

Agriculture in a Changing Climate: Challenges, Technologies, and Sustainable Solutions

Edited by

Dr. Tanmoy Sarkar, Dr. Purba Goswami, Mr. Sk Hasibul
Alam, Mr. Avimanyu Palit, Dr. Sudip Sengupta



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- Dr. Tanmoy Sarkar**
- Dr. Purba Goswami**
- Mr. Sk Hasibul Alam**
- Mr. Avimanyu Palit**
- Dr. Sudip Sengupta**

Preface

The accelerating pace of climate change presents an unprecedented challenge to global agriculture, demanding innovative, sustainable, and science-driven responses. Agriculture is both a victim and a contributor to climate change — it suffers from erratic rainfall, rising temperatures, and soil degradation while also contributing significantly to greenhouse gas emissions. As humanity faces the dual imperative of feeding a growing population and protecting the planet, agricultural systems must adapt, transform, and evolve toward resilience and sustainability.

This book, *“Agriculture in a Changing Climate: Challenges, Technologies, and Sustainable Solutions,”* brings together diverse research perspectives on how climate change interacts with agricultural systems and how emerging technologies, management practices, and policy interventions can offer sustainable pathways forward. The chapters address critical themes including carbon sequestration, food waste reduction, soil contamination, groundwater depletion, and innovative monitoring technologies. Together, they provide an integrated understanding of the scientific, environmental, and socio-economic dimensions of sustainable agriculture in the 21st century.

The contributions in this volume are authored by experts and researchers committed to advancing agricultural sustainability through innovation and collaboration. Their insights underscore the importance of interdisciplinary approaches—where agronomy, environmental science, technology, and policy intersect to shape a climate-resilient future.

This book aims to serve as a valuable resource for students, researchers, policymakers, and practitioners seeking to understand and address the complex relationship between climate change and agriculture. It is our hope that it inspires

further research, innovation, and action toward creating a more resilient and sustainable agricultural landscape for future generations.

Dr. Tanmoy Sarkar

Dr. Purba Goswami

Mr. Sk Hasibul Alam

Mr. Avimanyu Palit

Dr. Sudip Sengupta

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Carbon sequestration and its impact on agriculture

Abhinaba Samanta¹ and Ria Mukhopadhyay^{1*}

¹Department of Agriculture, Swami Vivekananda University,
Barrackpore, West Bengal

*Corresponding author email id: riam@svu.ac.in

Abstract:

Carbon sequestration, the process of capturing and storing atmospheric carbon dioxide (CO₂), has emerged as a critical strategy to mitigate climate change and its effects on agriculture. Soils, forests, and other ecosystems act as natural carbon sinks, holding vast potential for offsetting greenhouse gas emissions. In agriculture, carbon sequestration not only contributes to climate resilience but also enhances soil health, productivity, and sustainability.

Adopting practices like conservation tillage, agroforestry, cover cropping, and organic farming increases carbon storage in soils while improving water retention, nutrient cycling, and biodiversity. Additionally, integrating biochar and compost can further enhance soil organic carbon levels. These practices not only mitigate the negative effects of climate change, such as droughts and extreme weather events but also provide co-benefits like improved crop yields and reduced reliance on chemical inputs.

However, challenges remain, including the long-term stability of sequestered carbon, the economic feasibility for farmers, and the need for supportive policies. Advanced technologies, such as precision agriculture and remote sensing, can aid in monitoring carbon sequestration and ensuring sustainable implementation.

This paper explores the potential of carbon sequestration in transforming agriculture into a climate-positive industry while emphasizing the need for interdisciplinary collaboration among scientists, policymakers, and farmers.

Keywords: carbon dioxide, sequestration

1. Introduction

Rising atmospheric CO₂ is driving climate change; agriculture both emits GHGs and holds potential as a carbon sink. Carbon sequestration – the removal and durable storage of CO₂ in plants, soils or geological formations – helps limit climate warming. Two broad forms exist: natural (biological/terrestrial) sequestration via ecosystems (forests, grasslands, soils, oceans) and **engineered (artificial/technological)** sequestration (carbon capture technologies and land-use changes (Hogan et al.2024). In agricultural contexts, practices like cover cropping, agroforestry and no-till can boost soil organic carbon (SOC), partially offsetting emissions. Agricultural carbon sinks were long overlooked in climate policy, but recent studies highlight their large mitigation potential, especially in the Global South. For example, improved carbon management on farmland could sequester *up to 2.8 gigatonnes CO₂-eq per year by 2050* globally, reducing mitigation costs and even raising GDP through agricultural revenues. To realize these benefits, we must understand the types of sequestration, context-specific practices (e.g. in India), co-benefits, and the constraints on scaling them. Agriculture occupies a larger portion of global land area (about 35%) than any other human activity. Because of its scale and intensity, agriculture emits a large quantity of greenhouse gases into the atmosphere (Hutchinson, Campbell, Desjardins., et al. 2007). In India, agricultural land constitutes approximately 51.09% of the total geographical area. This translates to roughly 178.53 million hectares, or about 1,785,279 square kilometers.

Types of Carbon sequestration

Biological (Terrestrial) Carbon Sequestration: This encompasses carbon stored in living systems – plants, forests, grasslands, and soils – and is largely part of the natural carbon cycle(Lelechenko et al, 2024). For example, forests and wetlands act as vast carbon reservoirs; trees absorb CO₂ via photosynthesis and lock it in wood and roots, while soil microbes incorporate plant residues into SOC (Lelechenko et al, 2024). Terrestrial sequestration typically means using

photosynthesis (land plants) to draw down CO₂, storing organic carbon in biomass and soil. This differs from geological methods that inject human-emitted CO₂ underground.

Geological Carbon Sequestration: Involves capturing CO₂ (often from industrial or power-plant emissions) and injecting it deep underground into rock formations or depleted reservoirs. CO₂ is pressurized and pumped into porous rock (saline aquifers, old oil wells, unmineable coal seams, basalt) where it is trapped by physical and chemical processes. This form is potentially permanent (thousands of years) but requires engineered infrastructure and monitoring to prevent leakage.

Technological (Artificial) Carbon Sequestration: Refers to engineered methods to remove CO₂ from the atmosphere or emissions stream. Examples include direct air capture (DAC) (machines that chemically scrub CO₂ from ambient air and store it geologically), bioenergy with carbon capture and storage (BECCS) (growing biomass for energy and capturing the CO₂ produced), biochar (pyrolyzing biomass to stable charcoal added to soils), and other novel processes (e.g. electrochemical methods, engineered minerals) (Lelechenko et al, 2024). Technological methods are distinct from biological/land methods; they require high energy and investment but can potentially achieve “negative emissions” even from hard-to-abate sectors (Lelechenko et al. 2024).

Natural vs. Artificial Sequestration: Natural sequestration relies on ecosystems and the carbon cycle: e.g., forest regrowth, soil organic matter accumulation, and ocean uptake. Artificial (engineered) sequestration uses human-designed interventions: CO₂ capture systems, land use changes, or chemical enhancements (Lelechenko et al, 2024). Natural sinks are often cost-free but reversible (vulnerable to disturbance); artificial methods can be made permanent but are currently costly. In practice, many mitigation strategies combine both: e.g., agroforestry (natural vegetation) implemented as a deliberate climate measure (Nath et al. 2021), or biochar application (a technological product) to agricultural soil.

Carbon Sequestration in Agriculture: Importance and Practices in India

Agriculture is responsible for ~ 12 GtCO₂e/yr of global emissions, yet it also harbors large soil carbon reserves. India, with its vast farming population, stands to gain multiple benefits from soil and biomass carbon enhancement. Expanding carbon sinks in agriculture can help India meet its climate goals. For instance, modeling suggests that modest expansions of agroforestry on croplands could significantly offset India's projected emissions by 2050 (Nath et al. 2021). India's Nationally Determined Contributions (NDCs) call for additional carbon sinks from afforestation; incorporating agricultural practices like agroforestry directly supports these targets. Recognizing this, India launched a National Agroforestry Policy (2014) to boost tree cover in farming landscapes, aiming to meet timber, food, and fuel needs while creating carbon sinks. Large rural programs like MGNREGS (rural employment/land development) have built carbon sinks through soil and water conservation activities: one study estimated MGNREGS sequestered 102 MtCO₂ in 2017–18, rising to 249 MtCO₂ by 2030 (Murthy et al. 2021). Thus, agricultural carbon sequestration is increasingly seen as a climate–development strategy in India

Effective Agricultural Practices (India): Numerous farming practices can sequester carbon:

Conservation Agriculture (CA): No-till or reduced tillage, along with crop residue retention and crop rotation, preserve and build SOC (Kaur et al. 2023). Trials in the Indo-Gangetic Plains show that CA (zero-till, permanent beds) significantly increases soil carbon over time and also raises crop yields (Mishra et al., 2018). By minimizing soil disturbance and keeping organic matter on the field, CA is a key practice for Indian farmers.

Agroforestry: Integrating trees with crops (or livestock) vastly increases carbon stocks in biomass and soil. For example, agrosilvopastoral systems (crops+trees+livestock) in India's humid zones can capture far more carbon than conventional cropping (Nath, A.J. et al. 2021). Experts estimate that

expanding agroforestry area by just 5% every five years could offset India's projected 2050 emissions (Nath et al. 2021). In practice, alley cropping, farm shelterbelts, and multi-story cropping (e.g., coconut+pepper+banana) all sequester carbon while providing fruits, fodder and fuel.

Cover Crops and Crop Rotations: Sowing legumes or grasses in fallow periods adds root biomass and protects soil, boosting SOC. Rotations including pulses (mungbean, cowpea) increase below-ground carbon inputs and soil nitrogen. On Indian farms, adding cover legumes has improved yields and soil C in long-term trials (Hooper et al., 2005; Parihar et al., 2018).

Crop Residue Management: Avoiding burning and instead incorporating or mulching crop residues is crucial. Burning of rice/stubble is common in North India and leads to immediate carbon loss; conversely, retaining residues recycles carbon and nutrients. Along with improved nutrient management (balanced fertilization and organic amendments), this maintains SOC.

Organic Soil Amendments: Use of farmyard manure, compost, and biochar (charcoal from agricultural waste) enriches SOC and fertility. Biochar, in particular, is being studied in India as a way to lock stable carbon in soils (Rogelj, J. et al., 2018). Manure recycling also contributes a significant carbon sink in cropland.

Permanent Grasses and Pasture Improvement: In rangelands and orchard lands, maintaining vegetative cover year-round stores carbon. Sowing deep-rooted perennial grasses or improving grazing lands (by legume understory or rotational grazing) has been shown globally to sequester carbon (Rogelj, J. et al., 2018). In India, enriching common grazing lands or village pastures could similarly raise carbon stocks and fodder. (Nath et al. 2021)

Afforestation on Degraded Land: Planting trees on fallow or degraded fields (e.g. watershed plantations) builds biomass carbon. Even if not on prime cropland, such afforestation (e.g. under MGNREGS "drought proofing") provides carbon sinks and restores soil health. Over 2019–2025, India's MGNREGS

drought-proofing (tree planting) is projected to create an additional 281–561 MtCO₂ sink (Murthy et al. 2021).

These practices not only sequester carbon but also improve soil water retention, fertility, and farm incomes, creating co-benefits for farmers (Kaur et al. 2023)(Murthy et al. 2021). In the next section we detail the multiple co-benefits observed from agricultural carbon sequestration.

Co-benefits of Carbon Sequestration in Agriculture

Enhancing carbon in agricultural systems yields multiple side benefits beyond climate mitigation:

Improved Crop Yields and Food Security: Rising SOC generally improves soil fertility, water holding capacity and nutrient availability, directly boosting yields. For example, a world-wide analysis found that each 1 Mg/ha increase in SOC can increase cereal yields by tens of kg/ha (20–70 kg/ha wheat, 10–50 kg/ha rice, etc.), potentially adding tens of millions of tonnes of grain. Indian studies similarly report higher yields under no-till and residue management (Mishra et al., 2018). Thus, soil carbon gains support food production and incomes.

