chemical pollutants interact with other stresses, including climate change, habitat degradation, invasive species, nutrient pollution, and more. These interactions can cause complex and synergistic impacts on ecosystems, leading to unexpected ecological responses. These interactions complicate efforts to anticipate and mitigate the effects of pollutants. The cumulative effects of low-level exposure to pollutants over long periods of time are poorly understood, highlighting the need for better methodologies and research paradigms to fill this gap. There is also a lack of standardized methodology and guidelines for evaluating the environmental effects of contaminants, resulting in heterogeneous risk assessments and management approaches. The lack of common protocols hinders comparability and robustness of toxicological information, making it difficult to develop effective environmental protection policies and regulations. Furthermore, there is an

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urgent need for better communication and collaboration among scientists, policy makers, industry stakeholders and the general public to effectively address environmental toxicological challenges. To bridge the research gap between science and policy implementation, increased transparency and stakeholder involvement, as well as knowledge sharing, are needed to enable evidence-driven decision making and support sustainable environmental management approaches.[54] [55] [56] The future of environmental toxicology addresses the challenges posed by contaminants and advances our knowledge of their effects on ecosystems and on human health. Interdisciplinary approaches that bring together ecology, molecular biology and epidemiology, as well as computational science, offer promising opportunities to improve our understanding of toxicity mechanisms and ecological impacts of contaminants. Advances in analytical methods, including omics technologies, computational modeling, and biomarkers for exposure, effect and susceptibility, can help predict environmental responses to contaminants and identify chemicals that should be subject to regulatory scrutiny. Incorporating green chemistry & sustainable design principles into chemical risk assessment & management practices can help reduce the impact of toxicants on the environment and promote eco-friendly technologies and products. Collaboration between scientists, policy makers, industry stakeholders and the public is key to translating research findings into sound policies and regulations that safeguard ecosystems & human health. [52] [47] [30]

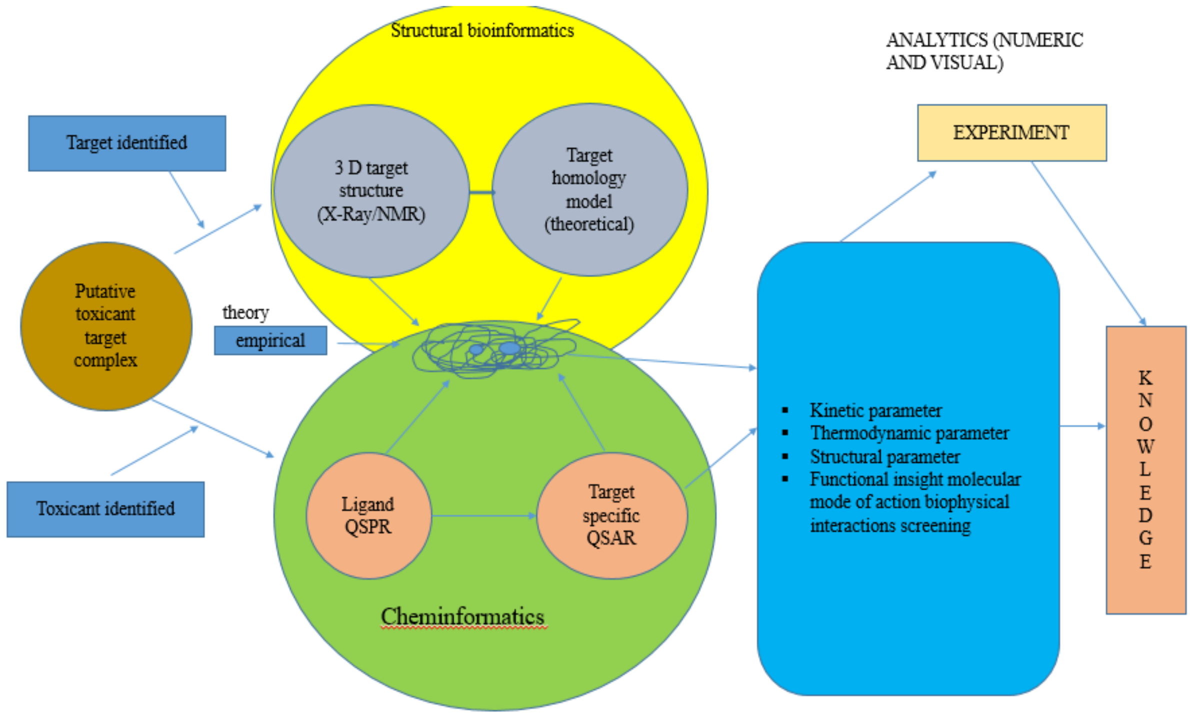

Fig.8: Diagram showing computational modeling software used in toxicology research.

Conclusion

Environmental toxicology serves as a crucial discipline in safeguarding the health of our planet and its inhabitants by meticulously examining the adverse impacts of various contaminants on living organisms and ecosystems. Operating at the intersection of numerous scientific fields including chemistry, biology, ecology, and physics, environmental toxicology employs a multidisciplinary approach to unravel the intricate interactions between pollutants and the environment. Through rigorous research and analysis, environmental toxicologists elucidate the pathways through which contaminants infiltrate ecosystems, their fate within environmental compartments, and their profound repercussions on vegetation and wildlife. The multifaceted nature of environmental toxicology enables researchers to tackle complex environmental challenges holistically, drawing insights from diverse disciplines to comprehend the behavior of pollutants and their implications for both ecosystems and human health. By furnishing scientific evidence on the hazards associated with various pollutants, environmental toxicologists play a pivotal role in shaping policies and regulations aimed at preserving environmental quality and human well-being. Furthermore, their findings inform decision-making processes regarding pollution control, remediation efforts, and sustainable resource management practices. A critical aspect of environmental toxicology lies in its exploration of the mechanisms underlying toxicity and bioaccumulation of contaminants. Through comprehensive assessments at molecular, cellular, organismal, and population levels, researchers discern the intricate responses of biological systems to environmental stressors. Advanced analytical techniques, including omics technologies and computational modeling, empower scientists to unravel molecular pathways, predict toxicity models, and identify biomarkers for exposure, effect, and susceptibility. Nevertheless, environmental toxicology grapples with myriad challenges in its quest to mitigate the impacts of pollutants. The ever-growing complexity and diversity of contaminants, coupled with their potential interactions with other stressors, pose formidable obstacles for risk assessment and management. Moreover, the cumulative effects of prolonged exposure to pollutants remain inadequately understood, highlighting the pressing need for standardized methodologies and interdisciplinary collaborations to bridge existing research gaps. Looking ahead, interdisciplinary collaborations and technological advancements hold promise in enhancing our understanding of toxicity mechanisms and ecological impacts of contaminants. Integrating green chemistry principles and sustainable design practices into risk assessment and management strategies can pave the way for eco-friendly solutions. However, effective translation of research findings into actionable policies necessitates heightened transparency, stakeholder engagement, and knowledge dissemination across scientific, governmental, industrial, and public spheres. In essence, the future of environmental toxicology hinges on concerted efforts to surmount existing challenges, foster interdisciplinary collaborations, and implement evidence-based strategies that safeguard ecosystems and human health in the face of evolving environmental threats.

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CHAPTER TITLE: CLIMATE CHANGE AND ITS IMPACT ON AGRICULTURE

Rashami Manaware[1], Pratibha Yadav[2], Ranjana Chouhan[3]

[1,2]Mata Jijabai Govt PG Girls College, Indore, Madhya Pradesh, India
[3]School of Biotechnology, DAVV, Indore, Madhya Pradesh, India
Corresponding E-mail: rashmi02w@gmail.com

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Abstract

Climate change due to human actions like industrialization, deforestation, and modification of agricultural land is inducing great transformations in worldwide climate patterns. It has also induced more emission of greenhouse gases (GHG) that contribute to higher temperatures, changed rainfalls, and more CO2 concentrations. Asia, which contains more than 60% of the world's population, is extremely exposed, and its agriculture systems are at risk from the increased frequency and intensity of extreme weather events, changes in climates, and increased sea levels. Principal effects include lowered crop production, particularly for staple crops such as rice, wheat, and maize, livestock, and fisheries. Rising temperature, changing precipitation, weather-related disasters, soil erosion, and the infestation of pests and diseases are some of the most salient threats to food security. The agricultural industry has to implement adaptation measures to reduce these risks, such as farm innovations such as AI for crop monitoring, sustainable farming practices such as crop rotation and conservation tillage, and carbon sequestration through agroforestry. Moreover, food waste reduction can play an important role in ensuring sustainable food systems and climate change mitigation. Combatting climate change in agriculture involves a multi-faceted approach that includes technological innovation, policy reform, and cooperation among governments, the private sector, and individuals. In order to promote long-term food security and a sustainable future, it is essential to mainstream climate resilience into agricultural production and minimize the environmental footprint of food systems.

Keywords: climate change, agriculture, greenhouse gases, adaptation strategies, food security, food waste, sustainable practices, carbon sequestration, temperature rise, precipitation patterns.

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Introduction

Climate change pertains to drastic, long-term alterations in the anticipated weather patterns over regions or the entire globe. It is defined by deviation from typical weather patterns, which may take long periods, sometimes decades, other times millions of years. However, human action, especially industrialization, urbanization, tree cutting, and land use practices, has caused this natural phenomenon to speed up by enhancing the release of greenhouses gases (GHGs). This sudden transformation resulted in warmer temperatures, shifting patterns of precipitation, and an increased level of atmospheric CO2 (IPCC, 2019).

The greenhouse effect, which is essential for supporting life on our planet, naturally contributes to a warm climate by trapping heat in the atmosphere. Although this process favors crop growth and general productivity, the increasing level of GHGs—like carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O)—as a result of human activities has intensified global warming (Mahato, 2014). Consequently, the temperature of the earth's surface has increased by around 0.74°Cover the late 19th century, and is expected to increase even more to 1.4°C to 5.8°C by the year 2100, with different effects in different regions. This temperature increase is followed by an increase in CO2, N2O, and CH4 levels, each playing a role in climate change with different intensities that can restructure ecosystems and agricultural production worldwide(IPCC, 2019).

Asia, where more than 60% of global population lives, is gravely affected by global climate change, especially in the rural communities with prevalent poverty. Having a huge and rapidly expanding population with much of its human resources reliant on agriculture, it is highly exposed to climate change in the weather patterns. Such shifts comprise extreme weather, long-lasting droughts, and sea level rise, all of which jeopardize the stability of food production systems (Guo et al., 2018; Hasnat et al., 2019). With relatively low GHG emissions, although compared to other parts of the world, China and India are among the top emitters of carbon in the world, thus making it difficult for the region to attain food security and economic stability (Gouldson et al., 2016; Ahmed et al., 2019).

Against this backdrop, the agricultural sector in Asia is becoming increasingly vulnerable to the volatile effects of climate change. Increased risks of flooding, droughts, and other climate-related shocks impose huge pressure on the livelihoods of smallholder farmers and agricultural productivity. Mitigating the impacts of GHG emissions while adapting to the new climate is essential in addressing the changing threats of climate change, which is vital for long-term food security and sustainable development in Asia, and needs innovative solutions and efficient policies.(Yadav and Lal, 2018; Rao et al., 2019).

The Science of Climate Change

Asia is extremely prone to the effects of climate change, which strongly challenges its farm productivity, food security, and natural resources. Climatic modeling projects an increase in global warming by 1.5°Centigrate between 2030 & 2050 and specifically impacts desert areas inPakistan, China, and India (IPCC, 2019). More frequent occurrence of extreme weather conditions such as heatwaves, unpredictable rainfall, and cyclones will be causing disruption to agricultural systems, particularly the rice and wheat cropping system that sustains half of Asia's population (Ghaffar et al., 2022). Higher temperatures and water scarcity are lowering crop yields, particularly wheat and rice, by reducing growing seasons and impacting crop quality (Asseng et al., 2019). Livestock agriculture is also vulnerable, as heat stress decreases forage quality and livestock production (Das, 2018). Forests and aquaculture sectors are equally affected, with alteration of forest structure, risk enhancement of forest fires, and loss of habitat for fish (Chitale et al., 2018; Jahan et al., 2017). In addition, climate extremes like floods, droughts, and ocean acidification are impacting fisheries and aquaculture, which are crucial to the economy of the region (Ahmad et al., 2019). Since millions of people rely on agriculture, it is important to establish adaptive measures to fight climate-induced threats and achieve food security in Asia(Downing et al., 2017).

Key Climate Change Effects on Agriculture

Climate change can impact agriculture through their direct and indirect impacts on the precipitation, Extreme weather condition, soils, Temperature, Crop and livestock and pests and disease. Rise in atmospheric carbon dioxide has a fertilization effect on crops with C3 photosynthetic pathway and hence enhances their growth and productivity.

Temperature Rise: Temperature is an important factor in agricultural production, with low and high temperatures affecting crop development and yield. High temperature is especially a major risk to crops, particularly at the flowering and grain-filling stages. At temperatures above optimal, they will disrupt key physiological processes in plants such as photosynthesis, respiration, and transpiration. This results in low crop yields and quality, as heat stress causes damage to plant tissues, lowers the efficiency of pollination, and impairs root function. For example, rice, wheat, and maize are especially sensitive to temperature, with research indicating that even a minor rise in temperature can lead to significant yield losses.
With increasing global temperatures as a result of climate change, these adverse impacts are likely to be more extensive, compromising food security, especially in areas that already experience sensitivity to climate variability. Additionally, high-temperature effects are exacerbated by other climate dimensions like drought and uneven patterns of rainfall. To counter these impacts, developing climate-tolerant crop varieties and practicing sustainable agriculture are a must to enable farmers to adjust to the climatic changes and have stable production to feed a surging population globally(Parthasarathi et al., 2022)

Shifting Precipitation Patterns: Precipitation has a significant effect on agricultural productivity since it has a direct impact on the availability of soil moisture and crop growth. Rainfall variability, such as the variability in amount, timing, and distribution, may result in agricultural planning and management difficulties. For rain-fed agriculture, the onset, termination, and duration of rainfall are important factors that control crop yield. In cases where rainfall is low, crops suffer from drought stress, hence decreased productivity. Conversely, too much rain can cause waterlogging, erosion, and leaching of nutrients, which have adverse impacts on crop health and soil structure(Bedane et al., 2022)

Extreme Weather Events: Weather catastrophes result in billions of dollars' worth of losses and enormous loss of life around the world. Droughts, floods, heat waves, severe storms, wildfires, and other extreme weather conditions lead to deaths, damage, and immense agricultural losses annually in different parts of the world. There has been a rising number of and intensity of such circumstances over the last few decades. Extreme weather conditions can hugely impact crop production, and, in turn, agricultural output. The vast majority of crops are vulnerable to the immediate effects of elevated temperatures, decreased precipitation, flooding, and premature freezes at critical growth phases. Furthermore, crops are also impacted indirectly by altered soil processes, nutrient cycling, and pest populations(Motha, 2011).

Soil: Lower quality and amount of organic substances content, already relatively low in Indian soil. Under increased CO_2 level, crop residues will have elevated C:N ratio, which will decrease their rate of decomposition and nutrient release. Rise of soil temperature will accelerate N mineralization but availability might decline as a result of elevated gaseous losses via mechanisms like volatilization and denitrification. Modification in the volume and frequency of rainfall and wind speed could modify the severity, frequency and degree of soil erosion. Sea-level rise can result in salt-water intrusion into coastal areas making them less conducive for traditional farming (Pareek, 2017).

Pests and Diseases: Food production systems are highly vulnerable to climate fluctuation such as fluctuation in precipitation and temperature, which results in an outbreak of diseases and pests thus lowering in food security of the nation by impacting harvest (Anupama Mahato 2004). Fluctuation in incidence and distribution of pests and pathogens leads to indirect impacts (Sutherst et al. 1995). Decline in farm production with climate change-induced variation in patterns of pests and diseases. Winter is a period of dry season, and so rising temperature and slightly more precipitation with the existing dry season may promote diseases and insect pests (Yadav et al 2020). Climate change speeds up the speed of the insect and pest reproduction cycle. Demand for pesticides usage in a greater extent due to the rising in the insect population, causing more negative impacts to the ecosystem and human society (Malla 2008).

Crop production and Livestock: Drought periods below temperature levels would halt or even wreck growth of the crop that would lead to decrease in crop yields (Mendelsohn 2014). The dominant pattern of average yearly enthusiasm towards net income varies according to seasons; the marginal would be decisive (if warm) or either unfavorable (if cold) (Chen et al. 2016). (Swaminathan et al. 2010) demonstrate that a 10C rise in temperature lowers wheat output by 4 - 5 percent. A study by the (IMF 2017) reports that for emerging market economies a 10C increase in temperature would lower agricultural output by 1.7%-, and 100-millimeters reduction in rain would lower growth by 0.35%. Animals are also affected by climate change (Ngondjeb 2013) and also harmful for aquaculture production (Mishra 2014). Livestock would be impressed in 2 ways by climate change: the quantity and quality of forage of steppe could be affected and there could be a direct effect on livestock due to higher temperatures. Under a 5.0°C increase in temperature, livestock yields in the U.S. would be reduced by 10% for cow/calf and dairy farming in Appalachia, the Southeast, the Delta States, the Southern Plains, and Texas; under a 1.5°C warming, yield reduction was projected at 1%. Being the next industries of crop agriculture, the production of livestock and processed food would also decline with increasing input costs. Global production of livestock and processed food would decline by 5.9% and 4.6%, respectively (Zhai and Zhuang., 2012).

Adaptation Strategies for Agriculture

Agricultural Innovation: Through predictive analytics, machine learning, and real-time data, AI enhances weather forecasting, soil analysis, pest control, and crop monitoring. Machine learning algorithms, IoT sensors, and drones facilitate accurate watering, fertilization, and early disease detection in crops, while generative AI models simulate climatic conditions for adaptive seed development. With its challenges of elevated implementation expenses and data privacy issues notwithstanding, the integration of field data and satellite imagery by AI assists farmers in maximizing resources, enhancing productivity, and ensuring sustainable agriculture, finally enhancing food security and alleviating climate change effects (Bell and Broklyn, 2024).