Soil Health and Fertility: Higher SOC improves soil structure and aggregation, reducing erosion and compaction. Improved soil moisture retention helps crops resist drought. Experts note that healthy soils enriched with organic carbon act like a sponge and “fertilizer”, reducing the need for synthetic inputs. Indeed, agroforestry and cover cropping enhance soil nutrients (via leaf litter and nitrogen fixation) and biological activity (Ravindranath, Murthy et al. 2021) (Ganeshamurthy and Srinivasarao, 2009; Hazra et al., 2018).

Livelihood and Economic Benefits: Carbon projects can provide income to farmers. Global modeling suggests that sequestration on cropland could generate up to \$375 billion in payments for carbon credits by mid-century (Frank, et al. 2024). In India, voluntary carbon markets are emerging for practices like agroforestry and rice-residue management (Chaudhary et al., 2020). Moreover, many carbon-enhancing practices (e.g. mulching, composting) often improve yields and reduce input costs, so farmers gain indirectly.

Ecosystem Services: Agroforestry and cover crops increase biodiversity (more habitat for birds, insects, microbes) and can reduce pest pressures. Vegetative cover prevents soil erosion and nutrient runoff, benefiting water bodies. Studies highlight that agroforestry provides habitat connectivity and reduces land degradation (Nath et al. 2021). In India's ecologically fragile areas, tree-based systems also support water infiltration and preserve topsoil.

Climate Resilience: Carbon-rich soils moderate temperature extremes and buffer against heavy rains or droughts. Vegetation (trees and perennial grasses) provides shade and windbreaks. Collectively, these co-benefits mean that carbon sequestration in agriculture often aligns with sustainable development goals, improving farm resilience and community well-being.

In summary, carbon-sequestering practices are often “no-regrets” from a farm perspective: they enhance productivity, soils, and livelihoods while also capturing CO₂ (Nath et al. 2021).

Mitigation Techniques via Carbon Sequestration

To harness carbon sequestration, a suite of mitigation techniques is employed:

Afforestation and Reforestation: Planting trees on non-forest land (afforestation) or replanting deforested areas (reforestation) creates large biomass carbon sinks. Although not strictly an “agricultural” practice, programs that convert marginal croplands or degraded lands into forests (e.g. shelterbelt plantations) provide carbon and ecosystem co-benefits. (However, care is needed: planted forests must be maintained for decades to be effective, as younger stands can be vulnerable to fire or harvest.

Agroforestry and Silvopasture: Integrating trees with crops/livestock sequester carbon in multiple pools. Silvopasture systems (trees in pasture) are included here. Techniques include alley cropping, windbreaks, fodder banks, and improved grazing. As noted, India's agroforestry has huge potential)(Nath,A.J. et al. 2021).

Conservation Tillage and Residue Management: No-till and strip-till systems leave crop residues on the surface, protecting soil carbon. Retaining or incorporating residues (rather than burning) increases SOC over time. Conservation agriculture is widely promoted in India for this reason (Mishra et al., 2018).

Cover Cropping and Crop Rotations: Growing legumes or grasses in the off-season adds organic matter to soil. Rotations with deep-rooted or high-residue crops (e.g. legumes, oilseeds, fodder cereals) improve carbon inputs. For example, adding mungbean or cowpea to rotations significantly raises SOC (Mishra et al., 2018).

Organic Amendments: Application of manure, compost or biochar (pyrolyzed organic waste) builds stable carbon in soil. Biochar is especially potent: studies show biochar can sequester carbon on decadal timescales while improving soil fertility (Frank, S., et al. 2024).

Grassland and Pasture Management: Improving grazing lands (reseed with mixed grasses, manage stocking rates) increases soil carbon. Maintaining perennial cover on grasslands stores more carbon than converting them to crops.

Blue Carbon (Wetland Restoration): Though less directly agricultural, restoring rice terraces, mangroves, and freshwater wetlands in farming landscapes can lock carbon in soils and biomass. (Coastal mangroves and paddy fields hold substantial “blue carbon”.)

Technology-Based CCS on Farms: Techniques like direct air capture (DAC) or industrial CO₂ capture are generally not farm-level practices but could complement decarbonization. For example, using crop residue bioenergy with CCS (BECCS) would remove CO₂. These are emerging and currently expensive.

Together, these mitigation techniques aim to increase carbon inputs or decrease carbon losses in soils and vegetation. By combining multiple practices (e.g. agroforestry + conservation tillage + residue retention), agricultural landscapes can become net carbon sinks while also improving productivity.

Factors Affecting Carbon Sequestration

Several factors influence how much carbon can be sequestered and how stable it is:

Land Management: Tillage intensity is critical. Frequent plowing accelerates soil organic matter breakdown and CO₂ release; conversely, no-till promotes accumulation (KAUR, R. et al. 2023) (Dey et al., 2020). Crop choice and residue handling also matter: high-biomass or deep-rooted crops contribute more carbon than shallow-rooted ones (Ganeshamurthy and Srinivasarao, 2009; Hazra et al., 2018).. Overgrazing or residue burning reduces SOC significantly. In India, decades of intensive cultivation have already depleted 30–75% of original SOC in arable soils, meaning management changes can potentially rebuild that loss.

Soil Properties: Soil texture and mineralogy affect carbon storage. Fine-textured (clay-rich) soils bind organic molecules more tightly, slowing decomposition (Mahbobeh, Hossein et al., 2019). Soils with higher cation exchange capacity also protect organic matter. Conversely, coarse sandy soils have lower carbon-holding capacity. Soil pH and fertility influence microbial activity: nutrient limitations or acidic conditions can limit biomass production or decomposition.

Climate and Environment: Temperature and moisture regimes drive decomposition rates and plant growth. Cooler, wetter climates tend to preserve SOC longer, whereas hot arid conditions promote rapid mineralization of organic matter. In India's tropical climate, high temperatures can limit stable carbon buildup unless organic inputs are large and continuous. Extreme events (drought, floods, storms) can also disrupt carbon stores.

Vegetation Type: Forests and perennial vegetation generally sequester more carbon than annual crops, due to larger biomass and litterfall. The species composition matters too: fast-growing trees capture carbon quickly but may turnover faster, while long-lived species store carbon longer. Mixed systems (diverse species) often outperform monocultures in sustained sequestration.

Disturbances and Land Use Change: Wildfires, pests, or disease outbreaks can release stored carbon back to the atmosphere. Land-use change (e.g. converting forest to cropland) is a major factor: it can instantly lose decades of soil carbon. Ensuring permanence of sequestration is a challenge; for instance, afforested land must be protected for generations, or the carbon will be released when trees die or burn.

Socio-economic and Policy Factors: Adoption of sequestration practices depends on farmers' access to credit, knowledge, and incentives. Policies (carbon markets, subsidies) can drive or hinder uptake. Inadequate measurement and verification capabilities also limit implementation; without robust monitoring, the carbon benefits may be uncertain. Thus, non-biophysical factors indirectly affect sequestration potential.

Overall, carbon sequestration is maximized under suitable climate–soil conditions and sustainable land management. Site-specific assessments are needed: for example, interventions on degraded soils often yield larger carbon gains than on already-rich soils. Understanding these factors helps target the most effective practices in each region.

Advantages and Limitations of Carbon Sequestration

Advantages:

Climate Mitigation: The primary benefit is reducing net CO₂ emissions. Agricultural sequestration can provide a large, cost-effective sink: studies suggest expanded farm carbon sinks could supply up to ~40% of AFOLU (agriculture, forestry & land use) mitigation needed for 1.5 °C targets by 2050 (Frank et al. 2024). Enhancing soil carbon works “with nature” to offset emissions that are otherwise hard to cut.

Co-benefits for Agriculture: As detailed above, increased soil carbon yields higher productivity and resilience. This “double dividend” helps convince policymakers and farmers, since mitigation is bundled with development gains (Nath., et al. 2021)

Economic Incentives: Carbon markets and payments can make sequestration economically attractive. Global analyses project multi-billion-dollar opportunities for farmers (e.g.

up to \$375 billion by 2050 under \$160/tCO₂) (Frank, S., et al. 2024). Income from carbon credits or cost savings on inputs (due to better soils) improves farm economics.

Biodiversity and Ecosystem Services: Sequestration practices often enhance biodiversity (e.g. mixed cropping, hedgerows) and ecosystem function (water retention, nutrient cycling). Improved soil health and forested areas also clean water and air. These ecosystem services, while not always quantifiable in carbon markets, have high societal value

Adaptation and Sustainability: Richer soils and vegetation cover help farms adapt to climate stress (drought, flood). By restoring degraded lands, sequestration measures secure long-term agricultural sustainability. For example, revitalizing overgrazed rangelands can restore productivity.

Limitations:

Permanence and Reversibility: Sequestered carbon can be re-emitted. In biological systems, carbon is not locked indefinitely – drought, fire, or change in management can reverse gains. For instance, an unmaintained plantation may burn down or be cut down, releasing its carbon. Geological storage, while more stable, carries a risk of leakage if not properly managed. Thus, sequestration requires long-term stewardship and monitoring.

High Costs and Technical Barriers: Some technologies (DAC, CCS infrastructure, biochar production) are expensive and energy-intensive. For example, direct air capture costs ~\$500–800 per ton of CO₂, making it unprofitable without high carbon prices or subsidies. Many farmers also lack the capital or knowledge to adopt advanced practices without support.

Land and Water Competition: Expanding afforestation or bioenergy crops can compete with food production or water use. If not carefully managed, “carbon farming” could inadvertently pressure land and water resources. Agroforestry mitigates this by combining uses, but large-scale tree planting still requires trade-offs (e.g. potential reduction in cereal area).

Measurement and Verification Challenges: Accurately quantifying soil carbon changes is technically difficult

and time-consuming (requires long-term trials and measurements) (Benbi and Senapati, 2010; Parihar et al., 2018). Carbon credit programs depend on verifiable data; without reliable methods, farmers may not be rewarded for sequestration.

Institutional and Policy Hurdles: Carbon sequestration in agriculture is not always recognized or incentivized in policy frameworks. Historically, agriculture has been excluded from emissions trading schemes due to complexity. Without clear markets or regulations, adoption is slower.

Saturation Effects: Soils have a finite capacity to sequester. After a period (often decades), a soil may reach a new equilibrium of SOC, limiting further uptake unless disturbed. This means sequestration rates typically decline over time in a given field.

In practice, these limitations mean sequestration is a supplement, not a substitute, for emissions reductions. Technological capture and negative-emission strategies must accompany aggressive emission cuts in the energy and industry sectors. However, the net balance of carbon sequestration (benefits minus any re-emissions) is overwhelmingly positive when practices are well-designed and managed.

Conclusion

Carbon sequestration in agricultural systems offers a powerful dual benefit: mitigating climate change while improving agricultural sustainability. Biological sequestration (through healthy soils, forests and agroecosystems) and engineered methods (e.g. CCS, biochar) together form a portfolio of strategies. In India and worldwide, practices like conservation agriculture, agroforestry, and residue management have demonstrated real-world potential to capture carbon and improve yields (Mishra et al., 2018). National programs (e.g. MGNREGS) and policies are increasingly recognizing these co-benefits (Murthy et al. 2021)

Nevertheless, realizing the full promise of carbon farming requires overcoming challenges – ensuring permanence, financing, and scientific monitoring. It also demands

aligning farmer incentives with environmental goals. When thoughtfully implemented, however, carbon sequestration can be a win-win, it helps meet climate targets while boosting soil fertility, crop productivity, and livelihoods. Continued research, innovation and supportive policy will be key. Future agricultural development in India and beyond will likely hinge on integrating carbon-smart practices into routine farm management, turning farms into part of the climate solution.

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Comparative Analysis of Food Waste Reduction in Agriculture: Challenges and Solutions

Sneha Nandi¹, Dipanwita Manna¹ and Tanmoy Majhi^{*}

¹School of Agriculture, Swami Vivekananda University,
Barrackpore, West Bengal

^{*}Corresponding author: tanmoymajhi@svu.ac.in

Abstract:

Food waste in agriculture is a significant global challenge, contributing to food insecurity, environmental degradation, and economic inefficiency, with an estimated one-third of all food produced globally lost or wasted annually. This issue imposes severe environmental pressures, including greenhouse gas emissions, resource depletion, and financial losses exceeding \$1 trillion each year. Food waste occurs at various stages of the agricultural value chain, from pre-harvest to post-harvest, transportation, and processing. Contributing factors include inadequate infrastructure, pest and disease losses, market inefficiencies, aesthetic standards, and economic barriers faced by smallholder farmers in developing regions. This paper explores the causes and consequences of agricultural food waste and evaluates a range of solutions. Technological advancements such as precision farming, IoT, blockchain, AI, and cold chain logistics are identified as transformative tools to improve supply chain efficiency and reduce losses. Composting, including co-composting and the use of organic/inorganic additives, is highlighted as a cost-effective recycling method for food waste, enabling nutrient recovery and reducing environmental impact. Additionally, policy frameworks, government incentives, and consumer awareness campaigns are emphasized as crucial mechanisms to promote sustainable practices and reduce waste at both local and global levels. Through a comparative analysis of food waste reduction practices in developed and developing

regions, this review underscores the need for context-specific strategies and systemic collaboration among stakeholders. Addressing agricultural food waste is vital for enhancing food security, conserving resources, and fostering economic resilience. By integrating technological innovations, improved farming practices, efficient supply chain coordination, and robust policy support, this paper highlights pathways toward a sustainable agricultural future that minimizes food waste and maximizes environmental and economic benefits.

Keywords: Food waste, precision agriculture, composting, food security, sustainable agriculture, technology in agriculture.

1. Introduction

Food waste has become a pressing global concern, with implications that extend far beyond agricultural productivity. According to the Food and Agriculture Organization (FAO), nearly one-third of all food produced globally – approximately 1.3 billion tonnes – is lost or wasted every year (FAO, 2019). This alarming figure not only represents a colossal inefficiency within the food system but also undermines global efforts to combat hunger, reduce greenhouse gas emissions, and build resilient food systems.

Agricultural food waste begins well before produce reaches the market. Unlike consumer-level waste, agricultural food waste often occurs due to pre-harvest factors such as improper timing, pest infestation, adverse weather, and post-harvest challenges including inefficient harvesting, poor storage infrastructure, and logistical constraints. These losses are particularly pronounced in developing regions, where smallholder farmers often lack access to modern technologies, market linkages, and cold chains (Parfitt et al., 2010).

In developed countries, by contrast, food waste is more prevalent at the retail and consumer levels due to stringent cosmetic standards, overproduction, and consumer habits. However, upstream losses still exist and are linked to mechanized overharvesting, supply chain miscoordination, and large-scale food recalls.

Reducing food waste is essential for ensuring food security. With the global population expected to surpass 9.7 billion by 2050, food production will need to increase by at least 60% (UN, 2020). Addressing food waste is a more resource-efficient and environmentally friendly strategy compared to expanding agricultural lands or intensifying production, which would further strain ecosystems.

In addition to its implications for food availability, food waste represents a considerable environmental burden. Decomposing food in landfills releases methane—a greenhouse gas with a global warming potential 25 times higher than carbon dioxide. Moreover, the water, energy, and labor used to produce wasted food further exacerbate environmental degradation (Gustavsson et al., 2011).

Given these challenges, the integration of innovative technologies, public policies, and behavioral shifts is critical. This paper explores the root causes of agricultural food waste, evaluates emerging solutions such as digital agriculture and composting, and highlights best practices through comparative analyses of developing and developed nations. By focusing on context-appropriate interventions, the paper provides a roadmap for reducing food waste and promoting a sustainable agricultural future.

2. Causes and Consequences of Food Waste in Agriculture

Understanding the multifaceted nature of food waste in agriculture requires examining both systemic and operational factors. From farm to fork, inefficiencies can be attributed to a combination of technical, infrastructural, economic, and socio-cultural reasons. In developing countries, pre-harvest and post-harvest losses account for the bulk of food waste. These occur due to a lack of timely harvesting, pest and disease outbreaks, absence of mechanization, and improper handling practices (Kitinoja et al., 2011).

Infrastructure plays a pivotal role. A significant proportion of food spoilage occurs due to inadequate cold storage facilities, especially for perishable crops like fruits, vegetables, and dairy. According to the Indian Council of Agricultural Research (ICAR), India loses nearly 18% of its fruit and vegetable

output annually due to poor post-harvest management and storage (ICAR, 2021). Similar trends are observed in sub-Saharan Africa and Southeast Asia.

Another contributing factor is market standards based on appearance and size. Farmers often leave visually imperfect produce unharvested due to an inability to meet cosmetic standards enforced by retailers. This loss is compounded by volatile market prices and overproduction driven by uncertain demand forecasts (Stuart, 2009).

At a macro level, systemic inefficiencies such as weak supply chain coordination, delayed transport, and lack of market access contribute to spoilage and surplus. During gluts, farmers in regions with limited infrastructure may discard excess produce due to low price realization and lack of storage options.

On the environmental front, food waste intensifies climate change through methane emissions from rotting biomass. It also squanders the finite resources used in production—fertilizers, irrigation, land, and labor—thus creating a ripple effect across the ecological chain. Economically, global food waste is estimated to cost \$1 trillion annually, affecting farmers, consumers, and governments alike (FAO, 2019).

The social implications are equally severe. In regions plagued by hunger and malnutrition, such waste represents a moral and ethical dilemma. Reducing agricultural food waste, therefore, is not just a production issue but a matter of resource justice and sustainability.

3. Solutions and Technological Innovations

Addressing agricultural food waste demands innovative and scalable solutions. Recent technological advances offer promising interventions across multiple stages of the value chain.

Precision agriculture, which uses GPS, GIS, sensors, and satellite imagery, allows farmers to optimize inputs and monitor crops in real time. It helps reduce overproduction and minimizes losses caused by weather extremes or pest attacks (Gebbers& Adamchuk, 2010). Similarly, **Internet**

of Things (IoT) sensors monitor temperature, humidity, and gas concentrations in storage units, enabling real-time adjustments that prolong shelf life and reduce spoilage.

Blockchain technology is being explored for supply chain traceability. It ensures transparency and helps prevent losses due to fraud, mislabeling, or recalls (Kamilaris et al., 2019). When integrated with AI-driven analytics, blockchain can offer predictive insights on harvest times, market demand, and logistics planning.

Cold chain infrastructure is critical for perishable produce. Countries like China and Brazil have invested heavily in refrigerated transport and storage, significantly reducing food waste in transit (Buzby & Hyman, 2012). Mobile cold rooms and solar-powered coolers are now being developed for rural deployment in Africa and Asia.

Composting, though traditional, remains one of the most cost-effective recycling methods. Co-composting with livestock manure, or the use of microbial additives, enhances decomposition and nutrient recovery. Modern composting facilities now integrate waste sorting, moisture control, and odor management systems to increase efficiency and reduce health risks (Adhikari et al., 2009).

Policy frameworks also play a crucial role. Government incentives for farmer cooperatives, storage development, crop insurance, and waste-to-energy projects help de-risk innovation and improve adoption. Public-private partnerships are emerging as essential vehicles for scaling up technologies and integrating food surplus redistribution networks.

However, no technology can succeed without behavior change. Awareness campaigns that educate farmers on post-harvest best practices and encourage retailers to accept imperfect produce are vital. Likewise, empowering women—who often manage on-farm storage and processing—can enhance food management outcomes.

4. Comparative Analysis: Developed vs Developing Regions

Food waste manifests differently across the globe. In developing regions, agricultural losses are typically due

to poor infrastructure, pre-harvest issues, and lack of post-harvest technology. In developed nations, however, the majority of waste occurs further down the chain—during retail and consumption.

For instance, in sub-Saharan Africa and parts of India, up to 40% of harvests are lost before they even reach the market, primarily due to lack of roads, cold storage, and timely transport (FAO, 2019). Conversely, in the United States and Europe, high consumer expectations, overstocking, and discard of “ugly” produce contribute to 30–40% of total food waste (Stenmarck et al., 2016).

Technological penetration is also unequal. In developed regions, precision farming, data analytics, and AI-driven logistics are increasingly common. Companies like IBM and John Deere offer platforms that integrate farm-to-market decision-making tools. Developing regions are still in the early stages of adopting such tools, often constrained by financial and educational barriers.

However, developing nations offer fertile ground for leapfrogging technologies. Mobile-based agricultural extension services, solar-powered cold storage units, and community composting systems are being successfully piloted in Kenya, Bangladesh, and India. These grassroots innovations demonstrate how local adaptation can rival high-end technologies in effectiveness and sustainability.

Policy orientation also differs. The EU’s Farm to Fork Strategy and the US Food Waste Reduction Goal provide formal structures for tackling food loss. In contrast, many developing countries lack comprehensive waste reduction legislation but are increasingly incorporating food loss into national development plans and climate commitments.

Ultimately, the comparison underscores that while the challenges are global, solutions must be localized. Sharing knowledge, investing in technology transfer, and fostering global cooperation are key to bridging the divide and ensuring all countries move toward sustainable agriculture.

5. Conclusion

Food waste in agriculture represents a multifaceted crisis—one that encompasses hunger, environmental degradation, and economic loss. Yet, it is a solvable problem. This review highlights that while causes differ across geographies, solutions are within reach, thanks to advances in technology, supportive policies, and growing global awareness.

Precision agriculture, cold chain logistics, blockchain, and composting are powerful tools to reduce losses. However, technology alone is insufficient. Effective change demands systemic collaboration involving farmers, agribusinesses, policymakers, researchers, and consumers. Education, financial support, and inclusive innovation ecosystems will be critical for success.

Comparative analysis between developed and developing regions reveals that context-specific approaches, aligned with local realities and capacities, are essential. Solutions that work in California may not apply directly in rural Odisha—but both regions can learn from one another.

Addressing food waste is not just a technical challenge but a moral imperative. Reducing waste increases food availability, decreases greenhouse gas emissions, conserves resources, and strengthens livelihoods. In a world facing the dual crises of hunger and climate change, minimizing agricultural food waste must be a top priority.

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Detection of Heavy Metals in Soil Using Sensors: A Review

Animesh Ghosh Bag^a, Nitin Chatterjee^b

a. Department of Agriculture, School of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, 700121

b. Department of Agricultural Chemistry and soil science
BCKV, Mohanpur

Corresponding author: ghoshbaganimesh610@gmail.com

Abstract:

Heavy metal contamination in soil poses significant risks to environmental health, agriculture, and human well-being. Traditional laboratory methods for detecting heavy metals are accurate but often time-consuming, expensive, and require specialized equipment. In recent years, sensor-based technologies have emerged as efficient alternatives for rapid, on-site detection and monitoring of heavy metal concentrations in soil. This review provides a comprehensive analysis of advancements in sensor technologies for detecting heavy metals in soil, focusing on their principles, performance, and practical applications. We examine various types of sensors, including electrochemical, optical, biosensors, and nanosensors, highlighting their sensitivity, specificity, and ability to detect multiple heavy metals simultaneously. Challenges such as interference from complex soil matrices, calibration, and long-term stability are discussed, along with potential solutions. The paper also explores emerging trends, such as the integration of sensors with the Internet of Things (IoT) and machine learning algorithms for real-time monitoring and data analysis. Case studies demonstrating the successful application of sensor technologies in detecting heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are presented. Finally, the review identifies research gaps and outlines future directions for the development of cost-

effective, portable, and user-friendly sensors for soil health monitoring. Sensor-based detection systems represent a promising approach to addressing the global challenge of soil contamination and ensuring sustainable agricultural practices.

Key Words: *Heavy Metal Contamination, Sensor Technologies, Soil Monitoring, Internet of Things (IoT), Sustainable Agriculture*

1. Introduction

Heavy metal contamination in soil has become a pressing global environmental issue, primarily due to its profound and far-reaching impacts on soil quality, agricultural productivity, ecosystem balance, and human health. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are of particular concern owing to their high toxicity, non-biodegradable nature, and strong tendency to accumulate in soil and living organisms over time. Once introduced into the soil, either through industrial activities, mining operations, excessive use of chemical fertilizers and pesticides, or improper waste disposal, these toxic elements persist for extended periods and gradually enter the food chain, ultimately threatening food safety and public health (Alloway, 2013). Prolonged exposure to heavy metals through contaminated soil can lead to reduced soil fertility, impaired microbial activity, and disruption of essential soil functions, ultimately diminishing crop yields and compromising the sustainability of agricultural systems. Furthermore, the bioaccumulation of heavy metals in edible plants poses severe health risks to humans and animals, including neurological damage, organ dysfunction, and increased risk of cancer.