Sustainable Practices: Organic farming practices are central to soil health, diversity, and conservation. Crop rotation minimizes erosion and nutrient loss, and composting is cheap, environmentally friendly fertilization. Cover crops eliminate erosion and enhance soil fertility through nitrogen fixation. Conservation tillage leaves crop residue on the land, minimizing erosion and saving water. Integrated Pest Management (IPM) utilizes biological, cultural, and chemical techniques to keep pesticide use at a minimum. Agroforestry combines trees with crops to improve soil fertility and biodiversity. Precision agriculture maximizes the use of resources using data and technology, whereas organic farming supports natural farming techniques. Water-saving methods like drip irrigation and green manure improve soil health and water use efficiency, leading to sustainable agriculture (Duguma, and Bai, 2025).

Mitigation of Climate Change through Agriculture

Carbon Sequestration: Carbon sequestration in agriculture involves the capture and storage of carbon dioxide (CO2) in the atmosphere within soil and plant biomass to prevent climate change. This can be done through numerous means, including carbon-sequestering farms, agroforestry, conservation tillage, and cover cropping (Rodrigues et al., 2023). Such methods improve soil fertility, boost organic matter, and encourage sustainable agriculture that not only minimizes greenhouse gas emissions but also enhances water retention and soil fertility. Incorporating carbon capture in agricultural practices presents an attractive option for mitigating the carbon impact of agriculture and supporting global climate objectives (Thamarai et al., 2024).

Sustainable Food Systems: Food waste is one of the key sustainability issues that impacts economic, environmental, and social systems. Food waste reduction has the potential to contribute to the attainment of several Sustainable Development Goals (SDGs), such as SDG 2 (zero hunger), SDG 12 (sustainable consumption), SDG 13 (climate action), and SDG 14 (life below water). Food redistribution, supply chain management of waste, and sustainable food management are some of the primary strategies for reducing food waste (Swetha et al., 2024). Innovations in technology, including smarter inventory management and energy-efficient processing, are important in preventing waste at every step of the food supply chain. Moreover, policy support for circular economy measures and improved consumption practices can prevent the environmental footprint of food waste, including reduced greenhouse gas emissions. Collaborative action among stakeholders, such as governments, companies, and consumers, is necessary to build a sustainable food system that is in line with the SDGs and helps towards a more sustainable future for everyone (Manzoor et al., 2024).

Conclusion

In summary, climate change presents serious challenges to agriculture, food security, and sustainable development, especially in countries such as Asia, where agriculture is highly reliant on stable climatic conditions. The effects of extreme weather events risk crop yields,increasing temperatures, altered precipitation patterns, livestock productivity, and food system stability. Adaptation measures, including agricultural innovation, sustainable agriculture, and carbon sequestration, are important in reducing these impacts. In addition, food waste reduction through redistribution, enhanced supply chain management, and sustainable consumption can help in the attainment of some of the Sustainable Development Goals (SDGs), including zero hunger, responsible consumption, and climate action. Joint action by governments, companies, and individuals is needed to establish a sustainable and resilient food system that not only addresses the problems of climate change but also delivers food security to generations to come while minimizing the environmental footprint.

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UNVEILING THE UNDERGROUND SYMPHONY: A COMPARATIVE MICROBIAL DIVERSITY IN LEGUMINACEAE AND FABACEAE RHIZOSPHERES

Shivani Tyagi, Pooja Barthwal and Aman Kumar

Quantum University, Roorkee, Uttarakhand
Corresponding E-mail: dr.shivanityagi@gmail.com

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Abstract

In order to shed light on the complex dynamics of plant-microbe interactions and their effects on soil health, this research analyzes the microbial diversity in the rhizospheres of plants belonging to the Leguminaceae and Fabaceae families. It looks at the microbial communities that are connected to various plant groups and shows how important it is for bacteria to fix nitrogen, namely *Rhizobium*, *Bradyrhizobium*, and *Sinorhizobium*. By turning atmospheric nitrogen into accessible ammonia via the formation of nodules on the roots of leguminous plants, these bacteria improve soil fertility and lessen the demand for synthetic fertilizers. Furthermore, improved nutrient absorption and root development are made possible by mutualistic connections with mycorrhizal fungi including *Rhizophagusirregularis* and *Glomus spp.*, which increase plant resistance. Furthermore, microorganisms that dissolve phosphate, such as *Bacillus and Pseudomonas*, facilitate the release of bound phosphorus, hence augmenting soil fertility and promoting plant growth. Comprehending these interplays is essential for formulating sustainable farming methodologies that maximize the synergy between plants and microbes to enhance soil fertility, crop productivity, and ecological sustainability.

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Introduction

The dynamic interface between soil and plant roots, or rhizosphere, is a hotspot for microbial activity that is essential to maintaining soil health and promoting plant growth and development. Two notable plant families, the Fabaceae and the Leguminaceae, stand out in this microcosm because to their symbiotic connections with nitrogen-fixing bacteria, which are essential for improving soil fertility and nutrient uptake. (1-2)

Plants of the Fabaceae and Leguminaceae families are well known for their capacity to develop symbiotic relationships with bacteria that fix nitrogen; these bacteria are mostly found in the genera *Rhizobium, Bradyrhizobium, and Sinorhizobium*. These bacteria, which go by the name rhizobia, form nodules on the roots of leguminous plants and use nitrogen fixation to convert atmospheric nitrogen into ammonia. The communication between the bacteria and the plant promotes this symbiotic relationship and results in the development of specialized structures known as nodules. Root exudates from the plant provide the rhizobia a carbon supply in exchange for fixed nitrogen, establishing a win-win partnership. (3-4)

It is impossible to overestimate the significance of nitrogen-fixing bacteria for Leguminaceae and Fabaceae plants. Rhizobia improve soil fertility by transforming atmospheric nitrogen into a form that is bioavailable, which is a crucial source of nutrients for plant development. This procedure lessens the demand for artificial nitrogen fertilizers, cleans up the environment, and encourages environmentally friendly farming methods. Furthermore, the mutualistic relationship between legumes and rhizobia boosts crop production, increases plant productivity, and advances global food security. (5-7)

Other microbial communities in the rhizosphere of Leguminaceae and Fabaceae plants, in addition to nitrogen-fixing bacteria, are important for maintaining soil health and promoting plant development. *Mycorrhizal fungi*, which include *Rhizophagusirregularis* and *Glomus spp*., establish symbiotic relationships with plant roots to aid in the absorption of nutrients and water from the soil, especially phosphorus. These fungus help plants grow longer roots, which improves their ability to acquire soil nutrients and increases their resistance to environmental challenges. Furthermore, by liberating bound phosphorus from both organic and inorganic sources in the soil, phosphate-solubilizing bacteria, such as Bacillus and Pseudomonas species, support soil fertility and nutrient cycling. This procedure increases soil fertility, especially in phosphorus-deficient soils, and encourages plant growth and nutrient usage efficiency. (8-10)

Rhizosphere Microbiota

The rhizospheres microbial variety is essential for soil health and plant development because different microorganisms are involved in the cycling of nutrients, the prevention of disease, and general plant health. Many genera, such as Rhizobium, Agrobacterium, Carbophilus, Chelatobacter, Ensifer, Sinorhizobium, Allorhizobium, Kaistia, and Shinella, stand out among the diverse microbial communities that live in the rhizosphere for their important contributions to plant-microbe interactions and ecosystem functioning**.** [16]

Rhizobium: It is well known that some species of Rhizobium may coexist harmoniously with leguminous plants, especially those in the Fabaceae family. The Rhizobium bacteria use nitrogen fixation to transform atmospheric nitrogen into ammonia, which the host plant uses for growth and development. The development of nodules on legume roots, where Rhizobium bacteria live and perform nitrogen fixation, mediates this symbiotic relationship. Both the plant and the bacterium gain from the nutrient exchange, which increases soil fertility and boosts plant production. (11-13)

Agrobacterium: Tumor-inducing (Ti) plasmids are known to be transferred into the plant genome by Agrobacterium species, which is why plants get crown gall disease. Although many Agrobacterium strains are harmful, others have been modified for use in biotechnology, namely in plant genetic engineering. A popular method for transferring foreign genes into plants, Agrobacterium-mediated transformation is a useful tool for biotechnological and agricultural advancement. (14-15)

Carbophilus: Beneficial bacteria called Carbophilus species support healthy soil and the cycling of nutrients. These bacteria contribute to the breakdown of organic matter, the mineralization of nitrogen, and the mobilization of nutrients, all of which improve soil fertility and encourage the development of plants. In order to keeps soil functioning properly and allowing the availability of important nutrients for plant absorption, Carbophilus bacteria are required. [15]

Chelatobacter: It is well known that some Chelatobacter species may dissolve insoluble minerals from the soil, especially phosphate and iron. Chelatobacter bacteria have the ability to mobilize and make these vital nutrients accessible to plants via the production of organic acids and chelating agents. This solubilization process increases crop yield and agricultural sustainability by encouraging plant growth and development, especially in soils with poor nutrient availability. [17]

Ensifer: Nitrogen-fixing bacteria called Ensifer species, previously known as Bradyrhizobium, work in symbiotic relationships with leguminous plants. These microorganisms invade host plants' roots and form nodules, where they transform atmospheric nitrogen into ammonia, which the plant uses for growth. In order to support sustainable agricultural practices, Ensifer bacteria are essential for improving soil fertility, boosting plant nutrition, and lowering the demand for synthetic nitrogen fertilizers. [18]

Sinorhizobium: Like other rhizobia, Sinorhizobium species are nitrogen-fixing bacteria that associate symbiotically with leguminous and Faiences plants. Because of their ability to nodulate and fix nitrogen, these bacteria help the host plant absorb nitrogen from the atmosphere by converting it to ammonia. Especially in soils lacking nitrogen, Sinorhizobium bacteria support plant nutrition, soil fertility, and agricultural sustainability. [19]

Allorhizobium: Nitrogen-fixing bacteria called Allorhizobium species form symbiotic relationships with leguminous plants, facilitating the fixation of nitrogen and stimulating plant development. Through their ability to transform atmospheric nitrogen into ammonia, which the host plant uses for a variety of metabolic activities, these bacteria improve soil fertility and plant nutrition. In areas where nitrogen is limited, Allorhizobium bacteria are especially important for increasing crop yield and agricultural sustainability.[20]

Kaistia: Beneficial bacteria called kaistia species support healthy soil and nutrient cycling. These bacteria contribute to the breakdown of organic matter, the mineralization of nitrogen, and the mobilization of nutrients, all of which improve soil fertility and encourage the development of plants. In order to maintain the structure and functionality of the soil and make necessary nutrients more accessible for plant absorption, kaistia bacteria are important. [17-18]

Shinella: Shinella species are well-known for their involvement in the rhizosphere's nitrogen fixing and nutrient cycle processes. These bacteria live in symbiotic relationships with leguminous plants, where they help fix nitrogen and stimulate plant development. Shinella bacteria transform atmospheric nitrogen into ammonia, which is then absorbed by the host plant, enhancing soil fertility and plant nutrition. Particularly in soils lacking nitrogen, Shinella species are essential for improving crop production and agricultural sustainability. [19-20]

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Table. 1: Indicator Species- Identify indicator species that are significantly associated with either Leguminaceae or Fabaceae plants.

Indicator Species	**Leguminaceae (Abundance/Prevalence)**	**Fabaceae (Abundance/Prevalence)**
Rhizobium leguminosarum	High (80% prevalence)	Low (20% prevalence)
Bradyrhizobiumjaponicum	Moderate (50% prevalence)	High (70% prevalence)
Sinorhizobiumfredii	High (70% prevalence)	Moderate (40% prevalence)
Mesorhizobiumciceri	Low (20% prevalence)	Moderate (50% prevalence)
Azorhizobiumcaulinodans	Moderate (50% prevalence)	Low (10% prevalence)

Comparative study on Leguminaceae and Fabaceae

Root Morphology and Nodulation Patterns: Throughout the growing season, Leguminaceae plants usually have indeterminate nodules on their roots, which are characterized by ongoing development and active nitrogen fixation. Conversely, determinate nodules, which stop fixing nitrogen once they reach maturity, are a common feature of Fabaceae plants. The rhizosphere's nitrogen-fixing bacteria's diversity and abundance may be impacted by these variations in nodulation patterns. [21-22]

Exudate Composition: Leguminaceae and Fabaceae plants have different root exudate compositions, which affects the microbial populations living in their rhizospheres. Certain exudates produced by Leguminaceae plants encourage nitrogen-fixing rhizobia to colonize them, increasing the variety of symbiotic relationships. Conversely, Fabaceae plants have the ability to secrete a variety of exudates in varying amounts, which may alter the makeup of the microbial population inside their rhizospheres. [23]

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Nitrogen-Fixing Bacteria Diversity: As contrast to Fabaceae plants, Leguminaceae plants often house a larger variety of nitrogen-fixing bacteria because of variations in root shape, nodulation patterns, and exudate composition. This increased diversity might be explained by the ongoing development of indeterminate nodules as well as the existence of specific root exudates that draw in a greater variety of symbiotic relationships. [24]

Non-Symbiotic Microbial Communities: Leguminaceae and Fabaceae plants may differ in the presence of non-symbiotic microorganisms, such as phosphate-solubilizing bacteria and mycorrhizal fungus, in addition to nitrogen-fixing bacteria. The number and diversity of these microbial communities may be influenced by changes in soil characteristics and root exudates, which might lead to differences in the two plant families' nutrient acquisition techniques and ecosystem functioning.[25]

Bacterial Texa: list of all bacterial species.

Function: Classifies each bacterial taxon according to its known or expected role in nitrogen fixation, plant growth promotion, or pathogenicity.

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Leguminaceae (%): Indicates the proportion of every bacterial taxon linked to plants in the Leguminaceae family.

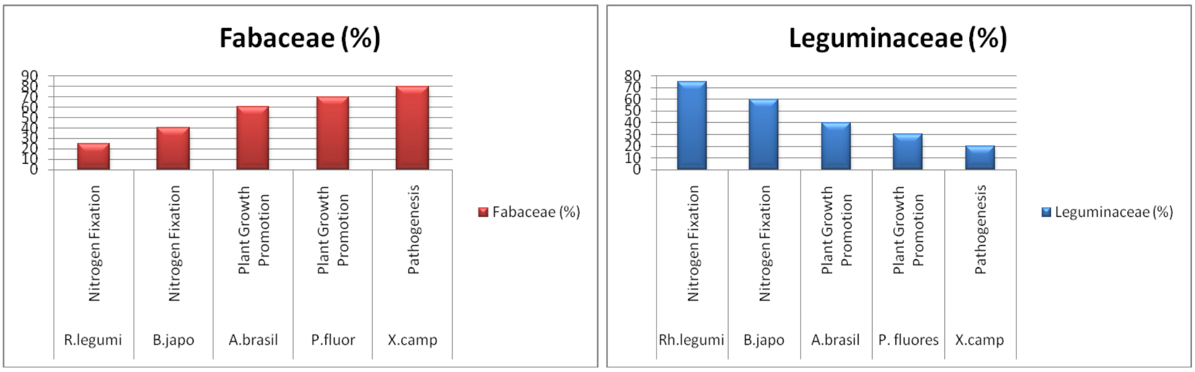
Fabaceae (%): Shows the proportion of each bacterial taxon connected to plants in the Fabaceae family.

For instance, *Rhizobiumleguminosarum* and *Bradyrhizobiumjaponicum*, which have a 75% and 60% connection with Leguminaceae plants, respectively, are predominantly engaged in nitrogen fixation. *Pseudomonasfluorescens* and *Azospirillumbrasilense* are recognized for their capacity to stimulate plant development, and they have stronger relationships with Fabaceae plants. *Xanthomonascampestris* is a pathogen that is mostly connected to Fabaceae plants.

Table.2: Functional Diversity

Bacterial Taxa	Function	Leguminaceae (%)	Fabaceae (%)
Rhizobium leguminosarum	Nitrogen Fixation	75	25
Bradyrhizobiumjaponicum	Nitrogen Fixation	60	40
Azospirillumbrasilense	Plant Growth Promotion	40	60
Pseudomonas fluorescens	Plant Growth Promotion	30	70
Xanthomonascampestris	Pathogenesis	20	80

Chart on Functional Diversity



Factor Affecting Microbial Diversity of Leguminaceae and Fabaceae

Plant Genotype: Rhizosphere microbial recruitment and the composition of root exudate are influenced by genetic diversity in plant species belonging to the Leguminaceae and Fabaceae families. Variations in symbiotic relationships with nitrogen-fixing bacteria and other microorganisms are caused by differences in genotype, which shapes microbial diversity and community structure in the rhizosphere. [26]

Soil Properties: The pH, amount of organic matter, and availability of nutrients in the soil are some of the factors that influence microbial diversity in the rhizosphere. While the amount of organic matter in the soil offers growth substrates for microorganisms, the pH of the soil affects the quantity and activity of certain microbial groups. The makeup of microbial communities that fix nitrogen and solubilize phosphate is influenced by the availability of nutrients, especially nitrogen and phosphorus. [27]

Land Management Practices: Microbial diversity in the rhizospheres of the Fabaceae and Leguminaceae families may be impacted by agricultural techniques such fertilizer application, tillage, and crop rotation. Crop rotation modifies the nutrient availability and root exudate patterns, hence promoting microbial community diversity. Tillage techniques have the potential to alter microbial diversity and activity by upsetting microbial habitats and soil structure. Furthermore, fertilizer application affects the microbial community composition and nutrient cycling in the rhizosphere. [28]

Environmental Conditions: The availability of light, moisture content, and temperature are examples of environmental variables that impact microbial diversity in the rhizosphere. The development, activity, and community composition of microorganisms are influenced by these parameters, which has implications for soil health and nutrient cycling. Fluctuations in microbial diversity and function might result from differences in environmental circumstances across distinct growth seasons or geographical locations. [29]

Table.3: Environment Factor

Environmental Factor	Leguminaceae Sites (Mean ± SD or Range)	Fabaceae Sites (Mean ± SD or Range)
Soil pH	6.2 ± 0.3	6.5 ± 0.4
Soil Moisture (%)	25 ± 5	30 ± 7
Organic Matter (%)	3.5 ± 0.8	4.0 ± 1.0
Nitrogen Content (%)	0.2 ± 0.05	0.25 ± 0.06
Temperature (°C)	25 ± 2	27 ± 3
Precipitation (mm)	800 ± 100	850 ± 120

Environmental Factor: Lists the environmental variables examined, including soil properties (pH, moisture, organic matter, nitrogen content) and climate variables (temperature, precipitation).