To monitor and assess heavy metal contamination in soil, conventional laboratory-based analytical techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF) have been widely employed. These methods are known for their high precision, sensitivity, and reliability in detecting trace concentrations of heavy metals. However, they require sophisticated instrumentation, trained personnel, and controlled laboratory environments. Additionally, these

techniques are often costly, time-consuming, and impractical for large-scale, real-time, or on-site soil monitoring, particularly in remote areas or resource-limited settings (Zhou et al., 2022).

In light of these limitations, the development of sensor-based technologies for heavy metal detection in soil has attracted significant research attention in recent years. These technologies offer rapid, cost-effective, and portable alternatives for in-situ monitoring, enabling timely detection of soil contamination without the need for complex sample preparation or laboratory infrastructure. Sensor systems, including electrochemical, optical, biosensors, and nanosensors, are capable of providing real-time data with reasonable sensitivity and specificity, making them suitable for both agricultural and environmental monitoring applications. This review aims to provide a comprehensive overview of recent advancements in sensor technologies for detecting heavy metals in soil, discussing their underlying principles, operational performance, advantages, limitations, and potential applications. Furthermore, the paper highlights the current challenges and future research directions needed to advance the practical deployment of sensor-based detection systems as reliable tools for soil health assessment and environmental protection.

2. Sensor Technologies for Heavy Metal Detection in Soil

The development of sensor technologies for detecting heavy metals in soil represents a significant advancement in environmental monitoring, providing rapid, cost-effective, and in-situ detection capabilities. Several types of sensors have been explored, each with unique operational principles, strengths, and limitations. Among these, electrochemical, optical, biosensors, and nanosensors have shown considerable promise for soil applications.

(i) Electrochemical Sensors

Electrochemical sensors are among the most widely researched and applied tools for the detection of heavy metals in soil due to their inherent advantages of high sensitivity, portability, and the ability to provide real-time,

quantitative measurements. These sensors function based on the electrochemical interactions between heavy metal ions present in soil samples and the surface of a working electrode. When heavy metals such as lead (Pb), cadmium (Cd), or mercury (Hg) interact with the electrode, they induce detectable changes in electrical properties, including current, voltage, or impedance (Gupta et al., 2020). Anodic stripping voltammetry (ASV) is one of the most popular techniques within this category, known for its exceptional sensitivity and low detection limits for trace levels of heavy metals. ASV operates by pre-concentrating metal ions onto the electrode surface through electro-deposition, followed by their subsequent stripping, which generates a characteristic electrical signal proportional to the metal concentration. Potentiometric sensors, which measure potential changes, and impedimetric sensors, which monitor changes in electrical impedance, are also widely used for heavy metal detection. The continuous advancements in miniaturization and microfabrication have enabled the development of compact, portable electrochemical sensors, making them highly suitable for on-site soil monitoring, especially in agricultural fields, contaminated sites, and mining areas.

(ii) Optical Sensors

Optical sensors are another prominent category for heavy metal detection, utilizing the interaction between light and matter to identify and quantify contaminants. These sensors operate based on detecting changes in optical properties such as absorbance, fluorescence, luminescence, or reflectance when heavy metals are present in the soil. Common types of optical sensors include colorimetric sensors, where color changes in a reagent indicate the presence of specific heavy metals; fluorescence-based sensors, which exploit the quenching or enhancement of fluorescence signals upon metal ion binding; and surface plasmon resonance (SPR) sensors, which detect changes in refractive index at the sensor surface. One of the significant advantages of optical sensors is their high specificity, enabling the selective detection of individual heavy metals even in the presence of other contaminants. Additionally, they offer rapid response times

and, in many cases, allow for visual or spectrophotometric detection, making them accessible for both laboratory and field use. Recent advancements in nanotechnology have led to the development of nanomaterial-based optical sensors, which incorporate nanoparticles, quantum dots, or other nanostructures to enhance sensitivity, selectivity, and the ability to detect multiple heavy metals simultaneously (Zhang et al., 2021). These innovations have significantly improved detection limits, making optical sensors viable for detecting trace heavy metal concentrations in complex soil environments.

(iii) Biosensors

Biosensors represent an emerging class of detection devices that utilize biological recognition elements to detect the presence of heavy metals with high selectivity and sensitivity. The core principle of biosensors lies in the specific interaction between a biological component such as enzymes, antibodies, nucleic acids, or even whole microbial cells and the target heavy metal ions in the soil. This interaction produces a measurable physicochemical signal, which may be electrical, optical, or thermal in nature (Kumar et al., 2022). Biosensors are particularly valued for their environmental friendliness and their ability to offer highly selective detection, even amidst complex soil matrices. Enzyme-based biosensors, for instance, can be designed to catalyze reactions that produce a detectable signal upon exposure to specific heavy metals. Similarly, microbial biosensors employ living microorganisms whose metabolic responses indicate the presence of toxic metals. The potential for on-site and real-time monitoring makes biosensors highly attractive for agricultural and environmental applications. However, practical challenges remain regarding their operational stability, sensitivity, and reproducibility, especially when deployed under diverse and variable soil conditions. Ongoing research is focused on enhancing the robustness of biosensors and improving their performance for long-term field applications.

(iv) Nanosensors

Nanosensors leverage the remarkable physicochemical

properties of nanomaterials to achieve ultra-sensitive and highly selective detection of heavy metals in soil. The integration of nanoparticles, carbon nanotubes, graphene, and other nanoscale materials into sensor platforms has opened new possibilities for environmental monitoring. Due to their high surface area-to-volume ratio, enhanced catalytic activity, and unique optical and electrical properties, nanomaterials enable nanosensors to achieve extremely low detection limits—often at parts-per-billion (ppb) levels or lower—for heavy metals such as arsenic (As), lead (Pb), and cadmium (Cd) (Ravikumar et al., 2023).

Nanosensors can operate through various mechanisms, including electrochemical, optical, or biosensing principles, with nanomaterials serving as the transducing or recognition elements. For example, gold nanoparticles are widely used in colorimetric sensors for their distinct optical properties, while carbon nanotubes and graphene enhance the conductivity and sensitivity of electrochemical sensors.

The miniaturization, portability, and high performance of nanosensors make them highly suited for rapid, on-site soil assessments. Furthermore, the integration of nanosensors with wireless communication technologies and smart devices is facilitating the development of advanced sensor networks for real-time soil health monitoring.

3. Challenges and Limitations

Despite remarkable progress in sensor technologies for the detection of heavy metals in soil, several technical, environmental, and socioeconomic factors continue to limit their widespread, practical deployment. These challenges must be critically addressed to enhance the reliability, usability, and affordability of sensor-based systems for routine soil monitoring.

(i) Interference from Soil Matrices: One of the most significant challenges faced by sensor technologies is the complex and heterogeneous nature of soil itself. Soils vary widely in texture, organic matter content, moisture levels, and mineral composition, all of which can interfere with sensor performance. For instance, organic matter and

dissolved ions present in soil may interact with sensor components, leading to false signals or reduced sensitivity. Additionally, soil heterogeneity can create spatial variability in contaminant distribution, making it difficult to obtain accurate and representative measurements. Overcoming matrix interference requires the development of sensors with enhanced selectivity, robust signal processing, and efficient sample preparation protocols.

(ii) Calibration and Standardization: Accurate and reliable sensor performance depends heavily on regular calibration. Environmental conditions such as temperature, humidity, and soil composition can affect sensor responses, necessitating frequent recalibration to ensure consistent results. However, the absence of universally accepted, standardized calibration procedures poses a significant barrier to the broader adoption of sensor technologies. Without standardization, comparing results across different sensor platforms, studies, or geographic regions becomes challenging. Establishing global or regional calibration protocols and quality control standards is essential to enhance the reliability and interoperability of sensor data.

(iii) Long-Term Stability and Durability: The long-term stability and operational durability of sensors remain critical concerns, especially for field applications in harsh environments. Exposure to moisture, dust, temperature fluctuations, and mechanical stress can degrade sensor components over time, leading to signal drift, reduced sensitivity, or complete sensor failure. This is particularly problematic for biosensors and nanosensors, which often rely on delicate biological or nanomaterial components. To address these limitations, research efforts must focus on developing robust, weather-resistant sensor designs with protective coatings, self-cleaning mechanisms, and longer operational lifespans.

(iv) Cost and Accessibility: While sensor technologies are becoming increasingly compact and portable, high-end, high-performance sensor systems often remain prohibitively expensive for smallholder farmers, local environmental agencies, and resource-limited regions. The cost of advanced

materials, specialized components, and maintenance further restricts accessibility. Moreover, the lack of technical expertise in rural areas hampers the effective use and interpretation of sensor data. Reducing production costs, simplifying operation, and providing affordable, user-friendly sensor options are essential for promoting equitable access to soil monitoring technologies. In summary, while sensor-based approaches hold great promise for transforming soil contamination monitoring, addressing these technical, environmental, and socioeconomic challenges is critical for ensuring their reliable, scalable, and cost-effective implementation in real-world settings.

4. Emerging Trends and Future Prospects

The way we monitor heavy metals in soil is undergoing a remarkable transformation, driven by rapid advancements in sensor technologies, the Internet of Things (IoT), and machine learning (ML). These technologies are no longer confined to laboratories or specialized research environments—they are increasingly becoming accessible tools that can make a real difference in how we protect soil health.

The integration of sensors with IoT networks is a game-changer for environmental monitoring. These smart sensor networks enable real-time, continuous collection of soil data across large areas, providing a level of insight and responsiveness that was unimaginable just a few years ago (Li et al., 2023). Instead of relying on time-consuming, manual sampling and laboratory analysis, farmers, researchers, and environmental agencies can now access up-to-date information about soil quality at the touch of a button.

Machine learning adds another layer of sophistication to this process. By applying advanced algorithms, ML helps make sense of the vast amounts of data generated by these sensors. It can detect patterns, identify potential contamination hotspots, and even predict future trends, significantly enhancing the accuracy and reliability of heavy metal detection systems.

Equally promising is the ongoing development of portable, affordable, and easy-to-use sensor devices designed for non-experts. These innovations are making it possible for farmers,

landowners, and community groups to play an active role in soil monitoring without needing specialized training. Recent real-world examples have shown how these sensor-based technologies can effectively detect hazardous metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) in contaminated soils.

Together, these advancements are not just technical milestones they represent practical, scalable solutions for addressing soil contamination. As these tools become more accessible and refined, they hold immense potential to support sustainable agriculture, safeguard public health, and inform evidence-based environmental policies for years to come.

5. Conclusion

Sensor-based technologies are emerging as a powerful and practical alternative to conventional laboratory methods for detecting heavy metals in soil. Unlike traditional approaches, which are often time-consuming, expensive, and require specialized equipment and expertise, modern sensors offer a faster, more portable, and cost-effective solution for on-site soil monitoring. Technological advancements in electrochemical, optical, biosensors, and nanosensors have significantly improved the sensitivity and reliability of detecting hazardous metals directly in the field. These tools empower farmers, researchers, and environmental agencies to assess soil quality quickly, enabling more informed and timely decision-making. However, despite their potential, some technical hurdles remain. Issues such as accurate sensor calibration, potential interference from complex soil compositions, and ensuring long-term stability and durability of sensors continue to limit their widespread adoption.

The integration of these sensor systems with Internet of Things (IoT) platforms and advanced data analytics—particularly machine learning—holds immense promise for the future. Together, they can create intelligent, automated monitoring networks capable of providing real-time, large-scale soil contamination data. Such systems not only improve detection accuracy but also support predictive modeling, helping to anticipate and mitigate contamination risks

before they escalate. Looking ahead, there is a clear need for continued research and innovation focused on developing affordable, robust, and user-friendly sensor technologies that can perform reliably across diverse soil environments. By overcoming existing challenges, these tools have the potential to transform how we monitor and manage soil health, contributing to safer food production, sustainable agriculture, and a cleaner, healthier environment.