Leguminaceae Sites (Mean ± SD or Range): Indicates the average or range of each environmental factor observed at sites where Leguminaceae plants were sampled. For example, soil pH at Leguminaceae sites has a mean of 6.2 with a standard deviation of 0.3.

Fabaceae Sites (Mean ± SD or Range): Shows the average or range of each environmental factor observed at sites where Fabaceae plants were sampled. For instance, soil pH at Fabaceae sites has a mean of 6.5 with a standard deviation of 0.4.

Conclusion

We have found notable variations in microbial diversity between the rhizospheres of plants belonging to the Leguminaceae and Fabaceae families in our comparative research. The form and function of microbial communities are influenced by the distinctive features of each plant family, such as nodulation capability, exudate composition, and root architecture. Comprehending these distinctions is essential to improving soil health, advancing sustainable crop production, and optimizing agricultural operations. The results of this research emphasize how crucial it is to take into account environmental factors, land management techniques, plant genotype, and soil type when assessing microbial diversity. We can create specialized methods for crop production and soil management that will provide the best possible nutrient cycling, plant health, and ecosystem sustainability by understanding the intricate interactions between these variables. The molecular processes behind plant-microbe interactions and their consequences for soil fertility and health should be the subject of future study. We can improve agricultural practices, lessen environmental effects, and create resilient agricultural systems that can handle challenges to future food security by developing our knowledge of these interconnections.

Future Prospect

Research on the variety of microorganisms in rhizospheres belonging to the Leguminaceae and Fabaceae families has the potential to significantly improve our understanding of plant-microbe interactions and enhance agricultural practices. By using state-of-the-art multi-omics techniques, we will be able to fully use the potential of beneficial microbial communities to improve soil health and plant production by gaining hitherto unattainable insights into the molecular processes underlying these interactions. Furthermore, there are exciting opportunities to enhance microbial diversity and function in agricultural soils via the use of cutting-edge soil management techniques including cover crops, biofertilization, and precision agriculture. We can create sustainable agricultural systems that promote crop resistance to biotic and a biotic challenges, improve nutrient cycling, and lessen environmental impact by using the synergistic benefits of various techniques. It will be essential for scientists, farmers, and legislators to work together to translate scientific findings into practical plans for environmentally responsible and sustainable farming practices. We can solve the issues of global food security and environmental sustainability while fostering the long-term resilience of agricultural ecosystems by bridging the gap between scientific study and practical implementation.

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STEVIA: A NATURAL SWEETENER WITH POTENTIAL HEALTH BENEFITS

Anjay Singh Bisht, Mihir Kashyap and Aman Kumar

Quantum School of Agricultural Studies, Quantum University, Roorkee, India
Corresponding E-mail: anjaybisht250@gmail.com

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Abstract

Sugar, once a luxury reserved for the elite, has become a ubiquitous ingredient in modern food production. Despite its role as a primary energy source for the human body, growing awareness of the adverse health effects of excessive sugar consumption—such as obesity, type 2 diabetes, cardiovascular disease, and certain cancers—has led to a significant shift in consumer preferences. In response, there is increasing interest in healthier, natural alternatives to refined sugar. Stevia, a plant-derived sweetener native to South America, has gained prominence as a viable substitute. Containing steviol glycosides—compounds several hundred times sweeter than table sugar—stevia offers a sweet taste with minimal calories and carbohydrates. As a result, it presents a promising solution for individuals seeking to satisfy their sweet tooth without compromising their health, marking a transformative step toward a more balanced and conscious approach to sweetness.

Key Words: Sugar consumption, Health risks, Natural sweeteners, Stevia, Steviol glycosides, Low-calorie alternative,

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Introduction

Once a highly valued commodity used only by the elite, sugar is now a common component in contemporary food manufacturing. Even though sugar is essential to our systems and serves as the main source of energy for our cells, the tide is shifting against unrestrained sugar intake. Numerous studies have connected eating too much sugar to a number of health issues, including as obesity, type 2 diabetes, heart disease, and even certain types of cancer. Personal experiences with these ailments along with public health awareness initiatives have increased demand for healthier alternatives. More and more customers are looking for natural, low-calorie sweeteners that will satiate their sweet desire without sacrificing their health. Because of this change in customer tastes, stevia—a natural sweetener made from a plant in South America—has become a popular substitute for regular table sugar. [1-3]

We find that stevia offers a convincing solution to our constantly changing relationship with sweetness. Originating from the lush plains of Paraguay in South America, these two botanical wonders conceal a valuable ingredient in their leaves: steviol glycosides. These organic substances are hundreds of times sweeter than table sugar, giving them a potent punch! However, in contrast to its sweet sibling, stevia provides a guilt-free way to enjoy.For individuals looking for a healthy method to indulge their sweet appetite, stevia has emerged as a ray of light due to its low calorie and carbohydrate content. This extraordinary plant not only tastes great, but it also creates the foundation for a perhaps better relationship with sugars. [4-6]

Applications of Stevia

The renown of stevia comes from its capacity to completely transform sweetening in all culinary applications. A little quantity of stevia may produce the appropriate degree of sweetness in a range of food and beverage applications since it is hundreds of times sweeter than sugar. This results in considerable calorie savings and makes stevia a popular option for customers who are health-conscious. [7-8]

Beverage: When it comes to sugar-sweetened drinks, stevia is king. Add a dash or two of stevia to any beverage, from the traditional fizzy pop to the cozy comforts of tea and coffee, to make it a guilt-free treat. There are many of stevia-sweetened drinks available for those looking for a healthy substitute for sugary sodas that nevertheless taste good without making you fall into sugar. Fans of tea and coffee may now savor their favorite blends sweetened with stevia, which keeps the sweetness just the way they want it without adding extra calories. [9-11]

Food Products: The adaptability of stevia goes well beyond drinks; it may be found in a wide variety of foods. Think about flavorful, creamy yogurts that are devoid of a high sugar content. This is made possible with stevia, which enables you to enjoy your favorite yogurt without compromising your nutritional objectives or flavor. For individuals who have a sweet craving, stevia provides access to an endless array of mouthwatering options. With stevia, bakers may make delicious, low-calorie cakes, cookies, and pastries that will fulfill appetites without giving them the guilt that comes with eating typical sugar-filled delights. Stevia is used to provide a hint of sweetness without overwhelming other tastes in sauces, marinades, and salad dressings. [12-16]

Beyond the Kitchen: There are more uses for stevia than just conventional foods and drinks. -To make pharmaceutical goods more pleasant for those who need to control blood sugar levels, several manufacturers add stevia to chewable pills or sugar-free syrups. The cosmetics sector has also started to investigate the possibilities of stevia, adding it to certain lip balms and toothpastes to provide a touch of sweetness without the cavity-causing properties of sugar. [17-19]

Stevia's Potential beyond Sweetness:
Although the main use of stevia is to sweeten food and drinks, its special qualities have potential uses outside of the kitchen. Here's a closer look at its possible applications in the cosmetics and pharmaceutical industries:

Pharmaceuticals:
Diabetes Management: Patients with diabetes who are trying to reduce their blood sugar levels will find stevia to be a natural match due to its zero-calorie nature. Unlike conventional sweeteners, research indicates that steviol glycosides, the sweet molecules found in stevia, may not dramatically raise blood sugar levels. This makes it possible to use stevia in diabetic diet plans or even sugar-free prescription drugs. To completely comprehend the influence of stevia on diabetes control and its ideal incorporation into treatment strategies, further thorough research is necessary. [20-22]

Broadening the View: Preliminary investigations indicate stevia may provide supplementary health advantages pertinent to the pharmaceutical industry. A few studies indicate to the possible anti-inflammatory qualities of stevia, which may be investigated for use in the treatment of ailments such inflammatory bowel disease and arthritis. Furthermore, some studies indicate stevia may have anti-hypertensive properties that might reduce blood pressure. To ascertain stevia's genuine therapeutic 6 potential and its possible future involvement in pharmaceutical development, these possibilities need for more inquiry. [23-25]

Cosmetics:

Sweetener in Lip Products: Stevia is a popular choice for lip balms and glosses since it may provide a touch of sweetness without adding calories. This may improve the user experience, especially for those who don't think standard lip balms taste good enough. Furthermore, customers looking for all-natural or botanical components for their cosmetics may find Stevia’s inherent sweetness appealing. [26-28]

Beyond Sweetness (Antibacterial Potential): New study indicates that a certain steviol glycoside called stevioside may have antibacterial qualities. Should these results remain true, stevia may be added to several cosmetic formulations to improve oral hygiene, such as toothpaste or mouthwashes. This possible use might completely change the dental care industry by providing a 7-natural substitute for conventional, sometimes harsh, antibacterial chemicals. [29-30]

Applications in Skincare: Preliminary research indicates that steviol glycosides may possess antioxidant qualities. If other studies support this, stevia extracts may find use in cosmetic products to counteract free radical damage, a significant cause of wrinkles and other indications of aging. This possible use is in line with the increasing trend of customers looking for skincare products that are high in natural antioxidant compounds. [31-32]

Nutritive Value of Stevia:

The secret to stevia's strength is its ability to fool our taste receptors into thinking it's sweet without adding calories or carbs. The stevia plant itself is a model of moderation since it has very little of either. This is in sharp contrast to regular sugar, which has twice as many calories and carbs per tablespoon. Let's examine the reasons stevia is the best guilt-free sweetener:

Calorie Conscious: Stevia has almost no calories per gram, compared to sugar's 4 calories per gram.For those who track calories and are passionate about weight control, this changes everything. Using stevia instead of sugar in your regular meals and drinks may result in noticeable calorie reductions over time. Enjoying a cool cup of coffee sweetened with stevia rather than sugar might result in a possible 16 calorie savings (based on one teaspoon of sugar)! These little adjustments may have a significant impact on your total caloric consumption.

Champion of Carb Control: Stevia also triumphs in the fight with carbs. It has very little in the way of carbs, and much less in the way of sugar and dietary fiber. This is especially helpful for those on low-crab or ketogenic diets, when the amount of carbohydrates consumed is strictly regulated. You may satisfy your sweet desire with stevia without sacrificing your nutritional objectives. A teaspoon of table sugar includes around 5 grams of carbs, compared to less than 1 gram in the same quantity of stevia leaf extract 9. You may still enjoy a hint of sweetness and maintain ketosis or remain within your low-carb restrictions thanks to this substantial decrease.

Stevia's ability to sweeten food is essential to its low calorie and carbohydrate profiles. Steviol glycosides are naturally occurring chemicals found in stevia leaves that give it its sweetness. Compared to sugar, these substances are highly strong, needing a very little quantity to attain the appropriate degree of sweetness. Because you use so little stevia, the stevia itself contributes very little in the way of calories and carbohydrates. Similar to adding a drop of food coloring to a big pot of water, the color changes considerably but has no effect on the water's total nutritional value.

Potential health benefits of Stevia:

Although the ability of stevia to sweeten without adding calories or carbs is its main selling point, the tale doesn't stop there. Beyond merely blood sugar control, the scientific community is presently investigating a number of other health advantages 10 linked to stevia:

Antioxidant Powerhouse: Steviol glycosides, the sugary components of stevia, may have antioxidant qualities, according to preliminary study. Free radicals are dangerous chemicals in the body that may cause cellular damage and chronic illnesses. Antioxidants aid in the fight against these molecules. If further research validates stevia's antioxidant capacity, it may be advantageous for general health and wellbeing.

Effects on Inflammation: A few researches suggest that stevia may have anti-inflammatory qualities. While inflammation is a normal reaction to damage or illness, prolonged

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inflammation may be a factor in a number of health problems. Future studies on stevia's anti-inflammatory properties may open the door for its use in the treatment of diseases including inflammatory bowel disease and arthritis.

Blood Pressure Regulation: New study indicates that stevia may help decrease blood pressure by having anti-hypertensive 11 properties. To completely comprehend this possible advantage and ascertain the best way to utilize stevia for blood pressure control, further thorough research is necessary.

Crucial Points to Remember: It's crucial to keep in mind that research is continuing and that further studies are required to firmly define safe and effective doses as well as validate these possible health advantages. Furthermore, stevia may need regulatory permission before it may be utilized for a particular medicinal purpose.

Distribution of Stevia:

The beginning of Stevia's tale takes place in the lush landscapes of Paraguay and its neighboring South American countries. This subtropical paradise's high temperature, plenty of sunlight, and well-drained soil make it the perfect place for stevia to grow. Here, stevia has long been utilized by the native Guaraní people, who refer to it as "ka'a he'ê," or "sweet herb." Its 12 leaves contained steviol glycosides, which they were unaware of, but they nonetheless loved its natural sweetening qualities in tea and as a delicious treat.

Centuries ago, stevia started its voyage outside its natural home. Because of its sweetening properties, stevia was brought to other regions of the globe by explorers. Stevia was widely cultivated in China and Japan, where it thrived in their warm, sunny climates. These civilizations found stevia to be sweet, therefore they quickly embraced it into their food and drink customs. More recently, the United States became a member of the stevia cultivation movement. But its journey wasn't quite that easy. The original limitations on the safety and approval of stevia as a food ingredient hindered its widespread use. The Food and Drug Administration (FDA) eventually approved stevia in 2008, allowing it to formally enter the American sweetener market after years of study and assessment.

Global Distribution: A Balancing Act: Several factors influence stevia's global distribution:

Climate: Stevia is a plant that prefers sunlight. It grows well in warm, sunny regions with well-drained soil. This limits the large-scale production of it to certain geographic areas that may meet these requirements. It may not be appropriate to cultivate stevia in areas with cooler temperatures or high levels of rainfall.

Regulation: Government laws governing the acceptability and safety of stevia as a food ingredient differ from nation to nation. In many areas, strict laws or drawn-out approval procedures may prevent stevia from being widely used and adopted. Stevia production and assimilation into food items often go more smoothly in nations with less stringent rules or established safety reviews.

Stevia's safety and possible health advantages are being further investigated, and if regulatory environments change, we may see a broader worldwide use of this natural sweetener.

Cultivation of Stevia:

Thriving Conditions: Stevia is drawn to the sun. It thrives in warm locations with regular temperatures in the range of 68 to 80°F (20 to 27°C), as well as lengthy days with plenty of sunshine. Due to its sensitivity to moisture, stevia requires well-drained soil. Choose a sandy loam mix that has enough drainage to make sure your stevia plants grow well.

Watering Prudently: Although stevia loves warm weather, it is intolerant of consistently wet soil. Just a little watering whiskey. Between watering, let the top inch of soil dry out a little. Err on the side of caution and modify the frequency of your watering according on your particular climate and soil conditions since overwatering might cause root rot.

Planting Power: Seeds vs. Cuttings: Stevia may be propagated primarily using two techniques: seeds and cuttings. Let's examine the benefits and factors to take into account for each:

Simple Seeding: For novices, planting seeds is an easy process. Six to eight weeks before the final frost, start seedlings inside. Give them constant moisture and warmth (around 70° for 21°C). You may move the seedlings outside into your prepared garden bed after they are a few inches tall and the risk of frost has gone.

Considerations: Compared to cuttings, stevia seeds may germinate at a reduced rate. Furthermore, stevia plants produced from seeds may take longer to reach their full sweetness potential.

Cutting Corners with Cuttings: Using stem cuttings to propagate stevia provide a quicker and more dependable method of producing plants with consistent sweetness levels. Choose robust, non-flowering stems from an established stevia plant. A few nodes and a length of 4–6 inches are ideal for cuttings. Before planting the well-draining potting mix, remove the lower leaves and optionally dip the cut end in a rooting hormone. Keep the soil consistently wet and warm for 16 good roots. The cuttings are prepared for outdoor transplantation after they establish a strong root system.

The Sweet Cycle: Growth, Harvest, and Processing

Stevia has a rather short growth cycle: Depending on the selected method of multiplication and growth circumstances, your stevia plants may reach maturity in 3–4 months after being transferred outside. The secret to optimizing sweetness is to harvest the plant before to its flowering stage. The pleasant substance in leaves called stevioside concentrations might drop as a result of flowering.

Harvesting for Sweetness: Regularly harvest stevia leaves throughout the growing season. In order to encourage bushier growth and the creation of new leaves, pinch off the top leaves or stems. You may gather many times over the growing season, ensuring a consistent supply of fresh stevia leaves for your requirements.

Processing the Sweet Rewards: There are many ways to prepare stevia leaves, and each has benefits of its own.

Fresh Leaves: Use fresh stevia leaves straight in your recipes for the purest and most natural source of sweetness. To liberate the leaves' sweetness, cut or mix them finely. Remember that fresh leaves need to be refrigerated since they have a limited shelf life.

Drying: One common technique for long-term preservation of stevia leaves is drying them. Use a dehydrator to dry the leaves, or let them air dry in a cool, dark, and well-ventilated area. For easy usage, crush or powder the leaves when they are totally dried. Compared to fresh leaves, dried stevia leaves are more concentrated in sweetness, so you'll need less.

Conclusion:

Stevia has become a popular natural sweetener that may be used guilt-free in place of sugar. Steviol glycosides give it a strong sweetness that makes it possible to significantly reduce your intake of calories and carbohydrates. Beyond its 18 beverage and culinary uses, stevia has potential use in medicine (diabetes control) and cosmetics (sweetener and perhaps antimicrobial qualities). Stevia is a well-liked natural sweetener that may be substituted guilt-free for sugar. Its rich sweetness comes from the steviol glycosides, which allow you to cut down on calories and carbs greatly. Beyond its eighteen culinary and beverage applications, stevia may also be used in medicine to manage diabetes and in cosmetics as a sweetener and maybe even an antibacterial. Stevia is a plant that originated in Paraguay, South America, and grows best in warm, well-drained soil. Although laws might affect a country's worldwide dissemination, stevia production is growing around the world. You may grow your own stevia from seeds or cuttings; all you need is lots of sunlight and moderate watering.