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Groundwater Depletion in a Changing Climate: Risks, Challenges, and Pathways to Sustainability

Arindam Santra, Sayani Bhowmick*

*Department of Agriculture, Swami Vivekananda University,
Barrackpore 700121, West Bengal, India*

*Corresponding author: sayanibhowmick94@gmail.com

Abstract:

Climate change is exacerbating groundwater depletion, a critical issue that threatens water security, ecosystems, and livelihoods worldwide. Rising temperatures, erratic precipitation patterns, and prolonged droughts are reducing natural groundwater recharge rates, while increasing demand for irrigation, industrial, and domestic use is accelerating extraction. This unsustainable exploitation of groundwater resources poses significant risks, including land subsidence, reduced streamflows, and the salinization of aquifers, particularly in arid and semi-arid regions. The interplay between climate change and groundwater depletion creates a feedback loop, where declining water availability further stresses communities and ecosystems, making them more vulnerable to climate impacts. To address these challenges, effective mitigation strategies are essential. These include promoting water-efficient agricultural practices, such as drip irrigation and crop diversification, implementing managed aquifer recharge (MAR) techniques to enhance groundwater replenishment, and adopting integrated water resource management (IWRM) frameworks. Policy measures, such as regulating groundwater extraction and incentivizing sustainable use, are equally critical. Additionally, leveraging advanced technologies like remote sensing, GIS, and AI can improve groundwater monitoring and management. Public awareness and community engagement are also vital to fostering conservation efforts. By combining scientific innovation, policy intervention, and stakeholder collaboration,

it is possible to mitigate the risks of groundwater depletion and build resilient water systems capable of withstanding the pressures of climate change, ensuring long-term water security for future generations.

Keywords: Climate change, groundwater depletion, water security, managed aquifer recharge, sustainable agriculture, integrated water resource management, land subsidence, mitigation strategies.

1. Introduction

Groundwater is the backbone of global freshwater supply, supporting domestic, agricultural, industrial, and ecological needs. It constitutes approximately 30% of the world's total freshwater resources and accounts for nearly 99% of accessible freshwater not locked in glaciers or ice caps (Davamani et al., 2024). Over 1.5 billion people rely directly on groundwater for drinking water, and up to 70% of global irrigation depends on groundwater withdrawals, underscoring its significance for food security and livelihoods.

However, the sustainability of groundwater resources is under increasing threat due to the compounded impacts of climate change and anthropogenic pressures. Over-extraction for agriculture, urbanization, industrial activities, and pollution have already strained aquifers, but climate-induced changes in precipitation patterns, temperature regimes, evapotranspiration, and land use further exacerbate groundwater depletion. According to the IPCC (2021), global temperatures are projected to rise by 2–4°C by the end of the 21st century, with significant implications for the hydrological cycle. These changes can reduce groundwater recharge, increase variability in discharge, alter groundwater temperature, and deteriorate water quality.

While surface water resources have received substantial attention in climate studies, groundwater—a more stable but less visible resource—has only recently become a focus of integrated climate-resilience planning. The complex interplay of hydrological processes under changing climate scenarios introduces significant uncertainties in groundwater management. Moreover, the indirect effects of climate change,

such as changes in vegetation, land cover, and socio-economic water demands, further complicate predictions.

Given the critical role groundwater plays in ensuring water security and climate adaptation, this review aims to synthesize existing knowledge on climate-groundwater interactions, highlight modelling innovations, and identify sustainable pathways for resource management. By integrating biophysical, technological, and policy perspectives, it seeks to offer a comprehensive understanding of the challenges and solutions related to groundwater depletion in a changing climate.

2. Climate Change and Groundwater Interactions

The interaction between climate change and groundwater systems is multifaceted, encompassing direct impacts such as altered precipitation patterns and increased temperatures, as well as indirect influences through changes in land use, vegetation, and water demand. Groundwater, which supports nearly 50% of global drinking water supplies and 70% of agricultural irrigation (Davamani et al., 2024), is highly sensitive to fluctuations in the hydrological cycle driven by climate variability.

One of the most direct consequences of climate change is the alteration of precipitation patterns—not just in quantity but also in intensity, seasonality, and type (e.g., snow vs. rain). In regions experiencing reduced rainfall or longer dry spells, recharge rates decline significantly, leading to falling groundwater levels. Conversely, areas receiving more intense rainfall events may still see limited recharge, as high-intensity precipitation often increases surface runoff rather than allowing infiltration (Kurylyk et al., 2014). Additionally, the shift from snow to rain in colder regions results in earlier and more rapid snowmelt, potentially reducing spring recharge and increasing winter recharge, thereby altering groundwater availability seasonally (Davamani et al., 2024).

Temperature rise is another critical driver. As global mean temperatures increase, evapotranspiration from soil and plants intensifies, reducing the amount of water that can percolate into the subsurface. This is particularly relevant in

tropical and arid regions, where higher evapotranspiration can drastically diminish recharge, even if precipitation remains constant (Liesch & Wunsch, 2019). Furthermore, climate-induced changes in vegetation, such as shifts in crop patterns or deforestation, also modify infiltration rates and water demand, creating complex feedbacks in groundwater dynamics.

The impacts on groundwater discharge are equally significant. Many rivers and streams rely on baseflow contributions from aquifers, and reduced groundwater levels diminish these flows, affecting surface water ecosystems. For instance, studies predict declining groundwater-fed spring flows in areas like the southwestern United States and the Himalayas due to prolonged dry periods and extraction pressures (Asoka et al., 2017; Russo & Lall, 2017).

In addition to quantity, groundwater quality is increasingly vulnerable. Warmer temperatures and variable recharge conditions facilitate the transport of contaminants such as nitrates and heavy metals from surface sources into aquifers. In coastal regions, saltwater intrusion—driven by sea-level rise and over-pumping—further degrades water quality, particularly in low-lying areas (Mustafa, 2019). Climate change can also intensify the leaching of pollutants during high recharge events, especially in agricultural zones with excessive fertilizer use (Alam et al., 2019).

Overall, the interaction of groundwater with climate systems is governed by a web of interdependent processes, including surface water exchanges, land cover dynamics, and socio-economic pressures. These complexities underscore the importance of integrated modelling approaches and vulnerability assessments to anticipate and manage groundwater sustainability in a warming world (Davamani et al., 2024).

3. Risks and Challenges of Groundwater Depletion

Groundwater depletion presents a multifaceted challenge to water security, environmental stability, and socio-economic development. The most immediate risk of excessive groundwater withdrawal is the reduction in water availability

for drinking, agriculture, and industrial use, particularly in arid and semi-arid regions where alternative water sources are limited (Davamani et al., 2024). This depletion threatens food security by undermining irrigated agriculture, which relies on groundwater for 60–70% of its supply globally (Velis et al., 2017).

One critical ecological consequence is the diminished groundwater discharge into streams, wetlands, and lakes, which sustains groundwater-dependent ecosystems (GDEs). Reduced baseflow alters aquatic habitats, impairs biodiversity, and contributes to the desiccation of wetlands and riverbeds, especially during dry seasons (Russo & Lall, 2017). Additionally, falling water tables force communities to drill deeper wells, escalating the energy and financial costs of water extraction. This creates a disproportionate burden on poor and marginalized populations, exacerbating social inequities (Asoka et al., 2017).

Another major concern is land subsidence, a phenomenon resulting from the compaction of aquifer systems due to long-term groundwater extraction. This has been observed in urban centers like Jakarta, Tehran, and regions such as California's Central Valley and northwestern India (Davamani et al., 2024). Land subsidence can damage infrastructure, compromise building foundations, and increase vulnerability to flooding, especially in low-lying areas.

In coastal zones, groundwater depletion accelerates saltwater intrusion, where seawater infiltrates freshwater aquifers. Rising sea levels due to climate change intensify this risk. Once salinized, aquifers become difficult and costly to remediate, posing long-term challenges for coastal agriculture and potable water supply (Mustafa, 2019).

Groundwater quality also deteriorates as aquifers are overexploited. Reduced recharge and fluctuating water tables increase the concentration of contaminants such as nitrates, arsenic, fluoride, and heavy metals. Agricultural runoff, industrial discharges, and poorly managed sanitation systems further compound this degradation, especially during high recharge events that mobilize pollutants into aquifers (Alam et al., 2019).

Overall, groundwater depletion is not merely a hydrological concern but a critical sustainability issue. It intersects with health, food, energy, and climate resilience, requiring integrated and adaptive management strategies that account for both natural and human-induced stressors.

4. Modelling Approaches and Groundwater Vulnerability Assessment

Simulation models are indispensable for assessing groundwater responses to climate stressors. Widely used models include MODFLOW, HYDRUS, and WetSpa, which integrate climate, land-use, and hydrogeological parameters (Scibek & Allen, 2006; Waikar&Somwanshi, 2014).

There are two broad categories of vulnerability assessment models: index-based (e.g., DRASTIC, GOD, GALDIT) and process-based or numerical models. Index-based models are simpler and require fewer data, making them suitable for rapid assessments. Process-based models provide more detailed outputs, including pollutant transport and recharge estimates, but require extensive data and computational power (Davamani et al., 2024).

Examples include:

Punjab, India: Predicted groundwater nitrate pollution to rise to 66% by 2040 (Sarkar et al., 2022).

Vientiane, Laos: Recharge projected to increase by 22–47% under future rainfall scenarios (Pham et al., 2019).

Arusha, Tanzania: Recharge may fall by 30–44% by 2050 due to increased evapotranspiration and reduced rainfall (Davamani et al., 2024).

5. Simulation Tools, Uncertainty, and Model Assumptions

Climate models used in groundwater assessments often include General Circulation Models (GCMs) under different Shared Socioeconomic Pathways (SSPs). However, these models are limited by coarse spatial resolution and assumptions regarding soil and aquifer properties (van der Knaap et al., 2015).

Key assumptions affecting accuracy include:

Use of lumped average slopes in topographic calculations.

Homogeneous aquifer characteristics across diverse geological settings.

Instantaneous sea level rise assumptions, rather than gradual trends (Golden et al., 2020).

Such oversimplifications may distort vulnerability estimates. Incorporating spatial variability through distributed models and high-resolution Digital Elevation Models (DEMs) is essential to enhance accuracy (Zume & Tarhule, 2011).

6. Hybrid Frameworks and Future Modelling Innovations

Hybrid approaches that combine index-based and process-based models offer promising advancements. For instance, integrating DRASTIC with MODFLOW allows spatial vulnerability mapping alongside predictive simulations (Aslam et al., 2019). These approaches leverage the strengths of both methodologies, reducing limitations related to data and scale.

Moreover, vulnerability assessments are increasingly incorporating exposure and sensitivity indicators, such as land use, evapotranspiration, slope, and groundwater depth. Adaptive capacity, a key IPCC vulnerability component, can be assessed using socio-economic indicators like income, education, and governance quality (Velis et al., 2017).

7. Artificial Intelligence, Machine Learning, and Quantum Computing in Hydrology

Recent years have seen growing use of AI and machine learning (ML) in groundwater modelling. Algorithms such as Random Forest, Boosting, and Neural Networks are used to predict groundwater levels, recharge zones, and contamination risks (Nyenje & Batelaan, 2012).

For example:

PERSIANN and its variants are leading ML-based tools for rainfall estimation.

Random Forests have been applied to model land subsidence due to over-extraction (Pham et al., 2019).

Quantum computing, though nascent, holds promise for solving complex inverse problems in hydrology. Algorithms like quantum annealing and inverse Laplacian solvers have been tested to accelerate groundwater simulations (Golden et al., 2020).

8. Policy Implications and Sustainable Water Resource Management

Addressing groundwater depletion requires multi-scalar, integrated policy responses. Key recommendations include:

Integrated Water Resource Management (IWRM): Encouraging basin-level planning that incorporates surface and groundwater, stakeholder participation, and ecological concerns (UNEP, 2021).

Adaptive Policies: Embedding flexibility into water governance to accommodate climate uncertainties.

Water Pricing: Reflecting the real cost of extraction and incentivizing conservation.

Infrastructure Investments: Supporting aquifer recharge projects, wastewater reuse, and monitoring systems.

Community Participation: Strengthening local governance and ensuring inclusive decision-making.