The Future of Sweetness:

It seems like stevia has a bright future. A positive picture is painted by ongoing research on its possible health advantages and rising consumer demand for natural sweeteners. With stevia's tasty and healthful alternative to sugar, the sweetener industry may see a substantial increase in its share. As science develops and laws change, stevia may one day adorn our kitchens and play a significant part in enhancing general wellbeing.

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PYROPHILOUS FUNGI: A NEW FRONTIER IN HYDROCARBON BIODEGRADATION

Ritu Rani[1], Naina Srivastava[2], Manisha Pandey[3] and Versha Parcha[4]

[1,2,3] Department of Botany, D.A.V. (P.G) College, Dehradun, Uttarakhand-248001[Hemvati Nandan Bahuguna Garhwal (A Central University) Srinagar, Garhwal, Uttarakhand, India.]
[4]Dolphin PG Institute of Biomedical and Natural Science,Maunduwala, Dehradun
Corresponding E-mail: ritu031995@gamil.com

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Abstract

Hydrocarbon contamination poses a significant threat to soil and water ecosystems, particularly in developing regions with limited waste management infrastructure. While physical and chemical remediation methods such as thermal desorption, chemical oxidation, and soil vapor extraction offer solutions, these approaches are costly, energy-intensive, and environmentally detrimental due to secondary pollution. Bioremediation, leveraging microorganisms or their enzymatic pathways to degrade pollutants, provides an eco-friendly and cost-effective alternative. Fungal bioremediation is gaining traction due to fungi's resilience in diverse environments and their ability to produce extracellular enzymes capable of breaking down complex hydrocarbons.[1,2] This article suggests that, similar to other fungi, Pyrophilous fungi can be effectively utilized for hydrocarbon degradation due to their unique enzymatic capabilities and adaptability to challenging conditions. Their potential application highlights an innovative and sustainable approach to addressing hydrocarbon contamination.

Key Words: Hydrocarbon Contamination, Bioremediation, Fungal Bioremediation, Pyrophilous Fungi, Extracellular Enzymes, Sustainable Remediation

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Source of Hydrocarbons and its Environmental Impact

Hydrocarbons, composed of hydrogen and carbon, are categorized as aliphatic or aromatic. Derived from crude oil, production-related leaks can lead to subsurface contamination, with pollutants such as BTEX, naphthalene, and fluorine. Refinery and industrial effluents are the primary sources of subsurface hydrocarbons, negatively impacting ecosystems by impeding the flow of moisture, nutrients, and oxygen to the subsoil.[2] Hydrocarbon products increase due to anthropogenic activity into the environment. Prevalent contaminants include petroleum hydrocarbons (PHCs), polycyclic aromatic hydrocarbons (PAHs), halogenated hydrocarbons, pesticides etc. These hydrocarbons affect the quality of water and soil by altering quality parameters and thus create pollution.[3]

Hydrocarbon Degradation by Fungi

Fungi have shown potential in the degradation of hydrocarbons, including total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons (PAHs).[4,5]Several fungal strains, such as *Aspergillus niger*, *tubingensis*, *Syncephalastrum* sp., *Paecilomycesformosus*, *Fusarium chlamydosporum*, and *Coniochaeta* sp., have been identified as effective hydrocarbon degraders.[5,6] These fungi have demonstrated high rates of TPH degradation in contaminated soil microcosms, with *Paecilomycesformosus* showing the highest degradation rate of 97%. *Purpureocilliumlilacinum* and *Penicillium chrysogenum* have also been identified as hydrocarbon-degrading fungi, with the ability to biodegrade hydrocarbons in oil sludge. Fungi achieve hydrocarbon degradation through mechanisms such as biosurfactant production and the use of fungal enzymes. Bist et. al., 2019screened twenty fungi for their potential to degrade the Chlorinated organic pesticide endosulfan and chlorpyrifos obtained from soil contaminated with pesticides collected from sal and pine forest, Forest Research Institute, Dehradun. Results showed that all fungi tested degraded a-endosulfan more efficiently than B-endosulfan. Endosulfan sulfate was found to be a major degradation product with all tested fungi.[16]

Biodegradation Mechanisms

Fungi biodegrade hydrocarbons through the production of extracellular enzymes and the involvement of specific metabolic pathways. The degradation process begins with the secretion of enzymes by the fungi, which fragment the hydrocarbon polymers into smaller oligomers.[12]These oligomers can then be taken up by the fungi and metabolized as a carbon and energy source.[13]

The metabolic pathways involved in hydrocarbon degradation vary depending on the type of hydrocarbon and the specific fungal species. For example, in aerobic bacteria, the degradation of chloroacetamide herbicides is initiated by an N/C-dealkylation reaction, followed by aromatic ring hydroxylation and cleavage processes.[14] In the case of polyesters, certain fungi are capable of completely depolymerizing the plastic, enabling the reformulation of the polymer with properties comparable to the virgin polymer.[15]

Kottbet. al., 2019 studied the biodegradation of petroleum hydrocarbons using locally isolated fungi from hydrocarbons polluted area in Suez Bay. Study reveals that fungi have several advantages than other microorganisms in biodegradation because of their ability to cultivate on a large group of substrates. They also produce extracellular enzymes, which can penetrate contaminated soil and remove pollutants. Fungal enzymes have the ability to degrade PAHs are cytochrome P450 monooxygenases, dioxygenases, proteases and lipases. Number of species are reported like *Aspergillus*, *Penicillium*, and *Cunninghamella*, are more efficient in degradation of PAHs.[17]

Overall, the mechanisms of fungal hydrocarbon degradation involve the secretion of enzymes and the subsequent utilization of the hydrocarbon fragments as a carbon and energy source through specific metabolic pathways.

Adaptation of Pyrophilous Fungi

Pyrophilous fungi, known for thriving in burned areas, were tested for their ability to aggregate soil. The study found that three specific pyrophilous fungi (*Geopyxiscarbonaria, Pyronemaomphalodes, and Morchella septimelata*)significantly increased soil aggregation over 40 days, suggesting their role in stabilizing soil after forest fires. This discovery implies that these fungi may reduce soil erosion and enhance soil moisture, crucial factors in early post-fire recovery. Additionally, pyrophilous fungi contribute to decomposition, carbon sequestration, and nitrogen capture.[18]

Hughes et al. 2020 study investigates the impact of a late fall wildfire in 2016 on pyrophilous fungi in the Great Smoky Mountains National Park, documenting their presence over 2 years based on burn severity and phenology. Using Nuc rDNA internal transcribed spacer (ITS) barcodes for confirmation, 41 taxa of Ascomycota and Basidiomycota were identified, with 22 species of Pezizales (Ascomycota) and 19 species of Basidiomycota, including five pyrophilousspecies (*Coprinellus angulatus, Gymnopilusdecipiens, Lyophyllumanthracophilum, Pholiotacarbonicola*, and *Psathyrella pennata*) were considered to be obligate pyrophilous taxa. Fruiting peaked 4–6 months post-fire, with some species continuing to fruit up to 2.5 years later. The study contributes 27 previously unrecorded taxa to the All-Taxa Biodiversity Inventory (ATBI) database, revealing both cosmopolitan and Northern Hemisphere distribution patterns, as well as detecting cryptic endemic lineages in Anthracobia and Sphaerosporella. Additionally, a new combination, *Hygrocybespadicea* var. *spadicea* f. *odora*, is proposed.[19]

Pyrophilous fungi have adapted to environments affected by fire and possess unique characteristics that contribute to their effectiveness in hydrocarbon degradation.[7] Understanding the genetic and physiological adaptations of these fungi in the context of hydrocarbon degradation is an important area of research.[8] These fungi are fire-responsive colonizers of post-fire soil and have historically been found fruiting on burned soil, indicating their ability to process pyrolyzed compounds.[9] Comparative genomic analyses have revealed an enrichment of gene families involved in stress response and the degradation of pyrolyzed organic matter.[10] Additionally, these fungi exhibit adaptations in protein sequence lengths and G+C content, similar to those observed in mesophilic/non-pyrophilous and thermophilic fungi.[11] The study of pyrophilous fungi, their adaptations, and their role in hydrocarbon degradation offers valuable insights into their potential applications in environmental remediation and biotechnology."

Prospective Insights

The use of Pyrophilous fungi for hydrocarbon biodegradation represents a promising, sustainable approach to environmental remediation. Their unique ability to thrive in fire-affected areas and degrade complex hydrocarbons highlights their potential in biotechnological applications. Future research should focus on understanding the genetic and physiological mechanisms of these fungi to optimize their use in hydrocarbon remediation efforts, particularly in resource-limited setting.

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BIOTECHNOLOGY AND GENOMICS IN AGRICULTURE

Ranjana Chauhan[1], Rashami Manaware[2] and Pratibha Yadav[3]

[1]School of Biotechnology, DAVV, Indore, Madhya Pradesh, India
[2, 3]Mata Jijabai Govt. PG Girls College, Indore, Madhya Pradesh, India
Corresponding Email: ranjana.indore83@gmail.com

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Abstract

The world's population is expected to reach over 9 billion people by 2050, which will make it extremely difficult for agricultural experts to meet the rising demand for food. To achieve this need, agricultural production must rise by 60% over 2007 levels. As a result of this change, investments in conventional inputs like pesticides and fertilizers are being replaced by technology-driven solutions, especially genetic changes, which can increase yields while using fewer resources. As governments prepare for a changing climate and expanding populations, food and nutrition security are now important issues in global debates. Meeting the food needs of present generations without sacrificing the potential of future generations to do the same is a major concern in emerging nations. It is crucial to guarantee sufficient crop output in the present and the future. In order to ensure future food supply, creative ways must be pursued, as current agricultural technologies will not be sufficient to meet future output needs. Breeders have worked for years, but traditional methods still have many problems. In this regard, biotechnology is essential to enhancing food, feed, and fuel to sustain the world's growing population. Current limits could be overcome and plant breeding could be much improved in previously unthinkable ways with the help of modern biotechnology and genome editing technologies. Crop genomes can be accurately altered by combining cutting-edge genome editing tools with high-throughput omics technologies (backed by next-generation sequencing). This makes it possible to develop crop types with particular characteristics and increased climate adaptation.

Key words: Biotechnology, genome editing technologies, next-generation sequencing, plant breeding.

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Introduction

Agriculture has undergone a radical change thanks to groundbreaking scientific discoveries like biotechnology and genomics. While genomics focuses on comprehending and modifying an organism's genetic composition, biotechnology exploits biological systems and creatures to create agricultural breakthroughs. These disciplines work together to address urgent global issues like sustainability, climate change, and food security.

Fundamental Concepts

Manipulating living organisms to increase crop yields, strengthen resistance to pests and diseases, and lessen environmental effects is the core of biotechnology in agriculture. Important instruments include CRISPR-Cas9, a precise genome-editing technique that has transformed genetic research, and genetic engineering, which introduces or modifies particular genes to give desired features. The study of an organism's entire genetic makeup, or genomics, has allowed scientists to pinpoint the genes causing particular characteristics, such resilience to illness or drought. The quick identification of these genes and their roles is made possible by cutting-edge genomic technologies like bioinformatics and high-throughput sequencing.

In order to create better crop types, boost their nutritional content, and shield them from biotic and abiotic challenges, genomics is essential. By comprehending the underlying biological mechanisms, crop cultivars can be improved to display desired features through the use of genomics. Application of genomics in crop breeding is vital for improving existing varieties and addressing the increasing demands of a growing world population (Sinha et al., 2023).

The goal of translational genomics is to convert genetic ideas into useful instruments. Translational genomics seeks to improve plant breeding operations with effectiveness, efficiency, and precision by using the vast quantity of genetic information that is already available. Phenotypic selection is the mainstay of traditional breeding techniques, and it requires a lot of time and resources (Choi, 2019). Using omics data and cutting-edge bioinformatics approaches, translational genomics provides an alternate strategy to overcome the shortcomings of traditional breeding programs. The analysis of genetic data has been completely transformed by next-generation sequencing (NGS) technology, which makes it possible to gather extensive omics data and enhances the precision of translational genomics techniques. Single nucleotide polymorphisms (SNPs), conserved orthologous set (COS) markers, cleaved amplified polymorphic sequences (CAPS), insertions/deletions (indels), simple sequence repeats (SSRs), and sequence-characterized amplified regions (SCARs) are among the functional molecular markers that have been made easier to study the genome sequencing (Satam et al., 2023).

Quantitative trait loci (QTLs) governing a range of agronomic variables and stress tolerances have been identified as a result of the use of genetic markers, including as SNPs and ESTs, to create physical and genetic maps. To fulfill the increasing need for food from a fast growing human population, it is essential to incorporate these QTLs into crop development projects employing transgenic technologies or marker-assisted selection/breeding (MAS or MAB). Recent developments in translational genomics and other omics methods used to improve the quantity and quality of crops and plants are the main topic of this chapter. The current methods of gene editing are also covered in this chapter. It examines the use of translational genomics in crop breeding and talks about the methods available for producing huge omics data (Ahmad, 2022).

Integration of genomics with other omics disciplines, such as proteomics (study of proteins), transcriptomics (study of RNA), and metabolomics (study of metabolites), provides a comprehensive understanding of biological systems. This holistic approach enables targeted interventions to improve agricultural productivity and sustainability.

Applications in Crop Improvement

I. Genetically Modified Organisms (GMOs) and Gene-Splicing

Genetically Modified Organisms (GMOs) represent a landmark achievement in biotechnology. By introducing foreign genes into crops, researchers have been able to develop varieties with enhanced resistance to pests, diseases, and environmental stresses. As shown in fig 1.

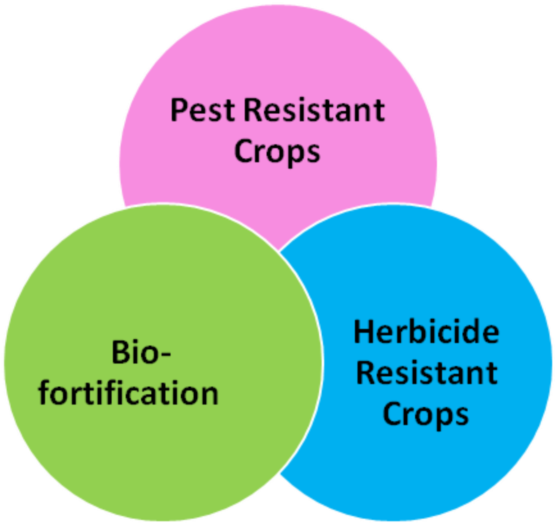

Fig: 1 Applications of GMO's in agriculture

Pest-Resistant-Crops

One of the most successful GMOs is Bt cotton, which incorporates a gene from the bacterium Bacillus thuringiensis (Bt). This gene produces a protein toxic to specific insect pests, such as bollworms, effectively reducing the need for chemical pesticides. Studies show that Bt cotton adoption has led to higher yields, reduced pesticide use, and increased profits for farmers.

Biofortification: Golden Rice

Golden Rice was developed to address vitamin A deficiency, a major health concern in many developing countries. It contains genes responsible for beta-carotene synthesis, enabling the human body to produce vitamin A**.** This innovation has the potential to reduce childhood blindness and mortality rates in vitamin A-deficient populations.

Herbicide-Resistant Crops

GM crops such a**s** glyphosate-resistant soybeans and maize have been engineered to tolerate broad-spectrum herbicides**.** This allows farmers to control weeds effectively without harming the crop, leading to simplified weed management, reduced labor costs, and increased farm productivity.

However, GMOs face criticism related to ecological risks, such as the potential for gene flow to wild relatives, the development of pest resistance, and non-target effects. Public skepticism and stringent regulatory requirements continue to challenge their widespread adoption (Raman, 2017) .Following are the simple steps to make a GMO plant as shown in fig 2.

1. Identifying gene of interest:
2. Cloning the gene of interest (plant transformation and insertion of gene into a transfer vector):
3. Selection of modified plant cells and their regeneration into full plants:
4. Detection of the transformation and identification of the inserted DNA fragment:
5. Performance testing of a plant:
6. Conduct a risk assessment:

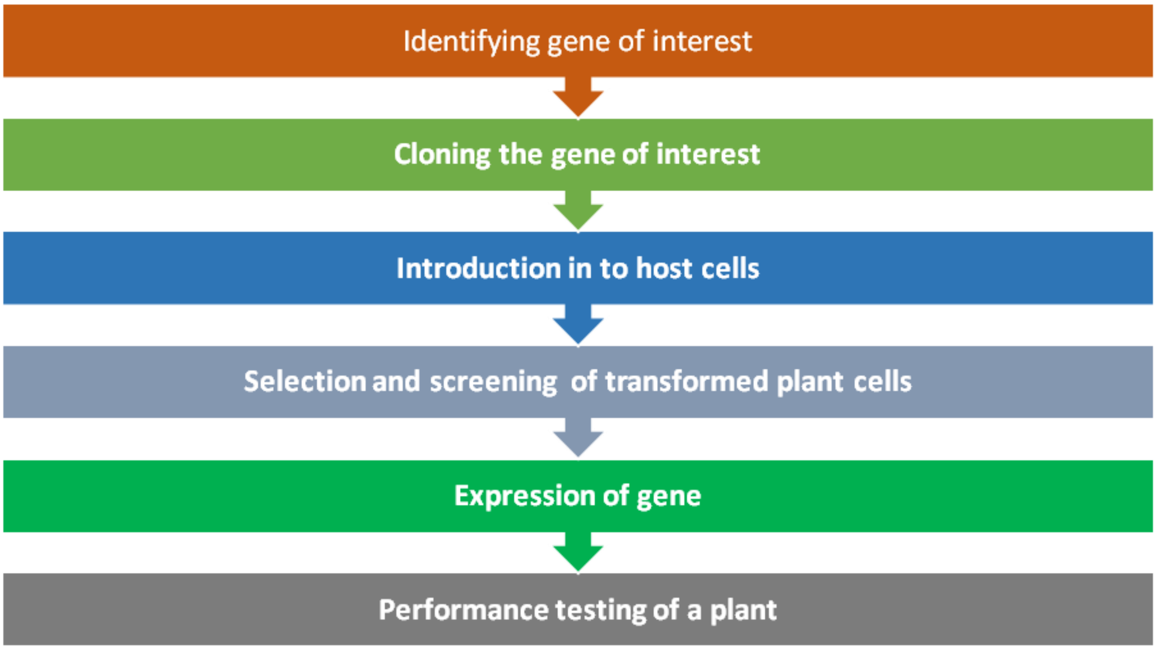

Fig: 2 Steps of GMO plant

A health and environmental risk assessment, as well as a test of the plant's overall performance, are all carried out.

Gene-Splicing and Genetic Modification

Finding, separating, and introducing a gene into a different host organism in order to exhibit a desired characteristic is known as gene-splicing. Three essential areas make up each gene: the coding sequence, which includes the instructions for producing proteins; the terminator, which indicates that transcription has ended; and the promoter, which starts transcription (Rodríguez-Molina., 2023). In order to extract a desired gene and transfer it into the DNA of another creature, genetic engineers employ restriction enzymes to cut particular DNA sequences. The discovery of these enzymes in the 1970s paved the way for the advancement of genetic engineering through the creation of recombinant DNA technology (Loenen., 2014).

The gene needs to be cloned and inserted into a host cell after it has been isolated. Plasmids, which are tiny circular DNA molecules present in bacteria, are commonly used for this. The plasmid is broken up by a restriction enzyme, producing sticky ends that make it easier for the foreign gene to implant. The plasmid is subsequently sealed by another enzyme, ligase, creating recombinant DNA. Plasmids are perfect vectors for transferring and reproducing foreign genes because they naturally move across bacterial cells. The plasmid is replicated by the altered bacterial cells, which also copy their own DNA and the foreign gene. Gene expression, or the effective conversion of DNA into RNA and translation into a useful protein, is the ultimate aim of gene-splicing. By altering their regulatory signals to resemble bacterial genes, higher organism genes—like those encoding insulin or human growth hormone—can be produced in bacteria (Jia.,2024). Similar steps are taken in plant genetic engineering, except a whole plant must be grown from genetically altered cells. The ideal method is protoplast culture, which promotes gene transfer by removing the cell wall before adding foreign DNA. After being altered, the protoplast grows back into a complete plant that may be planted in soil to continue growing (Reed., 2021).

Controlling gene expression, or making sure that genes are only activated in particular tissues or developmental stages, is a major difficulty in genetic engineering. In order to emulate natural processes like photosynthesis activation in leaves but not in roots, scientists are trying to understand gene regulatory elements that allow targeted gene expression. Furthermore, inserting foreign genes could inadvertently alter how existing genes are expressed, resulting in trade-offs including lower crop yields or poorer storage quality. Medicine and agriculture have been transformed by genetic manipulation. The Flavr Savr tomato, the first genetically modified plant, was designed to postpone ripening. Since then, GM crops have helped to improve food security and agricultural production. While GMOs hold promise for disease resistance, enhanced nutrition, and economic benefits, careful evaluation of risks and ethical considerations remains essential for their responsible use in modern agriculture (Raman., 2017).

Genome Editing Tools and Genetic Modification

Genome editing in agriculture involves modifying the DNA of plants and animals to enhance desirable traits such as disease resistance, higher yield, improved nutritional value, and environmental adaptability. Advanced genome-editing tools like CRISPR-Cas9, TALENs, and ZFNs allow precise genetic modifications without introducing foreign DNA, making them more acceptable than traditional GMOs.

CRISPR-Cas9

- Most widely used and efficient genome-editing tool.
- Uses guide RNA (g RNA) to direct the Cas9 enzyme to a specific DNA sequence, where it makes a precise cut. Allows for gene knockout, insertion, or correction with high specificity.
- Used in medicine (gene therapy), agriculture (GM crops), and biotechnology.

Genome editing techniques, especially CRISPR-Cas9, allow for precise gene alterations, they have completely changed crop improvement. In contrast to conventional genetic engineering, which frequently entails adding foreign DNA, genome editing can subtly alter a plant's current DNA to resemble natural mutations.

The most effective and extensively used genome editing technology for plants is the clustered regularly interspaced palindromic repeat (CRISPR)/CRISPR-associated (Cas) protein (CRISPR/Cas). A synthetic single-guide RNA (sgRNA) and the Cas endonuclease work together to guide the Cas protein to a specific genomic DNA (gDNA) sequence, which CRISPR/Cas9 subsequently recognizes and cleaves (Karlson et al., 2021; Hamdan et al., 2022). Cas9, Cas12a, Cas12b, Cas12j (Cas), and Cas12f (CasMINI) are among the several

Cas endonucleases (Alok et al., 2021). DNA cleavage frequently results in insertions or deletions (InDels), which can cause gene knockouts and frameshift mutations. Numerous plant species, including model plants, cereal crops, oil crops, fruits, vegetables, and horticulture plants, have had their genomes edited using CRISPR/Cas9 (Okamoto et al., 2022; Yao et al., 2022). However, there is little genome editing available for vegetables, and radish genome editing has not yet been studied. In this special issue, Muto and Matsumoto modified the GLABRA1 (GL1) orthologs, RsGL1a and RsGL1b, which are known to be involved in the development of leaf trichomes in radish, using a CRISPR/Cas9 system with a sgRNA.

The majority of the mutant alleles were stably inherited in the T1 generation, and the authors discovered that T0 plants had an editing effectiveness of at least 62%. This study demonstrated the possibility of obtaining genome-edited radish that lacks T-DNA (null-segregant) as unique breeding material. This might offer a more successful and economical method of creating new radish varieties with enhanced qualities, which could have a big impact on agriculture and crop improvement. Additionally, it is anticipated that the developed technology will be applicable to other vegetables and traits, such as enhanced nutritional value, resistance to pests and diseases, and tolerance to environmental stresses—all of which are critical in addressing food security and sustainable agriculture in the face of climate change.

In a different work, Cao et al. targeted the RS2 and RS3 genes involved in raffinose synthesis in soybeans using a multiplex CRISPR/Cas9 technique. They demonstrated the superior editing effectiveness of the single transcriptional unit (STU) and two-component transcriptional unit (TCTU) methods with tRNA as the cleavage point. Additionally, Cao et al. successfully induce mutations at RS2 and RS3 using the TCTU-tRNA method, which causes a considerable decrease in raffinose family oligosaccharides and a high level of sucrose in soybeans. According to their research, the multiplex CRISPR/Cas9 method may be a viable means of enhancing the quality of soybeans for monogastric animal and human consumption. The use of CRISPR/Cas technology in maize crops has demonstrated encouraging results. With an emphasis on gene function and creating new germplasm for enhanced yield, specialized corns, plant architecture, stress response, and haploid induction, Wang et al. provide an overview of the present uses and prospects of CRISPR/Cas technology in maize.

TALENs (Transcription Activator-Like Effector Nucleases)

TALENs are genome-editing tools that use engineered proteins to cut DNA at specific locations, allowing for targeted genetic modifications. They consist of two main parts:

- TALEs (Transcription Activator-Like Effectors): These are proteins that recognize specific DNA sequences.
- FokI Nuclease: An enzyme that cuts the DNA at the targeted site once the TALE proteins have bound to it.
- Uses engineered proteins (TALEs) fused with a nuclease (FokI**)** to target specific DNA sequences.
- More precise than CRISPR but requires complex protein design.
- Used in gene therapy and plant biotechnology.

ZFNs (Zinc Finger Nucleases)

- Uses zinc-finger proteins fused with FokI nuclease to recognize and cut specific DNA sequences.

- One of the first genome-editing tools, but less used now due to complexity and off-target effects.
- Applied in gene therapy (e.g., HIV resistance).

Mega nucleases (Homing Endonucleases)

- Naturally occurring enzymes that recognize long DNA sequences (12-40 base pairs).
- High specificity but limited flexibility compared to CRISPR and TALENs.

Prime Editing

- A more precise version of CRISPR that edits DNA without making double-strand breaks.
- Uses a modified Cas9 enzyme fused to a reverse transcriptase, allowing direct base Changes.

Prime Editor Complex

- A Cas9 nickase (a modified Cas9 enzyme that cuts only one DNA strand).
- A Reverse Transcriptase (RT) enzyme, which copies the desired genetic change into the DNA.
- A Prime Editing Guide RNA (pegRNA) that directs the editor to the target sequence and carries the desired edit.

Editing Process

- The pegRNA guides the Cas9 nickase to the target DNA site.
- Instead of cutting both strands (as in CRISPR-Cas9), it makes a single-strand break (a "nick").
- The Reverse Transcriptase copies the corrected DNA sequence into the cell.
- The cell naturally repairs the DNA, incorporating the precise genetic change. Promising for correcting genetic mutations without introducing random errors.

Base Editing

Different types of genomes editing tool as shown in fig 3

- A refined CRISPR technique that directly converts one DNA base to another (e.g., C to T or A to G) without cutting the DNA.
- Reduces unintended mutations and improves accuracy.
- Useful for treating genetic diseases like sickle cell anemia.

Each tool has its strengths and limitations, with CRISPR-Cas9 being the most commonly used due to its ease, efficiency, and cost-effectiveness.

Applications of Genome Editing In Crops Include

- **Disease Resistance**: Researchers have developed disease-resistant varieties by editing genes associated with susceptibility. For instance, CRISPR-edited tomatoes resistant to powdery mildew demonstrate the potential of this technology.
- **Abiotic Stress Tolerance**: Crops edited for enhanced tolerance to drought, salinity, and extreme temperatures are critical for agriculture in the face of climate change. Drought-tolerant rice and heat-resistant wheat are notable examples.

- **Nutritional Enhancement**: Genome editing has been used to increase the nutritional value of crops. For example, biofortified rice varieties with higher iron and zinc levels address micronutrient deficiencies in vulnerable populations.

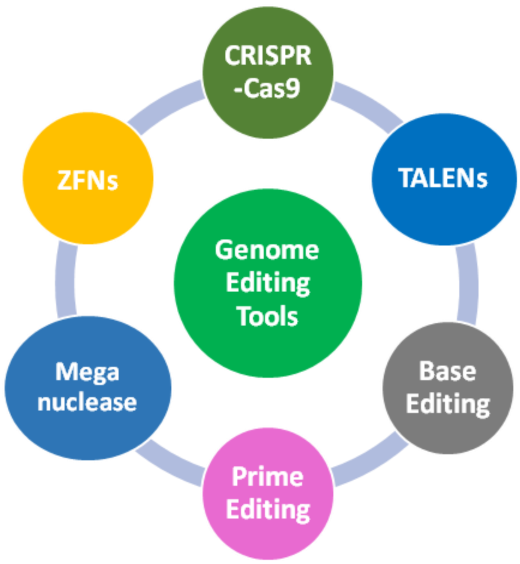

Fig: 3 Different types of Genomes editing tools

- **Yield Improvement**: By modifying genes involved in plant growth and development, researchers have achieved significant yield increases. Genome-edited maize and rice varieties with optimized plant architecture exemplify this approach.

CRISPR-Cas9's precision, efficiency, and cost-effectiveness make it a game-changer in agriculture. Its applications are expanding rapidly, offering solutions to challenges that were previously insurmountable.

Marker-Assisted Selection (MAS)

Marker-Assisted Selection (MAS) combines traditional breeding methods with molecular biology techniques to accelerate the development of improved crop varieties. Breeders can choose plants that possess desired qualities by detecting genetic markers linked to those traits, eliminating the need for lengthy field testing. Through marker-assisted selection (MAS), DNA markers have the potential to significantly improve the accuracy and efficiency of conventional plant breeding. Numerous mapping investigations of quantitative trait loci (QTLs) in different crop species have produced a multitude of relationships between DNA markers and traits. There are five main elements to consider when utilizing DNA markers in MAS: dependability, the amount and quality of DNA needed, the technical technique for marker testing, the level of polymorphism, and cost (Mackill & Ni 2000).Simple sequence repeats (SSRs), sometimes referred to as microsatellites, are the most widely used markers in main cereals (Gupta & Varshney 2000). These markers usually show a high degree of polymorphism, are co-dominant in inheritance, are reasonably simple and affordable to utilize, and are highly dependable (reproducible). Sequence-tagged sites (STS), sequence-characterized amplified regions (SCAR), and single nucleotide polymorphism (SNP) markers are extremely useful for marker-assisted selection (MAS) because they are derived from particular DNA sequences of markers like restriction fragment length polymorphisms (RFLPs) connected to a gene or quantitative trait locus (QTL) (Shan et al., 1999; Sanchez et al., 2000; Sharp et al., 2001).

Key applications of MAS include

- **Disease Resistance**: MAS has been instrumental in developing rice varieties resistant to bacterial blight, a major disease affecting rice production in Asia (Fiyaz et al., 2022).
- **Abiotic Stress Tolerance**: Breeding programs have utilized MAS to develop crops tolerant to drought, salinity, and submergence. For instance, Sub1 rice varieties can survive prolonged flooding, ensuring stable yields in flood-prone regions (Jiang et al., 2020).
- **Quality Improvement**: MAS has enabled the development of crops with improved grain quality, such as aromatic rice and high-oil maize.
- **Yield Enhancement**: By selecting for traits associated with high yields, breeders have achieved significant productivity gains in staple crops like wheat and maize.

MAS is particularly valuable in crops with long breeding cycles, such as fruit trees, where traditional methods are time-consuming and labor-intensive. By reducing the time required to develop new varieties, MAS contributes to the rapid adoption of improved crops.

Micropropagation

Plant tissue culture is a biotechnological technique involving in vitro methods to enhance crop improvement, increase genetic variability, and improve plant health. It plays a crucial role in modern agriculture by facilitating genetic enhancement, pathogen elimination, and large-scale plant production. Tissue culture techniques are available for most crops, though optimization is still needed for cereals and woody plants. When combined with molecular techniques, tissue culture enables gene transfer for incorporating desirable traits.
Protoplast, anther, microspore, ovule, and embryo culture techniques contribute to genetic variation, including haploid production. Somaclonal and gametoclonal variations from cell cultures have significant crop improvement potential. Additionally, single-cell and meristem cultures help eradicate pathogens, enhancing the yield of established cultivars.
A major commercial application of tissue culture is micropropagation, the in vitro clonal propagation of plants from small tissue samples. It surpasses traditional asexual propagation by ensuring rapid multiplication of genetically identical plants. Micropropagation rejuvenates aging cultivars and accelerates the development of new, stress-resistant varieties. Large-scale micropropagation laboratories are essential for commercial ornamental and agricultural crop production. As plant breeding advances, tissue culture technologies are expected to have an increasing impact on global agriculture and food security.

Steps involved in Micropropagation:

Steps involve in micropropagation as shown in Fig 4

- **Explant selection:** Choosing a healthy plant part (like a shoot tip) from the desired parent plant.
- **Surface sterilization:** Disinfecting the explant to eliminate contaminants.
- **Initiation of culture:** Placing the explant on a nutrient-rich agar medium in a controlled environment.

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- **Multiplication phase:** Promoting shoot proliferation by adjusting hormone levels in the medium to produce multiple shoots from the initial explant.
- **Rooting:** Transferring shoots to a different medium to induce root development.
- **Acclimatization:** Gradually adapting the plantlets to outdoor conditions before transplanting to soil.

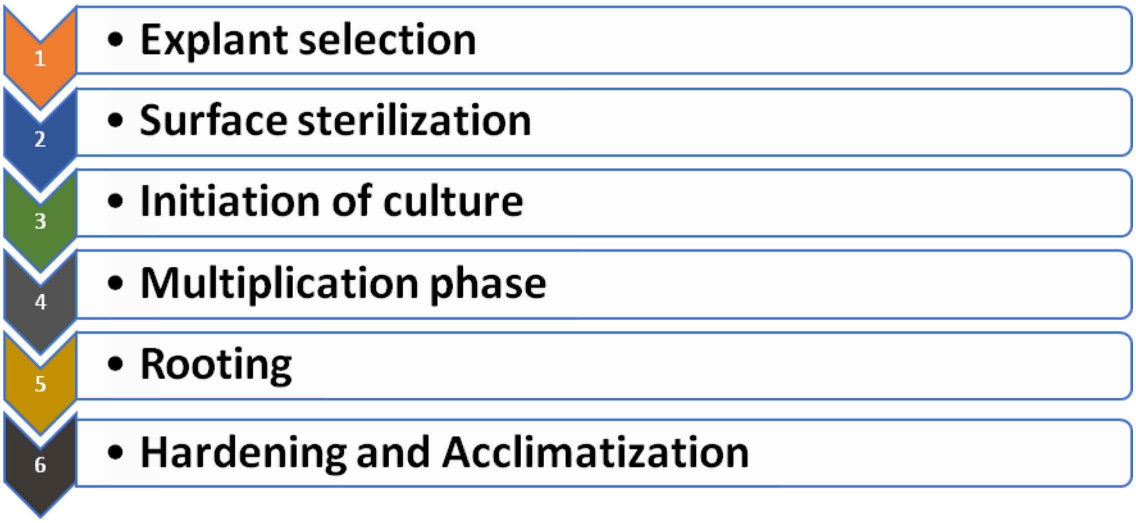

Fig: 4 Steps involved in micropropagation

Synthetic Biology

Synthetic biology applies engineering principles to biology, enabling the design and construction of novel biological systems. In agriculture, synthetic biology holds immense promise for addressing global challenges (Benner and Sismour. 2005).