Healthy ecosystems must be protected to preserve natural recharge zones and maintain water quality. Policies should promote land-use regulations and restoration of wetlands and forests.

9. Conclusion

Groundwater depletion under the stress of climate change presents a formidable challenge to global water security and environmental sustainability. As climate variability alters precipitation patterns, intensifies evapotranspiration, and exacerbates extreme weather events, the pressure on already overexploited aquifers continues to grow. This review underscores the intricate and interdependent

dynamics between climate drivers and groundwater systems, highlighting both the direct hydrological impacts and the cascading effects on water quality, ecosystems, food production, and human livelihoods.

Advancements in hydrological modelling, particularly the integration of artificial intelligence, remote sensing, and uncertainty quantification, offer promising pathways for assessing and mitigating these risks. However, challenges remain in scaling models appropriately, addressing data limitations, and incorporating socio-economic variables into decision-making processes.

Sustainable groundwater management requires a paradigm shift—from reactive crisis responses to proactive, integrated water governance. Policies must embrace adaptive, inclusive, and science-informed frameworks, balancing ecological protection with human development needs. Collaboration among governments, researchers, local communities, and global institutions is essential to building resilient water systems.

Ultimately, safeguarding groundwater in a changing climate is not just a technical or environmental task—it is a societal imperative central to achieving the Sustainable Development Goals and ensuring long-term resilience for future generations.

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Nano-Fertilizers: Revolutionizing Nutrient Management for Cereal Crops

Biswadeep Mazumder¹, Anirneeta De^{1*}

School of Agriculture, Swami Vivekananda University, Barrack pore, West Bengal- 700121

* Corresponding author: anirneetad@svu.ac.in

Abstract:

Nanotechnology offers an exciting solution to meet the nutrient needs of cereal crops like rice, wheat, and maize, which usually require large amounts of fertilizers. Traditional fertilizers, when used in excess, harm the environment by reducing soil health, lowering fertilizer efficiency, and contaminating water resources. Nano-fertilizers provide a better alternative to these conventional fertilizers, not only for cereals but also for other crops. Nano-fertilizers are incredibly small particles, even smaller than the pores of plant cell walls, allowing them to easily enter plant cells and reach the plasma membrane. Their tiny size gives them a surface area 100 times larger than regular fertilizers, improving their interaction with plant surfaces and making nutrient absorption much more efficient. This increases the nutrient-use efficiency of crops and positively impacts their growth, yield, and drought tolerance. By replacing traditional fertilizers with nano-fertilizers, farmers can enhance the physiological and growth performance of cereal crops while reducing environmental damage. This review discusses how nano-fertilizers affect the growth of cereal crops and their benefits for improving both qualitative and quantitative traits. In conclusion, nano-fertilizers are a highly effective nutrient source for cereal crops and represent a promising tool for sustainable nutrient management in agriculture. They can help boost yields, protect the environment, and ensure efficient use of resources, making them a game-changer in modern farming.

Keywords: Nano-Fertilizers, Cereal Crop Nutrition, Nutrient-Use Efficiency, Modern Farming Solutions

1. Introduction

Cereal crops, particularly rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.), account for more than 50% of the world's caloric intake and are essential to global food and nutritional security. However, these crops demand high inputs of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), often supplied through synthetic chemical fertilizers. While these fertilizers have significantly increased yields during the Green Revolution, their excessive and imbalanced use has contributed to declining soil health, nutrient imbalances, and environmental degradation through nutrient runoff, leaching, and greenhouse gas emissions (Chen et al., 2018). Moreover, traditional fertilizers suffer from low nutrient-use efficiency (NUE), often below 50% for nitrogen and even lower for phosphorus, resulting in financial losses for farmers and ecological harm.

Nanotechnology—the science of manipulating materials at the nanoscale (1–100 nanometers)—has emerged as a transformative tool in agriculture. Nano-fertilizers are designed to release nutrients slowly and in response to plant demands, offering site-specific delivery, minimizing nutrient losses, and enhancing crop productivity with minimal environmental footprint. Their small particle size allows them to penetrate plant tissues efficiently, thereby improving the bioavailability of nutrients and stimulating plant physiological and biochemical functions.

This paper explores the synthesis, mechanisms, benefits, and future scope of nano-fertilizers for improving the productivity and sustainability of cereal crop farming. It critically examines their agronomic performance, environmental implications, and practical challenges, providing a comprehensive overview of their role in the future of nutrient management.

2. Limitations of Conventional Fertilizers

Conventional fertilizers have played a pivotal role in increasing

crop yields and supporting the global food supply. However, their sustainability is increasingly being questioned due to their inefficient nutrient-use and negative environmental consequences. Fertilizers such as urea, ammonium nitrate, superphosphates, and muriate of potash are commonly applied to supply essential macronutrients like nitrogen (N), phosphorus (P), and potassium (K). While effective in the short term, these inputs exhibit poor synchronization with crop nutrient demand and are prone to substantial losses in the environment.

Low Nutrient-Use Efficiency (NUE)

Nitrogen-use efficiency (NUE)—defined as the proportion of applied nitrogen absorbed and utilized by the crop—is alarmingly low. It is estimated that only 30–50% of applied nitrogen fertilizers are actually taken up by crops, while the rest is lost through leaching, volatilization, and denitrification (Chen et al., 2018; Raliya et al., 2016). Phosphorus efficiency is even lower, generally less than 20%, as phosphate ions get quickly immobilized in the soil by forming insoluble complexes with calcium, iron, and aluminum compounds (Sharma et al., 2018). Potassium losses are also considerable, especially in sandy or light-textured soils with poor cation exchange capacity.

Environmental Consequences of Fertilizer Losses

The consequences of these nutrient losses extend far beyond agronomic inefficiencies:

Groundwater Pollution: Excess nitrogen, mainly in the form of nitrate (NO_3^-), leaches into groundwater aquifers, posing serious health risks such as methemoglobinemia (blue baby syndrome) and contributing to eutrophication in aquatic ecosystems (Tilman et al., 2002).

Greenhouse Gas Emissions: Nitrogen losses through denitrification produce nitrous oxide (N_2O), a potent greenhouse gas that has a global warming potential nearly 300 times greater than carbon dioxide (Mosier et al., 2004). Agriculture accounts for approximately 60% of global N_2O emissions, largely due to fertilizer misuse.

Soil Degradation: Long-term application of acid-forming nitrogen fertilizers (e.g., ammonium sulfate) leads to soil acidification, reducing pH and limiting the availability of nutrients. In arid and semi-arid zones, improper use of fertilizers and irrigation can contribute to soil salinization, further diminishing soil fertility and crop productivity (Yadav et al., 2020).

Disruption of Soil Microbiota: Heavy and continuous fertilizer inputs have been shown to reduce microbial diversity, suppress beneficial microorganisms, and increase pathogenic microbial populations (Geisseler & Scow, 2014). This undermines the soil's natural nutrient cycling processes and resilience.

Economic and Agronomic Drawbacks

From an economic standpoint, the inefficiency of conventional fertilizers leads to increased production costs for farmers. This is particularly burdensome in regions where input costs are high and crop returns are volatile. Moreover, repeated over-application can induce nutrient imbalances in plants, resulting in stunted growth, reduced yields, and increased susceptibility to pests and diseases (Fageria, 2009).

These widespread inefficiencies underscore the urgent need for alternative fertilizer technologies that improve NUE, reduce environmental impacts, and support sustainable agriculture. One such promising solution is the adoption of nano-fertilizers, which offer controlled release, targeted delivery, and minimal losses, thereby addressing the shortcomings of traditional nutrient delivery systems.

3. Nano-Fertilizers: Concept and Characteristics

What is Nano-Fertilizers?

Nano-fertilizers are defined as nutrient formulations engineered at the nanoscale, typically between 1 and 100 nanometers, designed to enhance nutrient uptake efficiency, reduce environmental losses, and improve crop performance (DeRosa et al., 2010). Their uniqueness lies in their extremely small particle size, which allows for greater surface area-to-volume ratio, leading to higher reactivity and interaction with plant tissues.

These formulations may include:

- Nano-sized particles of essential nutrients (e.g., nano-ZnO, nano-CuO, nano-Fe O),
- Nanostructured carriers (e.g., hydroxyapatite, mesoporous silica),
- Nanocomposites embedding nutrients in biodegradable polymers for controlled release (Naderi & Danesh-Shahraki, 2013).

Unlike bulk fertilizers, nano-fertilizers are capable of controlled and targeted release, ensuring that nutrients are available at the right time and in the right quantity, thereby reducing over-application and enhancing nutrient-use efficiency.

Physicochemical Properties

The beneficial traits of nano-fertilizers originate from their unique physicochemical properties, such as:

- Enhanced surface reactivity: Nanoparticles interact more efficiently with root surfaces, facilitating quicker and more thorough nutrient uptake.
- Higher solubility and dispersibility: They remain suspended in solution, improving foliar absorption and reducing precipitation in soil.
- Improved permeability: Due to their size, nanoparticles can penetrate the plant cuticle, cell wall, and plasma membrane, reaching target sites like chloroplasts and mitochondria (Tiwari et al., 2011).
- Sustained release: Nanostructures can be engineered to release nutrients gradually over time, reducing leaching and volatilization (Liu & Lal, 2015).

Mechanism of Action in Plants

The mode of action of nano-fertilizers differs significantly from conventional forms:

- Foliar Application: When applied on leaves, nanoparticles enter through stomatal openings or

penetrate directly through the cuticle. Once inside, they translocate via apoplast or symplast pathways to reach different tissues (Rico et al., 2011).

- **Root Uptake:** In soil, nano-fertilizers dissolve into ionic forms or remain as suspended particles. They are absorbed via root epidermal cells, then mobilized through xylem and phloem.

- **Enhanced Nutrient Bioavailability:** The sustained and localized nutrient delivery ensures continuous supply, reduces antagonism among nutrients, and mitigates fixation in the soil matrix.

Types of Nano-Fertilizers

Nano-fertilizers are broadly classified into the following categories:

- **Nutrient-based Nano-Fertilizers:** These include nanoparticles of essential macro- and micronutrients like nano-ZnO, nano-Fe₃O₄, nano-CuO, and nano-MnO₂. They are directly taken up by the plant and serve as slow-release nutrient sources (Subramanian et al., 2015).

- **Nanocomposite Fertilizers:** Nutrients are encapsulated in nanomaterials such as chitosan, zeolites, or polylactic acid, offering a dual advantage of targeted delivery and biodegradability (Liu & Lal, 2015).

- **Nano-encapsulated Fertilizers:** These are fertilizers coated with nanomaterials for controlled release, often triggered by moisture, temperature, or plant demand.

Reported Benefits in Cereal Crops

In cereal crops such as rice and wheat, nano-fertilizers have demonstrated:

- **Increased chlorophyll content and photosynthetic efficiency,** leading to improved biomass production (Suriyaprabha et al., 2012).

- **Higher grain yield and quality,** particularly with nano-zinc and nano-iron application (Dimkpa et al., 2017).

- Enhanced stress tolerance, especially against drought and salinity, due to improved root structure and water retention (Tarafdar et al., 2012).

These effects have made nano-fertilizers an increasingly attractive option for sustainable nutrient management in cereal-based cropping systems.

4. Application and Effects of Nano-Fertilizers in Cereal Crops

Nano-fertilizers are being increasingly explored for their direct application in cereal cropping systems such as rice, wheat, and maize due to their efficiency in nutrient delivery, impact on plant metabolism, and environmental compatibility. Their application techniques, dosages, and resultant effects vary depending on the nutrient formulation, growth stage of the crop, and environmental conditions.

Methods of Application

Nano-fertilizers can be applied through multiple routes, depending on the type of crop, growth stage, and desired response:

Soil Application: Incorporating nano-fertilizers into the soil at sowing or during topdressing allows for localized delivery and prolonged nutrient availability. For example, nano-urea and nano-hydroxyapatite have been shown to improve nitrogen and phosphorus retention in the root zone, reducing leaching losses (Liu & Lal, 2015).

Foliar Sprays: Spraying nano-formulations directly on leaves allows for quick absorption via stomatal and cuticular pathways, ensuring rapid translocation to sinks. Foliar application of nano-ZnO and nano-Fe₃O₄ has enhanced photosynthetic activity and chlorophyll synthesis in wheat and rice (Rameshaiah et al., 2015).