Applications in crop improvement include:

- **Enhanced Photosynthesis**: Researchers are engineering photosynthetic pathways to increase the efficiency of light capture and carbon fixation. These advancements have the potential to significantly boost crop yields.
- **Nitrogen Fixation**: Synthetic biology aims to engineer crops capable of fixing atmospheric nitrogen, reducing the need for chemical fertilizers. Nitrogen-fixing maize and wheat are under development, offering sustainable solutions for smallholder farmers.
- **Biosynthesis of Secondary Metabolites**: Plants produce a wide range of secondary metabolites with applications in nutrition, medicine, and pest management. Synthetic biology enables the scalable production of these compounds, reducing reliance on chemical inputs.
- **Resistance to Emerging Threats**: Synthetic biology can rapidly respond to emerging pests and diseases by designing new resistance mechanisms. For example, engineered RNA interference (RNAi) pathways provide targeted control of specific insect pests.
- Despite its potential, synthetic biology faces challenges related to public perception, biosafety, and regulatory approval. Addressing these issues is critical for the widespread adoption of synthetic biology in agriculture.

Omics Technologies in Crop Improvement

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, provide a systems-level understanding of plant biology. These tools enable the identification of key genes, pathways, and networks involved in desirable traits (Roychowdhury., 2023).

Applications of omics technologies include:

- **Stress Tolerance**: Transcriptomics has revealed gene expression changes in response to abiotic stresses, guiding the development of resilient crops.
- **Nutritional Enhancement**: Metabolomics has identified pathways involved in the biosynthesis of essential nutrients, enabling the biofortification of crops like rice, maize, and cassava.
- **Disease Resistance**: Proteomics has uncovered proteins involved in plant defense mechanisms, informing the design of disease-resistant varieties.
- **Yield Improvement**: Integrating omics data has enabled the identification of yield-related genes, accelerating breeding programs for staple crops.
- Omics technologies are integral to modern crop improvement, offering insights into complex traits that were previously difficult to study (Tian et al., 2020).

Biotechnology in Sustainable Agriculture

Climate-Resilient Agriculture

Climate change poses significant challenges to agriculture. Biotechnology offers solutions through the development of crops that can withstand extreme weather conditions. For example, drought-tolerant maize varieties developed using genetic engineering ensure stable yields in water-scarce regions (Villalobos., 2022).

Biofertilizers and Biopesticides

Microbial genomics has enabled the development of eco-friendly biofertilizers and biopesticides. These products reduce chemical inputs, improve soil health, and minimize environmental pollution. For instance, nitrogen-fixing bacteria enhance soil fertility naturally, reducing dependence on synthetic fertilizers.

Carbon Sequestration and Soil Health

Biotechnological innovations contribute to carbon sequestration and improved soil health. Engineered microbial communities can capture atmospheric carbon, enhancing soil organic matter and mitigating climate change effects.

Public Perception of Biotechnology

Public acceptance of biotechnology varies widely. While GMOs and genome-edited crops have demonstrated significant benefits, skepticism persists due to concerns about safety, environmental impact, and ethical implications. Transparent communication and robust regulatory frameworks are critical to building trust (Lucht.,2015)

Economic Impacts

Biotechnology has transformed agriculture, benefiting farmers through increased yields and reduced input costs. In developing countries, biotech crops have improved livelihoods by addressing local challenges such as pests and diseases. However, issues such as corporate control over seed patents and high technology costs need to be addressed to ensure equitable benefits.

Ethical Dilemmas

Ethical considerations include the potential loss of biodiversity, unintended ecological effects, and the morality of modifying living organisms. Addressing these concerns requires collaboration among scientists, policymakers, and ethicists to develop responsible practices and regulations.

Conclusion

Biotechnology and genomics have ushered in a new era of agricultural innovation, addressing critical challenges such as food security, climate change, and sustainability. This chapter has explored their fundamental concepts, applications, ethical considerations, and future directions. The path forward requires interdisciplinary collaboration, public engagement, and sound policies to harness these technologies responsibly. By doing so, we can unlock their full potential to create a more resilient, equitable, and sustainable agricultural future.

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MEDICINAL PLANTS AND ETHNOBOTANY: A NEXUS OF TRADITIONAL KNOWLEDGE AND MODERN SCIENCE

Jyoti Birle and Pratibha Yadav

Mata Jijabai Govt. PG Girls College, Indore, Madhya Pradesh, India
Corresponding Email: jyotibirle@gmail.com

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Abstract

Medicinal plants have been utilized in traditional medicine systems for centuries. The information regarding these plants and their application has been passed down from generations. The traditional knowledge is now being coupled with modern science to find new and effective drugs for different diseases. This book chapter will discuss the interface of traditional knowledge and modern science in the realm of medicinal plants and ethnobotany. It will cover the significance of conserving traditional knowledge, the approaches applied to research medicinal plants, and the prospects of finding new drugs from nature. The translation is below. The medicinal plant and ethnobotanical field is an important intersection between traditional knowledge and contemporary science. This intersection offers a link between traditional knowledge and contemporary science, which can be used to create new and innovative methods of healthcare, conservation, and sustainable development. In this research, we examined the traditional knowledge and utilization of medicinal plants and tried to comprehend its connection with contemporary science. We discovered that there is a strong link between traditional knowledge and modern science, which can be used to create new and innovative methods for healthcare and conservation. The findings of this research can be used to create new and innovative methods for healthcare, conservation, and sustainable development.

Keywords: Medicinal plants, Ethnobotany, Traditional knowledge, Modern science Healthcare, Conservation, Sustainable development

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Introduction

Man has relied on plants from ancient times and the early human society understood the different uses of plants. We learn about the indestructible bond between man and plants largely from common traditions. Ethnobotany has gained much attention not historically or scholastically but because of its economic potential. It is largely concerned with different aspects of botany, history, anthropology, culture and literature. The activities performed by the tribals residing in various regions of the globe on drugs derived from the plants of their native land and the information gathered from forestry and travels are of great value to ethnobotany.

Medical plants have been used in human welfare from ancient times to treat all forms of diseases (Fabricent., and Pharnasvarth, (2001). Practical knowledge of medical plants, which is being practiced through theories, is the foundation of ethnography, which is the study of the association between people and special practical (Martin 2010).

Ethnobotany acts as a crucial bridge between folk medicine and scientific medicine offering significant insights into the effectiveness of plants for the identification of new claims and treatments. (Cox and Balick, 1994). Scientific documentation and validation of traditional medicinal plant uses help maintain indigenous science of medicinal agents and lead to the discovery of new therapeutic agents (Kala, 2005).

Ethnobotany and Traditional Knowledge

Ethnobotany refers to the research on how various cultures utilize plants for medicine, food, rituals, and other uses. Harshberger (1895) coined the term ethnobotany and defined it as the scientific investigation of the interaction between plants and native people. His focus was on the need to record plant knowledge prior to its loss as a result of cultural and environmental shifts (Harshberger, 1895).Robbins, Harrington, and Freire-Marreco (1916) made a contribution to ethnobotany through research on the use of plants among Native Americans, focusing on Pueblo societies in the United States. In their work, they recorded traditional plant medicines, foods, and rituals, pointing to the strong relationship between native knowledge and ecological sustainability.

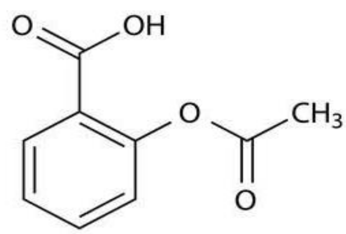
Traditional knowledge often passed through the generation, plays a crucial role in biodiversity conservation and sustainable resource management (Berkes 2018)

Ethnobotany refers to the science of the interactions between humans and plants, specifically how various cultures utilize and manage plant resources for medicine, food, rituals, and other uses (Balick & Cox, 2020). It entails comprehending the indigenous and local communities' traditional knowledge about plant species and their uses in everyday life. Traditional knowledge, usually transmitted from one generation to the next, is important in biodiversity conservation and sustainable resource management (Berkes, 2018). Traditional knowledge assists in the identification of edible plants, their nutritional quality, and ecologically sound harvesting methods (Kuhnlein & Receveur, 2020).Some plants are culturally significant, with their use in religious rituals, ceremonies, and traditional medicine (Posey, 1999). Indigenous plant biodiversity knowledge has played a critical role in ensuring sustainable land use and management of ecosystems (Gadgil et al., 1993).Although crucial, traditional knowledge is threatened by globalization, deforestation, and loss of culture. Preservation and recording this knowledge is essential in maintaining biodiversity and honoring the intellectual property rights of indigenous communities (Posey, 1996).

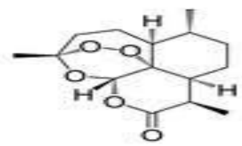
Medicinal Plants: A Treasure Trove of Natural Remedies

The prevalent theme in ethnobotanical literature. Medicinal plants have long been utilized in traditional medicine systems worldwide across cultures, forming the foundation for numerous contemporary pharmaceuticals. Ethnobotanical research has detailed the extensive medicinal properties of plants, highlighting their use in alleviating different diseases as well as promoting health (Balick & Cox, 2020).

Aspirin (Salicylic Acid) was isolated from Salix (willow) bark, a traditional medicine to relieve pain (Samuelsson, 2004).Quinine, a drug used against malaria, was isolated from Cinchona tree bark, a traditional medicine in use by ancient South Americans (Cowan, 2019).Artemisinin, derived from Artemisia annua, is an essential malaria treatment and was used in traditional Chinese medicine (Tu, 2016).



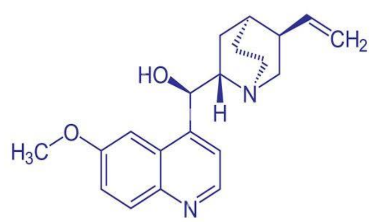
Acetylsalicylic acid



Artemisinin

$C_{15}H_{22}O_5$

Quinine



Ethnobotany's Contribution to Modern Medicine

Ethnobotanical research assists in the identification of bioactive constituents of plants. Most contemporary medications are derived from substances that were initially identified in traditional medicine and afterward researched using science (Heinrich et al., 2009).Ethnobotany, which is the analysis of how indigenous cultures utilize plants, has provided great contributions towards modern medicine. Some of them include:

It is from the plants that indigenous cultures first used and discovered that many modern medicines are derived from. For instance, the bark of the willow tree has been utilized by Native Americans for centuries to treat fever and pain. This contributed to the identification of aspirin, which is among the most commonly consumed drugs globally (Struwe et al., 2018).

Ethnobotanical knowledge may offer insights into the aetiology and therapy of diseases. For instance, traditional Chinese medicine has been practiced for centuries in treating various conditions, and a number of these treatments have been found to be effective when tested in clinical trials (Li et al., 2017). Ethnobotany also has the potential for the creation of new therapies. For instance, scientists are exploring the use of ayahuasca, an Amazonian traditional medicine, to treat depression and anxiety (Palasz et al., 2019). Digitalis This medication for heart failure was first obtained from the foxglove plant, which Welsh doctors in the 18th century utilized (Aronson, 2010). Taxol This pharmaceutical, utilized as an anticancer agent, initially came from the Pacific yew tree, where it was exploited by North America's native peoples (Suffness, 2002).Morphine (Papaver somniferum) – An opium poppy alkaloid employed as a potent analgesic in contemporary medicine (Brownstein, 1993).

Conservation and Ethical Considerations

Ethnobotany is the study of the interactions between humans and plants, which makes conservation and ethics critical to the protection of both biodiversity and traditional knowledge. Sustainable use guarantees that medicinal and culturally important plants are preserved for future generations without violating indigenous and local communities' intellectual property rights. Ethnobotanical research assists in the identification of plant species threatened by habitat loss, over-exploitation, and climate change (Gadgil et al., 1993). Conservation efforts involve:

In situ conservation: Conservation of plants in their natural habitats, e.g., through national parks and community-managed forests (Hamilton, 2004).

Ex situ conservation: Protecting plant species away from their natural environments in botanical gardens, seed banks, and research facilities (Heywood & Iriondo, 2003).Traditional ecological knowledge (TEK) possessed by indigenous people usually involves sustainable land-use practices that promote conservation. Combination of TEK with contemporary conservation science maintains ecological equilibrium (Berkes,2018).One of the significant ethical dilemmas in ethnobotany is biopiracy, where companies or researchers sell traditional knowledge without rewarding indigenous people (Shiva, 1997). Ethical principles involve:

The Nagoya Protocol (2011): Facilitates equitable and just sharing of benefits derived from genetic resources (CBD, 2011). Prior Informed Consent (PIC): Researchers need to get direct consent from indigenous communities prior to recording their knowledge (Alexiades, 1996).

Conclusion

This chapter has examined the intriguing crossroads of ancient knowledge and contemporary science in the world of medicinal plants and ethnobotany. We have witnessed how indigenous societies have a treasure trove of information regarding the medicinal qualities of plants, information that has been handed down through generations. This ancient knowledge, usually closely linked to cultural practices and beliefs, has been a rich source of information for contemporary science. Through the examination of plants that are traditionally used in medicine, researchers have been able to isolate and identify active ingredients with therapeutic potential for the treatment of various diseases. This has resulted in the creation of new drugs and treatments, which have greatly contributed to contemporary healthcare. It is, however, important to recognize that this process should be done with respect for indigenous cultures and their intellectual property rights. In the future, joint work between ethnobotanists, scientists, and local communities is needed. This will not only help to conserve traditional knowledge but also lead to the identification of new medicinal plants and the creation of sustainable methods for their use. By bridging the gap between traditional knowledge and contemporary science, we can realize the full potential of medicinal plants for the good of all.

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EMPOWERING HILL AGRICULTURE: THE IMPACT OF INTEGRATED FARMING SYSTEMS ON SUSTAINABLE LIVELIHOODS

Ankit Sati[1], R.S Negi[1], J. S. Butola[2], Santosh Singh[1] and, Nabdeep Singh*

[1]Department of Rural Technology, School of Agriculture & Allied Science, H.N.B Garhwal University (Central University) Srinagar, Uttarakhand- 246174, India
[2]Department of Forestry & Natural Resources, School of Agriculture & Allied Science, H.N.B Garhwal University (Central University) Srinagar, Uttarakhand- 246174, India
Correspondence E-mail: ankitsatihnbgu@gmail.com

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Abstract

Hill farming in Uttarakhand faces a myriad of challenges, including fragmented landholdings, low productivity, and ecological constraints. The Integrated Farming System (IFS) offers a sustainable approach to address these challenges by combining various agricultural enterprises to optimize resource use and enhance income. This article explores the potential of the IFS in transforming the hill farming landscape of Uttarakhand. It emphasizes the system's economic, environmental, and social benefits while highlighting case studies and best practices. The article also delves into the policy framework, research gaps, and future prospects for scaling up the IFS in the region.

Key Words: Hill Farming, Uttarakhand, Integrated Farming System (IFS), Sustainability, Agricultural Transformation

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Introduction

The Indian Himalayan Region (IHR), including Uttarakhand, is characterized by fragile ecosystems and unique socio-economic conditions (Joshi et al., 2020). Agriculture in these areas often struggles with low yields, soil erosion, and a lack of market connectivity. The IFS, an approach integrating crops, livestock, fisheries, agroforestry, and other components, provides a holistic solution to these challenges (Altieri, 2009). This system not only enhances productivity but also ensures environmental sustainability and food security (Singh & Pande, 2019).

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Key Elements of Hill Farming System in Uttarakhand

Uttarakhand's hill farming systems are very different from plains agriculture because of the state's distinct physiography, climate, and socioeconomic circumstances. Small landholdings (average size 0.67 hectares) and terrace farming on steep slopes are characteristics of the mostly subsistence-oriented agriculture found in the hills (Govt. of Uttarakhand, 2022). 75% of the water available during the summer cropping season comes from rainfall, but insufficient soil and water conservation practices cause a large amount of water to be lost through runoff (ICAR, 2020). Cereals (wheat, rice, and maize), pulses, oilseeds, fruits, vegetables, and medicinal herbs are all grown in this area. Notwithstanding these benefits, the system has a number of drawbacks, such as inadequate infrastructure, erratic weather patterns, and farming population out-migration. The article's primary goal is to evaluate the difficulties and seize the opportunities in the hill areas of Uttarakhand.

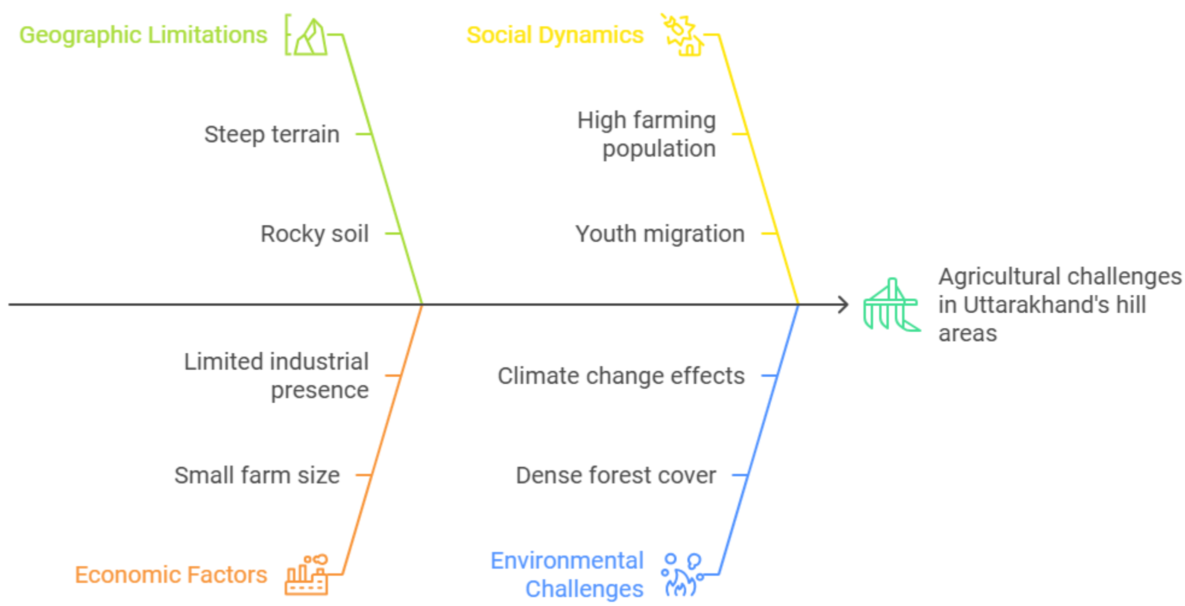

Fig.1: Key Challenges in the Hill Farming System of Uttarakhand

Concept and Components of Integrated Farming System

Integrated Farming Systems (IFS) represent a holistic approach to agriculture, aiming to enhance productivity, sustainability, and economic viability by integrating various agricultural components. The core principle of IFS is the recycling of resources within the farm ecosystem, which not only optimizes resource use but also minimizes waste. This system is particularly beneficial for small and marginal farmers, as it increases income and employment opportunities while ensuring environmental sustainability. The following sections detail the key components of IFS.

- **Crop-Livestock Integration**: Combines crop cultivation with livestock rearing to utilize by-products efficiently such as manure for fertilization and crop residues as animal feed. (Kumar & Gupta, 2021). Enhances soil quality and nutrient cycling, reducing the need for external inputs and promoting economic viability(Castagnara et al., 2024) (Shanmugam et al., 2024).

- **Agroforestry**: Incorporates trees and shrubs into agricultural landscapes for soil conservation and additional income through timber and non-timber products. (Sharma et al., 2018). Enhances biodiversity and ecological balance within the farm ecosystem. (M. et al., 2024).

- **Horticulture**: Promotes fruit and vegetable cultivation for nutritional and economic benefits (Government of Uttarakhand, 2022). Can be integrated with other components like livestock and aquaculture to maximize resource use and income(Singh et al., 2024) (Shanmugam et al., 2024).

- **Aquaculture**: Integrates fish farming in water-scarce areas using farm ponds to enhance water use efficiency and diversify income sources. (Das et al., 2018). Provides a sustainable protein source, contributing to food security (Singh et al., 2024).

- **Renewable Energy**: Utilizes biogas and solar energy for farm operations reducing reliance on fossil fuels and lowering greenhouse gas emissions. (Mohanty et al., 2019). Converts agricultural and animal waste into energy, further promoting resource recycling (Singh et al., 2024).

While IFS offers numerous benefits, challenges such as the complexity of managing diverse components and the need for knowledge exchange among stakeholders must be addressed. Encouraging initiatives that support systemic approaches and innovation can help overcome these barriers, fostering broader adoption and sustainability transitions in agriculture (Moojen et al., 2024).

Significance of IFS in Hill Farming

- **Economic Benefits:** The IFS enhances farmers' incomes by diversifying sources of revenue. For instance, integrating livestock with crop farming ensures year-round income through dairy or poultry products (Das & Mishra, 2017).

- **Environmental Sustainability:** By emphasizing resource recycling and agroforestry, the IFS minimizes external inputs, reduces carbon footprints, and prevents soil degradation (Singh et al., 2020).

- **Social Impact:** The system promotes inclusive development by engaging small and marginal farmers. Women's participation in horticulture and animal husbandry activities further strengthens rural livelihoods (Kumar & Singh, 2022).

Table 1: Economic Impact of Integrated Farming System

Parameter	Conventional Farming	IFS Adopters	Source
Annual Income/HH	₹70,000–₹1,00,000	₹1,50,000–₹2,50,000	Uttarakhand Agri Dept. Survey (2022)
Employment (Days)	150–200 days/year	300–350 days/year	NABARD Report (2021)
Crop Yield	Wheat: 1.8–2.2 t/ha	Wheat + Legumes: 2.5–3 t/ha	ICAR Study (2020)

Challenges in Hill Farming of Uttarakhand

Hill farming in Uttarakhand is fraught with challenges such as:

- **Fragmented Landholdings**: Make mechanization and large-scale farming difficult (NBSS&LUP, 2019). Approximately 50% of landholdings are sub-marginal, with many measuring less than 1 hectare (Rana et al., 2019).The fragmented nature of land makes it challenging to adopt mechanization, limiting productivity and efficiency (Dahal et al., 2022).

- **Poor Infrastructure**: Lack of road connectivity and market linkages limits farmers' access to inputs and markets (World Bank, 2021). Inadequate road networks restrict farmers' access to markets and essential inputs, exacerbating economic challenges (Mukherjee et al., 2020).

- **Climate Vulnerability**: Erratic weather patterns and reduced snowfall threaten traditional cropping systems (Yadav & Singh, 2020). These climatic changes adversely affect agricultural productivity, making it difficult for farmers to sustain their livelihoods (Dahal et al., 2022).

- **Youth Migration**: The exodus of youth to urban areas leaves farming to aging populations (Gupta & Kumar, 2018).The migration of youth in search of better opportunities leaves an aging population to manage farms, which can lead to a decline in agricultural practices. Many families are diversifying their income sources, often at the expense of traditional farming, which further diminishes agricultural viability (Naudiyal et al., 2019).

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Table 2: Challenges & Current Data Gaps

Challenge	Data Status
Land Fragmentation	78% of farms are <1 hectare (Census 2015–16); no recent micro-level data.
Water Scarcity	60% of farms rely on rainfed irrigation; only 12% have access to micro-irrigation.
Wildlife Conflict	40% of farmers report crop damage (monkeys, boars); no compensation data post-2020.
Market Linkages	<20% of IFS farmers are linked to FPOs/cooperatives (State Agri Dept., 2023).

Implementation of IFS in Uttarakhand: Case Studies

Case Study 1: Crop-Livestock Integration in Chamoli District

The success story of Devendra Singh Negi, a farmer from Nauli Village, Chamoli District, Uttarakhand, who has significantly transformed his agricultural practices through an integrated farming approach. From a modest background, Devendra adopted modern agricultural techniques and diversified his farm to include crops and animal husbandry. His interventions in organic farming, playhouses, and water-efficient irrigation systems have earned him local and national recognition, resulting in annual earnings exceeding ₹3 lakh. This case study highlights the role of integrated farming in achieving sustainable agriculture in hilly regions and its potential to inspire other rural farmers. His story highlights the potential of integrated farming in rural, hilly regions where agriculture can be challenging. By adopting sustainable practices, he has become an inspiration for his village and beyond, demonstrating that innovation, dedication, and community involvement can lead to both economic success and social upliftment. His journey serves as a model for other farmers seeking sustainable and profitable farming methods. Devendra's contributions to agriculture have

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been recognized at both the local and national levels. He has received numerous awards, including the Kisan Bhushan Award, Kisan Shree Award, and others for his leadership in organic farming. In 2012, he had the opportunity to train at the prestigious Indian Agricultural Research Institute (Pusa Institute), further refining his skills and knowledge in agriculture.

Fig. 2: Integrated Farm of Devendra Singh Negi in Village- Nauli, Chamoli Garhwal Uttarakhand

Case Study 2: Integrated Farming Model of Alam Singh Negi: A Success Story from Peri Village, Chamoli District

Alam Singh Negi, a progressive farmer from Peri village in the Ghat block of Chamoli district, Uttarakhand, has established a thriving integrated farming system that serves as a model for sustainable agriculture in hill regions. Negi's compact and efficient farming model integrates diverse components, including a kiwi orchard, a well-maintained mushroom cultivation unit, medicinal crops such as Kutki (*Picrorhiza kurroa*), Kuth (*Saussurea costus*), and Dolu (*Rheum australe*), alongside seasonal vegetables like cabbage, cauliflower, and peas.

Recognizing the potential of his innovative approach, the Chamoli Horticulture Department provided him with financial and technical support to establish a fully operational mushroom unit. This integration has not only maximized the productivity and profitability of his smallholding but also exemplifies the benefits of a holistic approach to farming in the challenging terrain of Uttarakhand.

Negi's success story underscores the viability of integrated farming systems in enhancing rural livelihoods while conserving natural resources. His model is a testament to how diversification and resource optimization can lead to self-

Fig 3: Integrated Farm of Alam Singh Negi in Village- Peri, Ghat Block, Uttarakhand

reliance and inspire other hill farmers to adopt sustainable practices. This case study highlights the critical role of local support systems in scaling innovative farming practices for regional development.

Policy Support and Institutional Framework

The integration of policy support and institutional frameworks is crucial for the effective implementation of Integrated Farming Systems (IFS) in India to promote sustainable agricultural practices and enhance farmers' livelihoods.

- **MGNREGA and Watershed Development Programs**: Provide financial and infrastructural support for implementing IFS components (Ministry of Agriculture and Farmers Welfare, 2021). Watershed programs have shown varying success, often dependent on community participation and effective leadership (Mishra & Kalra, 2021).

- **State Horticulture Mission**: Promotes diversification into high-value crops (Government of Uttarakhand, 2022). This mission encourages diversification into high-value crops, which can significantly increase farmers' incomes and improve resource management (Joshi et al., 2004). By focusing on high-value crops, the mission aims to enhance the economic viability of farming in diverse agro-climatic zones (Gandhi, 2010)

- **Kisan Credit Card Scheme**: The scheme enhances credit access for small and marginal farmers, enabling them to invest in IFS and improve productivity. (Kovalenko & Ulez'ko, 2024). Facilitates credit access for small and marginal farmers (Jain & Tiwari, 2019).

Table 3: Government Schemes & Progress (2023–24)

Scheme	Target	Funds Allocated	Achievement
PKVY	Promote organic IFS clusters	₹12 crore (2023–24)	150 clusters established; 3,000 farmers trained.
State Horticulture Mission (SHM)	Boosts horticulture (fruits, medicinal plants) in IFS.	₹6.8 crore	850 ha new orchards (apple, peach), 2,000 farmers trained.
PM-KISAN	Income support for IFS farmers	₹6,000/yr/farmer	85% coverage in Garhwal (pending verification).
RKVY-RAFTAAR	Infrastructure for IFS	₹8.5 crore (2023–24)	45 vermicompost units and 20 polyhouses were built.
Uttarakhand Organic Commodity Board	Certifies and markets organic products from IFS.	₹3.2 crore	Certified 1,200+ farmers for turmeric, rajma, and honey.

MGNREGA	Develops rural infrastructure (ponds, trenches, terraces) for IFS support.	₹25 crore (State share)	12,000 water conservation structures, 500 ha terraced farming.
Kisan Credit Card (KCC)	Provides low-interest credit for IFS components (livestock, horticulture).	₹200 crore (state disbursement)	18,000+ KCCs issued; 45% utilized for dairy/poultry units.

Research and Development Needs

- **Technology Development**: Focus on high-yielding, climate-resilient crop varieties (Pant & Sharma, 2022).There is a pressing need for the development of climate-resilient crops that can withstand extreme weather and variable conditions, which is essential for maintaining productivity under climate stress (Langridge et al., 2021)(Mani, 2023).

- **Capacity Building**: Implementing comprehensive training for farmers in Integrated Farming Systems (IFS) is vital. Extension services can leverage innovative technologies to improve resource use and productivity. Establishing regulatory frameworks and financial incentives can enhance the effectiveness of training programs and promote sustainable practices (Ananda et al., 2024).

- **Market Development**: Strengthen supply chains and establish farmer-producer organizations (FPOs) (Tripathi et al., 2021).Encouraging cross-disciplinary research and international collaboration can facilitate knowledge exchange and technology transfer, further supporting market development (Ananda et al., 2024).

Conclusion and Future Directions

The Integrated Farming System presents a transformative opportunity for hill farming in Uttarakhand. By addressing ecological, economic, and social challenges, it paves the way for sustainable development. Scaling up this model requires concerted efforts from policymakers, researchers, and farming communities (ICAR, 2022). Integrated Farming Systems (IFS) offer a sustainable solution to the challenges of hill agriculture in Uttarakhand, enhancing resource efficiency, income, and ecological balance. Success stories like Alam Singh Negi's highlight the potential of integrating horticulture, medicinal crops, mushroom cultivation, and vegetables. Future directions include capacity building, market linkages, financial incentives, research on climate-resilient crops, and community-based models. Emphasis on branding, water management, and policy support can further scale IFS adoption. By fostering innovation and collaboration, IFS can transform hill farming into a resilient, profitable, and sustainable practice, ensuring food security and improved livelihoods for farmers in the region.

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PRESERVING INDIGENOUS KNOWLEDGE SYSTEMS IN HILL FARMING: SUSTAINABLE PRACTICES IN THE HIMALAYAN REGION

Rohit Kumar[1] *and Seema Kumari*[2*]

[1]Faculty of Agriculture, Baba Raghav Das Post Graduation College, Deoria, Affiliated to Deen Dayal Upadhyay Gorakhpur University, Gorakhpur, Uttar Pradesh- 274001, India
[2]Institute of Agriculture and Natural Science, Deen Dayal Upadhyay Gorakhpur University, Gorakhpur, Uttar Pradesh- 273001, India
Corresponding E-mail: seemakumari302gkp@gmail.com

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Abstract

The Indigenous Knowledge System (IKS) in hill farming across the Himalayan region represents a legacy of sustainable agricultural practices developed over centuries. These traditional systems, deeply embedded in local culture and biodiversity conservation, employ methods such as crop rotation, polyculture, and agroforestry to enhance ecological resilience. However, modern socio-economic challenges—including urban migration, land-use changes, and climate shifts—threaten the preservation of these knowledge systems. This paper explores the historical context, cultural significance, and environmental impact of indigenous farming techniques, while also highlighting the threats posed by globalization and industrial agriculture. Through collaborative research and policy support, the integration of indigenous knowledge with contemporary agricultural practices presents a viable path toward sustainable food security and ecological preservation. Recognizing and revitalizing these traditional knowledge systems is essential for sustaining biodiversity, cultural identity, and climate resilience in the Himalayan region.

Keywords: Indigenous Knowledge Systems (IKS), Hill Farming, Himalayan Agriculture, Traditional Farming Practices, Sustainable Agriculture, Agroforestry, Biodiversity Conservation

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Introduction

The Indigenous Knowledge System in hill farming in the Himalayan region represents a rich tapestry of traditional agricultural practices developed over centuries by local communities. These systems are characterized by a profound understanding of biodiversity and sustainable farming techniques, which are intricately tied to the socio-cultural identities of the indigenous populations. As these communities face increasing pressures from socio-economic changes, such as urban migration, market shifts towards cash crops, and environmental challenges including climate change, the significance of their indigenous knowledge has become increasingly vital for maintaining ecological resilience and food security in the region. Notably, indigenous farmers have employed methods such as crop rotation, polyculture, and agroforestry, which not only enhance agricultural productivity but also foster biodiversity and mitigate environmental degradation. Rituals and cultural practices, like the Limbu community's ChasokTangnam festival, highlight the spiritual and ethical dimensions of their farming systems, reinforcing a deep-seated commitment to sustainable practices that honor ancestral traditions and natural cycles. However, the erosion of these knowledge systems due to external influences—such as globalization, deforestation, and the imposition of modern agricultural techniques—poses significant risks to both food sovereignty and cultural heritage among these communities. Controversially, the imposition of policies that favor industrial agriculture and land acquisition for non-agricultural uses threatens to undermine the effectiveness of traditional knowledge systems, leading to biodiversity loss and socio-economic instability. Efforts to revitalize indigenous practices through collaborative research, educational outreach, and recognition of the rights of Indigenous peoples are crucial for sustaining these traditional agricultural systems. By integrating indigenous knowledge with contemporary agricultural practices, there is potential not only for enhancing resilience to climate change but also for preserving the cultural identities and ecological heritage of Himalayan communities. In summary, the Indigenous Knowledge System in hill farming in the Himalayan region serves as a critical framework for sustainable agriculture that is deeply embedded in local culture and ecological stewardship. As these communities navigate contemporary challenges, the recognition and revitalization of their traditional knowledge systems will be essential for ensuring food security, ecological integrity, and cultural continuity in the face of rapid change.

Historical Context

Traditional Pastoral Practices

The historical backdrop of hill farming in the Himalayan region is deeply intertwined with traditional pastoral practices, which have evolved over centuries. During the time of historical monarchs, documentation regarding pasture use was likely initiated, reflecting the socio-political landscape of the era [1]. High-altitude pastoral communities in South Asia have long been reliant on these practices, which have shaped their resource management and agricultural strategies.

Socio-Economic Changes

In recent decades, however, these traditional practices have faced significant challenges due to various socio-economic changes. Factors such as increasing access to education, the migration of younger generations to urban areas, and the cultivation of cash crops have all contributed to a decline in traditional pastoral livelihoods and knowledge systems [2] [3]. Research indicates that communities in the Indian western Himalaya are shifting away from time-honored resource management systems, leading to intensified resource use and a growing dependence on immigrant labor for livestock management [3].

Cultural Heritage and Festivals

The cultural practices surrounding agriculture in the Himalayan region are rich with historical significance. For instance, the Limbu community celebrates the ChasokTangnam festival, rooted in the ancient Nwagi ritual, which honors deities and ancestors by offering newly harvested crops before consumption [4]. Such rituals reveal the deep connections between agricultural practices, community identity, and spiritual beliefs, illustrating how historical customs continue to influence contemporary farming and cultural expressions.

Biodiversity and Indigenous Knowledge

The farming systems developed by indigenous communities in the Himalayas are characterized by a profound understanding of biodiversity and sustainable practices. Historical adaptation to the region's diverse ecosystems has enabled indigenous farmers to maintain high agro-biodiversity, including the preservation of numerous landraces of local crops. For example, the Apatani tribe is known for cultivating 106 species of plants, highlighting the intricate relationship between historical agricultural practices and the preservation of local biodiversity [5].

Environmental Challenges

The historical context of hill farming also includes the impact of environmental challenges. Indigenous communities have historically demonstrated resilience in the face of climate change, employing various adaptive techniques such as drought-tolerant crop varieties and polyculture [6]. However, contemporary pressures such as deforestation and land degradation pose significant threats to these traditional agricultural systems, necessitating a reevaluation of both historical and modern practices to ensure sustainability and cultural preservation.