Seed Treatment (Priming): Pre-sowing seed soaking in dilute nano-fertilizer solutions enhances early vigor, enzyme activation, and root-shoot balance. Studies report improved germination, seedling establishment, and stress resilience with nano-Ca, nano-Si, and nano-Zn priming in cereals (Tarafdar et al., 2012).

Reported Agronomic Benefits in Cereal Crops

The application of nano-fertilizers in cereal crops has led to multiple physiological, biochemical, and yield-related benefits, supported by several field and greenhouse studies:

- **Increased Nutrient Uptake and Use Efficiency:** Nano-encapsulated fertilizers such as nano-urea or nano-phosphate show controlled release kinetics, ensuring availability throughout the crop cycle and increasing NUE by up to 30–50% over conventional fertilizers (Raliya et al., 2016; Dimkpa et al., 2017).
- **Enhanced Photosynthesis and Metabolism:** Nano-iron and nano-zinc have been linked to increased chlorophyll content, stomatal conductance, and Rubisco activity, contributing to higher CO₂ assimilation and energy use efficiency (Suriyaprabha et al., 2012).
- **Improved Growth and Biomass Accumulation:** Treated cereal plants display enhanced plant height, tillering capacity, leaf area index (LAI), and dry matter accumulation, especially under nutrient-stress or saline conditions (Subramanian et al., 2015).
- **Boost in Yield and Quality Parameters:**
 - In rice: Nano-Si and nano-Zn improved panicle number, grain weight, and head rice recovery (Yang et al., 2020).
 - In wheat: Nano-Cu and nano-Fe enhanced spike length, grain filling rate, and protein content (Prasad et al., 2012).
 - In maize: Nano-MnO₂ and nano-biochar led to increases in cob weight, kernel size, and zinc density, aiding in biofortification (Dimkpa et al., 2020).

Stress Mitigation and Resilience

Nano-fertilizers also demonstrate remarkable potential in alleviating abiotic stress in cereal crops:

Drought: Nano-Si and nano-Zn enhance root depth, relative water content (RWC), and osmoprotectant synthesis (e.g.,

proline), mitigating drought-induced oxidative damage (Khodakovskaya et al., 2012).

Salinity: Nano-Ca and nano-Si reduce sodium uptake, stabilize membrane permeability, and promote antioxidant activity, thereby improving salt tolerance in rice and maize (Haghighi & DaSilva, 2014).

Heat Stress: Foliar sprays of nano-boron and nano-K support enzyme stability and pollen viability, enhancing reproductive success under high temperatures (Zhao et al., 2019).

5. Environmental Implications, Challenges, and Future Prospects of Nano-Fertilizers

Environmental Implications of Nano-Fertilizers

While nano-fertilizers offer promising solutions to enhance nutrient-use efficiency and reduce the ecological footprint of conventional fertilizers, their long-term environmental safety and interactions with ecosystems remain areas of concern. The nanoscale size that enables deeper penetration into plant tissues can also allow unintended entry into non-target organisms, soil microflora, and aquatic systems through leaching and runoff.

- **Soil Health and Microbiome Disruption:** Excessive or unregulated application of metallic nanoparticles (e.g., nano-ZnO, nano-CuO) may alter soil enzymatic activities, disrupt beneficial microbial communities, and interfere with natural nutrient cycling processes (Judy et al., 2011; Geisseler & Scow, 2014).

- **Bioaccumulation and Ecotoxicity:** Studies suggest that nanoparticles may accumulate in plant tissues, raising concerns about their entry into the food chain and potential health impacts on humans and animals (Rico et al., 2011). Moreover, their interaction with heavy metals or persistent pollutants may exacerbate toxicity in soil and aquatic environments.

- **Regulatory Gaps:** A major limitation in environmental governance of nano-agriculture is the lack of clear regulatory frameworks, guidelines for application rates,

and standardized assessment tools to evaluate risks associated with nanoparticles in open-field settings (Kah et al., 2018).

Despite these concerns, it is widely acknowledged that when applied judiciously and in appropriate formulations, nano-fertilizers can significantly reduce nutrient runoff, lower GHG emissions, and promote sustainable farming systems when compared to traditional fertilizers.

Challenges in Adoption and Field Implementation

While nano-fertilizers have demonstrated success under controlled conditions and experimental field trials, several barriers hinder their widespread commercial adoption:

- **Lack of Standardization:** There is significant variation in nanoparticle size, shape, concentration, and coating materials, which affects consistency in efficacy and safety profiles (Tarafdar et al., 2012).
- **Cost and Accessibility:** The production of high-purity nano-formulations requires specialized facilities and cost-intensive processes, making them less affordable for small and marginal farmers, especially in developing nations (Nair et al., 2010).
- **Limited Awareness and Training:** Farmers and extension workers often lack awareness, training, and guidance on optimal application methods, dosage, and storage protocols for nano-fertilizers, which may lead to misuse or underuse.
- **Storage and Handling Issues:** Nanomaterials are sensitive to aggregation, oxidation, and instability over time. Maintaining their dispersion and reactivity during storage and transport remains a technical bottleneck.

Future Prospects and Strategic Roadmap

To fully harness the potential of nano-fertilizers while mitigating associated risks, a multi-pronged approach must be adopted:

- **Integrated Risk Assessment:** Long-term toxicological and ecological studies must be conducted across diverse agroecological zones to understand the fate, transport, and persistence of nanoparticles in agricultural ecosystems (Ma et al., 2010).

- **Policy Development and Regulation:** There is an urgent need for the development of globally harmonized regulations, labeling requirements, and usage limits based on scientific risk assessments to guide safe deployment (Parisi et al., 2015).

- **Green and Bio-based Nano-fertilizers:** Research should emphasize biocompatible and biodegradable nanomaterials, such as nano-clays, chitosan, and carbon-based materials, to ensure eco-friendly formulations (Liu & Lal, 2015).

- **Farmer-centric Models:** Establishing pilot demonstration programs, farmer training camps, and local production hubs can improve adoption, customization, and knowledge-sharing at the grassroots level.

- **Integration with Precision Agriculture:** Combining nano-fertilizers with sensor-based delivery systems, drone spraying, and smart irrigation can enhance input efficiency while reducing waste and environmental exposure.

In conclusion, with focused innovation, risk-aware regulation, and grassroots-level adoption, nano-fertilizers can revolutionize the future of sustainable nutrient management in cereal crops, helping meet the twin goals of productivity enhancement and environmental stewardship.

6. Conclusion

Nano-fertilizers represent a transformative advancement in modern agriculture, offering a sustainable solution to the challenges posed by inefficient conventional fertilization practices. Their nanoscale properties allow for targeted delivery, enhanced nutrient-use efficiency, and reduced environmental losses—making them particularly valuable in cereal crop production systems. By facilitating improved crop growth, yield, and stress resilience, nano-fertilizers hold

immense potential to support global food security amidst the dual pressures of increasing population and climate variability.

However, their adoption must be coupled with careful attention to safety, standardization, and awareness. The transition from laboratory-scale innovation to large-scale field implementation requires an integrated approach involving researchers, policymakers, industry stakeholders, and farmers. With responsible use and strategic investment in research, education, and policy, nano-fertilizers can emerge as a key component of sustainable nutrient management and a driving force behind the next green revolution in agriculture.

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Organic vs. Conventional Farming: A Comparative Study of Sustainability and Environmental Impact

Rick Banerjee, Dr. Mahafuzar Rahaman¹

¹Swami Vivekananda University, Barrackpore

*Corresponding author email: mahafuzarr@svu.ac.in

Abstract:

The current review paper presents a comparative evaluation of organic and conventional farming practices, with a focus on their sustainability and environmental impact. With global agricultural practices facing increasing criticism owing to environmental degradation, climate change, and resource depletion, the need for more sustainable approaches to farming has become imperative. Organic agriculture, which considers biodiversity, soil health, and natural inputs first, is often seen as the environmentally friendly option compared to conventional agriculture based on synthetic chemicals and high-input methods. This paper considers the benefits and drawbacks of the two systems, with an eye to issues such as soil quality, water use efficiency, greenhouse gas emissions, and biodiversity conservation. It also considers the economic practicability and societal implications of each system, especially focusing on long-term sustainability. The results indicate that, although organic farming generally yields environmental benefits, such as reduced chemical runoff and healthier soil, conventional farming can achieve greater yields per unit of land, which could aid in food security. Finally, this report promotes an integrated approach that combines the most effective practices of both farming systems to achieve a balance between productivity and environmental conservation.

Keywords: Conventional farming, organic farming, Environmental Impact, high-input methods , greenhouse gas emissions.

1. Introduction:

Agriculture is crucial for rural life and food security. However, the modern methods of farming have radically altered ecosystems, resulting in climate change and environmental degradation (Tilman et al., 2002). With the concern for long-term productivity and environmental impact on the rise, the debate about whether different systems of farming—particularly conventional and organic—are sustainable has intensified. With a focus on sustainability and environmental impact through the main variables, this article endeavors to offer a comprehensive comparison between conventional and organic farming techniques.

2. Defining Organic and Conventional Farming:

Organic Farming:

Organic farming is a farming system that shuns or significantly reduces the application of synthetic fertilizers, pesticides, genetically modified organisms (GMOs), and growth regulators. Instead, it uses methods like crop rotation, cover cropping, composting, biological control of pests, and mechanical tillage to keep soil healthy, control pests and diseases, and enhance biodiversity (IFOAM Organics International, n.d.). Organic agriculture complies with certain requirements and standards laid down by certifying agencies (such as USDA National Organic Program, EU Organic Regulation).

Conventional Farming:

Conventional agriculture, or industrial agriculture, aims to produce high yields by making intensive use of chemical fertilizers, pesticides, herbicides, and irrigation. It tends to be based on monoculture cropping systems and is reliant on mechanized farming. Conventional agriculture emphasizes efficiency and economy, sometimes at the cost of environmental issues.

3. Comparative Analysis of Sustainability and Environmental Impact:

Soil Health:

- **Organic Farming:** Through methods such as cover crops, composting, and minimal tillage, organic farming promotes soil health. By adding soil organic matter (SOM), these methods enhance microbial diversity, water retention, nutrient cycling, and soil structure (Reganold et al., 1993). Besides mitigating climate change, additional SOM can contribute to carbon sequestration (Lal, 2004).

- **Conventional Farming:** Intensive plowing, monoculture cultivation, and over-application of synthetic fertilizers are among the practices which lead to soil degradation in conventional farming. Montgomery (2007) observes that these practices can lead to SOM depletion, reduction in fertility of the soil, enhancement of soil erosion, and a negative impact on the biodiversity of soil. Aside from disrupting normal nutrient cycles, an excessive dependency on synthetic fertilizers can also lead to acidity of the soil.

Water Quality:

- **Organic Farming:** Organic farming decreases water pollution by removing synthetic pesticides and herbicides, which can pollute surface and groundwater. Water quality is also safeguarded by the application of cover crops and reduced tillage, which minimize soil erosion and sediment runoff (Lotter, 2003).

- **Conventional Farming:** Because synthetic fertilizers and pesticides may leak into water sources, conventional farming presents a serious risk to the quality of the water. Fertilizer runoff nitrate contamination is a common issue that causes rivers to become eutrophic and poses health hazards (Camargo & Alonso, 2006).

Biodiversity:

- **Organic Farming:** Organic farming, as compared to conventional farming, generally promotes more biodiversity. Beneficial insects, birds, and other animals are present in

higher numbers and variety in and around organic farms because of the absence of synthetic herbicides and pesticides (Bengtsson et al., 2005). Biodiversity is also enhanced by providing habitats such as buffer strips and hedgerows and crop rotation in varied manners.

- **Traditional Farming:** Monoculture sowing and intensive herbicide usage are traditional forms of farming that destroy biodiversity. Pesticides can directly kill non-target organisms and disrupt ecosystem functioning as well. Habitat destruction and fragmentation caused by land clearing to accommodate extensive agriculture also reduce biodiversity (Krebs et al., 1999).