Characteristics of Indigenous Knowledge Systems

Biodiversity and Sustainable Practices

Indigenous knowledge systems in hill farming, particularly in the Himalayan region, are fundamentally rooted in the principles of biodiversity and sustainable agriculture. These systems have evolved through centuries of interaction between local communities and their environment, showcasing a rich diversity of crops and farming techniques that contribute to ecological resilience. Indigenous farmers often practice methods such as crop rotation and polyculture, which not only enhance soil health but also support a myriad of species, leading to robust ecosystems.[7]. For example, in the Himalayas, integrated farming systems that combine crops with livestock allow for resource recycling, significantly enhancing soil fertility and ensuring the sustainability of agricultural practices. [7] [8].

Ethical Stewardship and Cultural Heritage

The essence of indigenous agriculture is characterized by ethical stewardship and a profound respect for natural cycles. Local farmers possess deep historical knowledge that guides their adaptation of crops and farming techniques to challenging environments, ensuring the preservation of both biodiversity and cultural heritage. [7]. The Andean practice of terracing illustrates this, as it prevents soil erosion and conserves water while maintaining agricultural productivity in steep terrains. [7] [9].

Framework for Rights and Recognition

A crucial element in sustaining indigenous agricultural practices is the recognition of the rights of Indigenous peoples. Frameworks like the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) emphasize the importance of preserving traditional agricultural knowledge, political, and cultural institutions. Such frameworks affirm the significance of indigenous ways of life and their intrinsic connection to the land, which underpins their farming systems. [7] [10].

Educational Outreach and Collaborative Research

Engaging in educational outreach is vital for the wider dissemination and recognition of indigenous agricultural knowledge. This involves integrating indigenous perspectives into educational curricula and fostering collaborations between indigenous communities and academic institutions. Such partnerships not only enhance the understanding of traditional practices but also contribute to modern agricultural science, promoting a mutually beneficial learning process. [7] [10].

Threats and Challenges

Despite their importance, indigenous agricultural systems face significant threats from modern agricultural practices, deforestation, and land degradation. The loss of biodiversity and traditional practices poses challenges to the sustainability of these systems. Addressing these threats requires a comprehensive understanding of the socio-economic dynamics affecting these communities and the implementation of policies that support their rights and preserve their cultural heritage.[7] [6] [3].

Indigenous Knowledge and Hill Farming

Indigenous knowledge systems play a crucial role in the sustainability of hill farming practices in the Himalayan region. Farmers in these areas have developed a profound understanding of their environment through generations of experience, which informs their agricultural techniques and resource management strategies.

Ecological and Cultural Foundations

Integration of Indigenous Practices

The integration of indigenous agricultural practices into modern farming systems offers a sustainable approach to agriculture that respects local traditions while enhancing productivity. The application of traditional knowledge—such as pest management using plant extracts from neem, chili, and tobacco—demonstrates the potential of indigenous methods in addressing contemporary agricultural challenges. [5]

These practices not only improve agricultural yields but also contribute to ecological integrity and resilience against environmental stressors.

Cultural Significance

The cultural foundations of these indigenous practices underscore their importance beyond mere agricultural productivity. These systems are rooted in the cultural identity of the communities, embodying a holistic relationship with nature and the land. The knowledge passed down through generations encompasses not only technical aspects of farming but also ethical considerations regarding environmental stewardship. [7]

Key Traditional Practices

Traditional Agricultural Techniques

Indigenous communities in the Himalayan region employ a variety of traditional farming techniques that reflect their deep connection to the environment. These practices include crop rotation, polyculture, and agroforestry, which are essential for maintaining soil fertility and promoting biodiversity. Crop rotation helps to prevent soil depletion, while polyculture allows farmers to grow multiple crop species in the same area, reducing the risk of pest outbreaks and decreasing the reliance on artificial inputs [7] [4].

Cultural and Spiritual Dimensions

The agricultural practices of indigenous communities are intricately tied to their cultural and spiritual beliefs. For example, the Limbu people celebrate rituals such as ChasokTangnam, which emphasizes a sacred relationship with the earth. This ceremony incorporates offerings made from harvested crops to express gratitude to nature and ancestral spirits, reinforcing the community's commitment to sustainable agricultural practices [4]. Such rituals foster a sense of identity and community cohesion, as knowledge about farming techniques is passed down through generations.

Ethical Practices and Community Engagement

Ethics play a crucial role in the agricultural practices of these communities. Indigenous farmers engage in reciprocal relationships with the land, treating it with respect and care in exchange for sustenance. This ethical framework encourages sustainable practices such as organic farming and local agro-biodiversity maintenance, which are critical for climate resilience [5]. Collaborative research initiatives that document and synthesize indigenous practices with modern agricultural science can lead to improved productivity while preserving ecological balance [7] [8].

Innovations and Adaptations

Indigenous farmers have also adapted their practices to meet contemporary challenges. In regions like the Himalayas, innovative approaches have been implemented to

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enhance the cultivation of traditional crops, such as legumes, which are vital for both nutrition and economic stability [11].The empowerment of women through technical training and leadership development has been identified as a key strategy to bolster agricultural success and community resilience [11] [8].

Case Studies and Local Knowledge

Examining specific case studies, such as the diversification of cultivation in West Bengal, illustrates how local knowledge informs farming practices and systems. Farmers engage in mixed cropping and value-added production to improve their economic conditions while ensuring sustainability [8]. The knowledge gained through participant observation and interviews highlight the significance of adapting farming systems to local climatic conditions and community needs.

Case Studies

Traditional Farming Techniques in the Himalayas

Indigenous farmers in the Himalayan region have developed a range of traditional farming techniques uniquely suited to their challenging environments. One notable method is the use of terracing, which maximizes arable land on steep slopes and minimizes soil erosion. This practice not only enhances agricultural productivity but also preserves the integrity of the fragile mountain ecosystems [7] [5]. Additionally, farmers engage in crop rotation and polyculture, which foster biodiversity and help mitigate pest outbreaks without relying on artificial inputs. These techniques are integral to maintaining soil fertility and sustaining food security in the face of climate variability [7] [5].

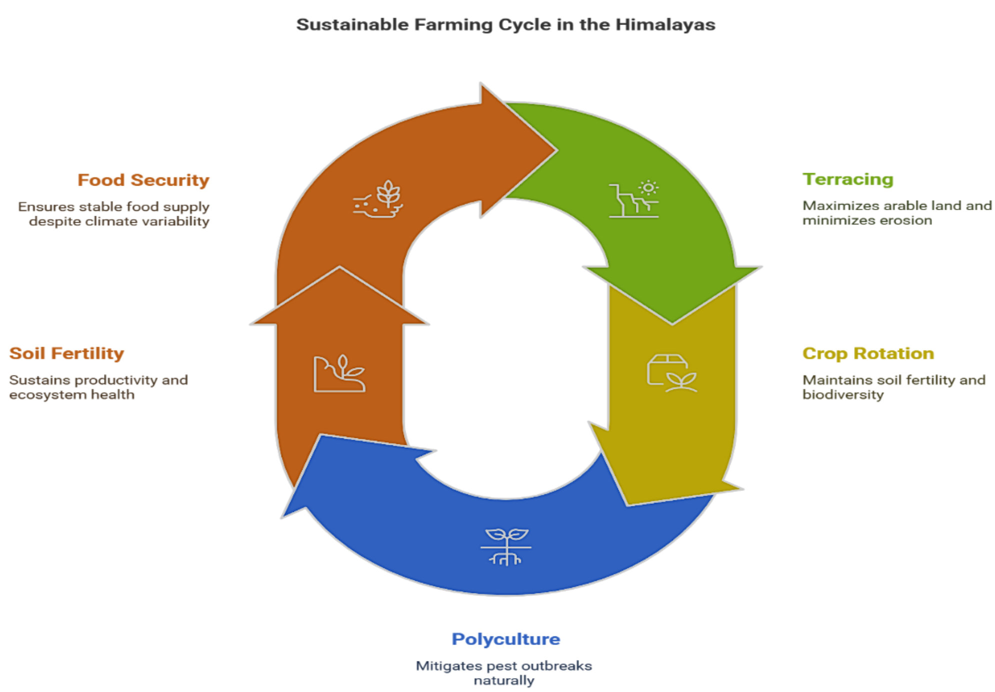

Fig. 1: Sustainable farming cycle in Himalayas

Insights from Andean Agriculture

In the Andean highlands, indigenous communities have implemented innovative agricultural practices that provide valuable lessons for sustainable farming. The Incas, for example, utilized sophisticated irrigation systems and terraces, which are still in use today. These practices reflect a profound understanding of local ecosystems and highlight the cultural heritage embedded in agricultural methods [7] [12]. Case studies from the Andes demonstrate the success of inter-cropping and polyculture, where multiple crop species are cultivated together to enhance resilience against climate impacts and pests, serving as models for integrating Indigenous knowledge into broader agricultural frameworks [12] [5].

Collaborative Research and Knowledge Integration

Collaboration between indigenous communities and researchers has yielded fruitful outcomes in documenting and synthesizing traditional agricultural practices. This approach has revealed the importance of indigenous knowledge in modern agricultural contexts, particularly in the development of sustainable farming strategies. For instance, integrating traditional soil fertility management techniques has shown promise in improving productivity while maintaining ecological balance [7] [12].

Partnerships among indigenous farmers, academic institutions, and policymakers are vital for recognizing and incorporating these insights into contemporary agricultural development initiatives, thereby fostering respect and understanding of diverse agricultural practices across cultures [8] [5].

Addressing Climate Change Adaptation

Indigenous farmers have a long history of adapting their agricultural practices to changing climatic conditions. By employing drought-tolerant local varieties, practicing agroforestry, and utilizing water harvesting techniques, they effectively mitigate the risks associated with climate-driven crop failures [5]. Case studies illustrate how these adaptive strategies are grounded in a deep understanding of local ecosystems and are passed down through generations, showcasing the resilience of indigenous agricultural systems in the face of environmental challenges [7] [5].

Socio-Economic Challenges

The socio-economic landscape of hill farming in the Himalayan region is marked by several significant challenges that impact agricultural practices and the livelihoods of local communities. A notable decline in the number of cooperatives, poor seed replacement rates, and stagnant irrigation capacities contribute to a stagnation in agricultural growth, while a shifting agricultural land base poses long-term threats to sustainability [12]. Additionally, the existing marketing systems are often inefficient and disorganized, depriving farmers of the benefits they should receive through various marketing channels [12].

Influence of Socio-Economic Status

Socio-economic status (SES) is a critical determinant of access to resources, livelihood patterns, and food security within these communities. It encompasses a combination of economic and social position, which can predict various psychological and behavioral components such as knowledge, attitude, perception, and risk-bearing ability [13]. A study conducted in Bhagar Tola and Maniagar villages of Dhauladevi block in Almora district highlighted the correlation between SES and the adoption of improved farming practices intended to enhance yields and ensure sustainable livelihoods [13]. The socio-economic factors influencing these farmers included age, education, occupation, social participation, and landholding size [13].

Changing Aspirations and Labor Dynamics

The younger generation's shift towards lucrative job opportunities, such as government employment and cash crop cultivation, has led to a labor shortage in traditional livestock herding practices [1]. This shift in priorities is compounded by the arrival of immigrant labor, who may lack the traditional ecological knowledge (TEK) necessary for effective livestock management, thus affecting the continuity of pastoral practices [1]. Studies have shown that socio-economic changes, including education access and the emigration of local youth to urban areas, negatively impact the livelihoods and traditional knowledge systems of pastoral communities in high-altitude regions [1].

Impact of External Factors

The interplay of tourism and agriculture also presents challenges. While tourism has increased income for some urban populations, it has also disrupted traditional farming practices, leading to the cultivation of cash crops that demand high inputs of chemicals and water [6]. This transformation affects the local economy and diminishes self-reliance in food production, as many pastoralists shift away from age-old farming methods [6]. Furthermore, the area has witnessed a significant increase in land designated for non-agricultural use, which has implications for land availability and agricultural productivity [6].

Land Tenure and Resource Management

Issues related to land tenure further complicate the socio-economic challenges faced by hill farmers. Land acquisition often occurs through customary rights, leading to disputes and fragmentation that can hinder effective agroforestry practices [14]. The Pnar community's reliance on forest land for cultivation and the absence of secure land tenure exacerbate vulnerabilities, particularly for women who may have limited access to land resources [14]. Although policies such as the National Agroforestry Policy aim to provide support for sustainable land management practices, the lack of incentives for indigenous agroforestry products remains a barrier to achieving economic stability in these communities [14].

Climate Resilience and Food Security

The intersection of climate resilience and food security is critical in the Himalayan region, particularly for indigenous farming communities who face unique challenges due to climate change. Traditional agricultural landscapes function as linked social-ecological systems (SESs), where resilience is characterized by the capacity to absorb shocks, self-organize, and learn and adapt to changing conditions [5]. Agriculture in this region, heavily influenced by climate patterns, is particularly sensitive to the impacts of climate change, which poses significant threats to global food security, notably through declining food production and rising prices [5] [12]. Food security is intricately connected to the socio-economic status of communities and directly influences human health and sustainable development [12]. In the Himalayas, local agricultural productivity is essential for ensuring food security, as it affects the purchasing power of communities. Major constraints to food security include fragmented agricultural land, low soil fertility, and inadequate infrastructure, which can exacerbate the challenges posed by climate change [12] [15]. The shifts in temperature and rainfall patterns have rendered food production increasingly difficult, necessitating adaptive strategies to sustain agricultural practices and local food systems [15]. Indigenous knowledge plays a crucial role in developing climate-smart agriculture (CSA) techniques that enhance resilience to climatic shocks. These practices encourage sustainable agriculture while increasing the adaptive capacity of communities [5] [16]. Indigenous farmers have historically relied on their extensive knowledge of local ecosystems to manage biodiversity, which is vital for maintaining the health of crops and the environment. For instance, traditional crop varieties are better suited to withstand the changing climate and can provide food security amidst adverse conditions [15] [7]. Incorporating indigenous weather forecasting methods with modern science can improve early warning systems and enhance community preparedness for extreme weather events. Moreover, engaging local communities in agro-biodiversity management ensures that conservation efforts are effective and culturally relevant [17] [16]. The integration of these indigenous practices into broader agricultural policies is essential for promoting resilience and securing food production in the face of climate change, ultimately safeguarding the livelihoods of millions in the Himalayan region [5] [12] [16]. Thus, fostering climate resilience through the recognition and application of indigenous knowledge not only enhances food security but also supports the sustainability of the diverse ecosystems found in the Himalayas, enabling these communities to thrive despite the challenges posed by a changing climate.

Conservation and Revitalization Efforts

Importance of Indigenous Knowledge in Agriculture

Indigenous farming practices in the Himalayan region, particularly in areas like Darjeeling and Sikkim, have developed over generations and play a critical role in conserving natural resources. These practices involve sustainable management of land, water, and vegetation, which are essential for maintaining soil fertility and minimizing erosion. The integration of ecological management with modern agricultural techniques, alongside traditional knowledge, is crucial for enhancing agricultural productivity while safeguarding the environment [8] [18].

Community Engagement in Conservation

Efforts to conserve agro-biodiversity must involve local communities in the management of their resources. This includes participatory plant breeding and advocacy for the rights of smallholders, which are vital for recognizing the unique identities of local landraces within commodity supply chains [17]. Engaging Indigenous communities ensures that conservation strategies are culturally relevant and more likely to succeed, as they leverage local knowledge and practices that have stood the test of time.

Policies Supporting Conservation Efforts

Various national policies, such as the National Forest Policy of 1988 and the Forest Rights Act of 2006, provide frameworks for the conservation of forests and biodiversity in the Himalayan region. These policies aim to restore forested landscapes and acknowledge secure land tenure as critical for effective conservation strategies [14]. Indigenous practices, such as Piper agroforestry, highlight the importance of traditional knowledge in achieving successful land restoration and biodiversity conservation, especially where governmental efforts may fall short.

Challenges and Recommendations

Despite these efforts, indigenous agricultural systems face significant threats, including deforestation and land degradation, which undermine environmental sustainability and cultural heritage. To counter these challenges, future studies should encompass a broader geographic area to capture the rich tapestry of indigenous knowledge across different communities[9]. Furthermore, exploring incentive mechanisms, such as REDD+ and payment for ecosystem services, could provide financial benefits to indigenous populations while promoting conservation efforts [14].

Resilience and Adaptation Strategies

Indigenous communities demonstrate resilience in the face of climate change through adaptive practices tailored to local environmental conditions. For instance, the Mising community in Assam has developed strategies to cope with frequent flooding, while the Kadar tribe in Kerala practices sustainable forest management [16]. Integrating Indigenous knowledge with modern technologies, including agritech data analytics, can optimize agricultural practices, reduce environmental impact, and support the livelihoods of farming communities in the Himalayas [6].

Educational Initiatives

Promoting educational outreach that incorporates indigenous agricultural knowledge into curricula can foster mutual learning between indigenous and non-indigenous communities. This approach not only reinforces the significance of traditional practices but also counters cultural assimilation, ensuring that these invaluable knowledge systems continue to thrive [7]. Strengthening partnerships among indigenous communities, researchers, and policymakers is essential for the systematic integration of traditional knowledge into broader agricultural and conservation frameworks.

Conclusion

Indigenous knowledge systems in Himalayan hill farming serve as a crucial framework for ecological sustainability, food security, and cultural preservation. The resilience of these farming methods lies in their deep-rooted understanding of biodiversity and environmental stewardship. However, contemporary challenges such as urbanization, deforestation, and shifting economic priorities threaten these traditional practices. The erosion of indigenous agricultural wisdom can lead to biodiversity loss, weakened climate resilience, and socio-economic instability among local communities. Thus, safeguarding these practices requires a multidimensional approach that includes policy reforms, community-driven conservation initiatives, and integration with modern agricultural techniques. By fostering educational outreach and collaborative research, we can ensure that the invaluable knowledge of Himalayan farmers continues to thrive in a rapidly changing world. Preserving these systems is not only vital for the sustainability of the region but also for global agricultural and environmental resilience.

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