Greenhouse Gas Emissions:

- **Organic Farming:** Depending on a number of variables, organic farming has a complex impact on greenhouse gas emissions. Organic farming can require more energy for tillage and weed control but tends to require less energy for the production of synthetic fertilizer. Research shows that since organic farming creates more SOM, the soil can sequester more carbon (Lal, 2004). Nevertheless, one study has pointed out that as organic farming sources its nutrients organically, then it will more likely release greater amounts of nitrous oxide for every unit produced (Skinner et al., 2014).

- **Conventional Farming:** Conventional farming is a major source of greenhouse gas emissions as it has extensive use of fossil fuels for mechanical operations, manufacture of fertilizers, and manufacture of pesticides. The application of nitrogen-based fertilizers can also lead to nitrous oxide emissions, which are a potent greenhouse gas. Nevertheless, conventional farming tends to have higher yields, which can reduce the greenhouse gas emissions per product unit in certain instances (Tilman et al., 2002).

Yield:

- **Organic farming:** When compared to conventional farming, organic farming often suffers from yield gaps, particularly in the initial years of conversion. Organic yields can vary anywhere from 5% to 34%, which is typically lower than that

of conventional farming, depending on the crop and location, based on meta-analyses (Ponisio et al., 2015; Seufert et al., 2012). With appropriate choice of crop and management strategy, however, the gap in yields may be bridged.

- **Conventional Farming:** Since traditional farming employs artificial fertilizers, pesticides, and irrigation, it generally yields more. Higher productivity is a consequence of the maximum nutrient supply, insect control, and water availability facilitated by these inputs.

4. Discussion:

There are benefits and drawbacks to both conventional and organic farming techniques. Conventional farming excels at meeting the needs of an expanding population and maximizing yields but does so at a high environmental cost. Although long-term soil well-being and sustainability of the environment take precedence in organic farming, conventional yields could be hard to beat.

There is more to the conflict between organic and conventional farming than appears on the surface. With the potential for integrated agriculture systems that meld the benefits of both approaches, a more nuanced solution is necessary. This can involve bringing sustainable methods to conventional farming, such as less tillage, cover crops, and integrated pest management. Likewise, precision agriculture and advances in technology can assist organic farming in terms of productivity and yields.

5. Conclusion:

Overall, organic farming is more environmentally sustainable, promotes biodiversity, water quality, and soil health. It may, however, struggle to provide yields comparable to conventional farming. Even though conventional farming produces more yields, it often has a very negative environmental impact. Establishing sustainable agricultural practices that can balance environmental conservation and productivity is paramount for the future of agriculture. This involves a shift towards more environmentally friendly methods, either termed as “organic” or “conventional.” To

ensure food security for an expanding population, reduce the impact on the environment, and optimize the use of resources, more research is needed. In order to build a more resilient and sustainable food system, there is a need to promote agro-ecological practices, promote innovation in sustainable agriculture, and establish legislations to promote them.

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Unseen Heroes of the Soil: The Vital Role of Microbes in Nutrient Cycling

Kankana Panda, Sudip Sengupta*

Department of Agriculture, Swami Vivekananda University,
Barrackpore 700121, Kolkata, West Bengal, India

*Corresponding author: sudips@svu.ac.in

Abstract:

Soil microbes, often overlooked, are essential players in the intricate web of nutrient cycling within terrestrial ecosystems. These microscopic organisms, including bacteria, fungi, and archaea, facilitate the transformation and availability of nutrients essential for plant growth. By breaking down organic matter, they release vital elements such as nitrogen, phosphorus, and potassium into the soil, making them accessible to plants. Furthermore, soil microbes engage in complex interactions with plant roots, enhancing nutrient uptake through symbiotic relationships. Their activities not only support plant health but also contribute to soil structure and fertility, promoting sustainable agricultural practices. As the global demand for food increases, understanding the role of soil microbes in nutrient cycling becomes crucial for developing effective strategies to enhance soil health and productivity. This article delves into the diverse functions of soil microbes in nutrient cycling, highlighting their significance in ecosystem sustainability and agricultural resilience.

Keywords

Soil Microbes, Nutrient Cycling, Soil Health, Ecosystem Sustainability, Plant Nutrition

1.Introduction

Background and Significance

Soil, often regarded as a passive growth medium, is in reality a dynamic and living ecosystem teeming with billions of microorganisms per gram. These unseen soil dwellers—bacteria, fungi, archaea, actinomycetes, protozoa, and other microscopic life forms—perform indispensable roles in maintaining terrestrial ecosystem functions. One of their most crucial contributions lies in **nutrient cycling**, the process by which essential elements such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and various micronutrients are transformed and mobilized within the soil system. Nutrient cycling ensures that these elements are available in forms that plants can absorb, thereby sustaining crop productivity and soil health over time.

Microorganisms act as the invisible engineers of these processes, facilitating both the decomposition of organic matter and the biochemical transformations of inorganic compounds. They regulate critical soil functions such as **organic matter degradation, nitrogen fixation, nitrification, denitrification, phosphate solubilization, and metal chelation**, ultimately influencing plant growth, ecosystem stability, and agricultural productivity (Paul, 2015; Singh et al., 2020).

The Need for Sustainable Soil Management

The exponential rise in global population has placed immense pressure on agricultural systems to produce more food, feed, fiber, and biofuel. To meet these demands, modern agricultural practices have heavily relied on synthetic fertilizers and pesticides, often at the expense of long-term soil health. Such intensive management disrupts native microbial communities, depletes organic matter, causes acidification, and impairs soil structure—all of which hinder natural nutrient cycling (Tilman et al., 2002; Lal, 2015).

Conversely, **microbial-driven nutrient cycling** offers a nature-based solution to these challenges. Enhancing microbial activity and diversity in soils can not only restore

soil fertility but also reduce dependency on external chemical inputs. It fosters a **circular nutrient economy** wherein plant residues and organic wastes are recycled back into the system, mediated by microbial action.

Microbes: The Soil's Hidden Workforce

Microorganisms are the **biochemical gatekeepers** of nutrient transformations. For instance, nitrogen-fixing bacteria such as *Rhizobium*, *Azotobacter*, and *Frankia* convert atmospheric nitrogen into ammonium—a form that plants can assimilate. Ammonia-oxidizing bacteria (AOB) and archaea (AOA) carry out nitrification, while denitrifying bacteria facilitate the conversion of nitrate back into gaseous nitrogen. Similarly, phosphate-solubilizing microbes (PSMs) like *Bacillus* and *Pseudomonas* make phosphorus available by releasing organic acids that dissolve insoluble phosphates (Rodríguez and Fraga, 1999).

Soil fungi, especially **mycorrhizal fungi**, form mutualistic associations with plant roots and enhance uptake of P, Zn, and other immobile nutrients. In parallel, saprophytic fungi and actinomycetes break down complex organic materials such as lignin and cellulose, releasing essential nutrients trapped in plant residues. These microbial processes operate synergistically and are influenced by biotic interactions, abiotic conditions, and anthropogenic activities.

Microbial Interactions and Rhizosphere Dynamics

The **rhizosphere**—the narrow zone surrounding plant roots—is a hotspot of microbial activity. Root exudates, composed of sugars, amino acids, and organic acids, act as signals and substrates for microbial colonization. In turn, the microbes within this zone modulate nutrient availability, produce plant growth-promoting hormones, and suppress pathogens (Berendsen et al., 2012). This intricate web of interactions not only enhances nutrient cycling but also imparts resilience to environmental stress.

Importantly, plants are not passive beneficiaries; they actively recruit and shape their microbiome through exudation patterns and signaling molecules. This **plant-microbe-soil**

continuum is crucial for efficient nutrient cycling and is a focal point for designing future agroecological interventions.

Linking Microbial Activity to Soil Health and Ecosystem Services

The health of soil is inherently tied to the diversity and activity of its microbial inhabitants. Microbial processes are vital not just for crop productivity but also for broader ecosystem services such as carbon sequestration, water retention, detoxification of pollutants, and climate regulation. For instance, microbial-driven organic matter decomposition contributes to humus formation and carbon storage, while microbial EPS (extracellular polymeric substances) help in soil aggregation and porosity (Lehmann and Kleber, 2015).

Given the global challenges of climate change, land degradation, and food insecurity, integrating microbial processes into soil management strategies offers a **sustainable path forward**. Understanding and leveraging microbial nutrient cycling can lead to innovations in biofertilizers, microbial consortia, and soil amendments that enhance nutrient use efficiency while preserving ecological integrity.

2. Diversity of Soil Microorganisms

Soil is a complex and dynamic ecosystem teeming with a diverse community of microorganisms that perform essential roles in nutrient cycling. These microbial communities consist of bacteria, fungi, archaea, protozoa, and actinomycetes, each contributing to specific biochemical processes in the soil environment (Fierer & Jackson, 2006).

Bacteria

Soil bacteria are the most numerous microorganisms in soil ecosystems, often exceeding 10^9 cells per gram of soil. They are central to nitrogen fixation, nitrification, denitrification, and organic matter decomposition. Prominent genera include *Bacillus*, *Pseudomonas*, *Azotobacter*, *Nitrosomonas*, and *Rhizobium* (Torsvik & Øvreås, 2002).

Fungi

Fungi, including saprophytic and mycorrhizal fungi, are

critical in the decomposition of complex organic matter such as lignin and cellulose. Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), form mutualistic relationships with plant roots and enhance nutrient uptake (Smith & Read, 2008).

Archaea

Archaea, once considered extremophiles, are now recognized as key players in soil ecosystems, particularly in ammonia oxidation and carbon cycling. Members of the *Thaumarchaeota* phylum have been implicated in nitrification under oligotrophic conditions (Leininger et al., 2006).

Protozoa and Nematodes

Protozoa and nematodes contribute to nutrient cycling by grazing on bacteria and fungi, thereby releasing nutrients in bioavailable forms. They also regulate microbial population dynamics (Bonkowski, 2004).

Actinomycetes

Actinomycetes are filamentous bacteria known for degrading complex organic materials and producing antibiotics. They play a pivotal role in humus formation and the nitrogen cycle (Goodfellow & Williams, 1983).

3. Mechanisms of Microbial Involvement in Nutrient Cycling

Microorganisms facilitate nutrient cycling through various biochemical and physiological mechanisms:

Decomposition and Mineralization

Microbes decompose organic matter, converting complex macromolecules into simpler inorganic compounds. Mineralization releases essential nutrients like NH_4^+ , PO_4^{3-} , and SO_4^{2-} (Kuzakov & Blagodatskaya, 2015).

Immobilization

Immobilization refers to the temporary unavailability of nutrients as microbes assimilate them into their biomass, a critical process for maintaining nutrient balance in soils (Butterly et al., 2009).

Redox Transformations

Microbial redox processes are essential in cycling of N, S, and Fe. For example, denitrifying bacteria reduce nitrate to N_2 under anaerobic conditions, completing the nitrogen cycle (Philippot et al., 2007).

Solubilization and Chelation

Microbes produce organic acids and siderophores that solubilize phosphate and chelate micronutrients, enhancing their availability to plants (Richardson et al., 2009).

4. Microbial Roles in Specific Nutrient Cycles

Microorganisms mediate a range of elemental cycles in the soil, significantly affecting nutrient bioavailability and soil fertility. Their metabolic activities catalyze the transformation, mobilization, and recycling of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients like iron (Fe), zinc (Zn), and manganese (Mn). These biogeochemical transformations occur through intricate biochemical pathways, often mediated by specialized microbial taxa.

Nitrogen Cycle

The nitrogen cycle is a cornerstone of soil fertility, governed largely by microbial transformations. It includes nitrogen fixation, ammonification, nitrification, and denitrification.

Biological Nitrogen Fixation (BNF): Diazotrophic bacteria like *Rhizobium*, *Azospirillum*, *Frankia*, and cyanobacteria convert atmospheric nitrogen (N_2) into ammonium (NH_4^+), which plants can assimilate (Zahran, 1999). Symbiotic nitrogen fixation, particularly in leguminous crops, plays a vital role in natural nitrogen replenishment.

Ammonification: Decomposition of organic nitrogenous compounds by heterotrophic bacteria and fungi leads to the release of ammonium. This step is critical for converting complex organic matter into simpler inorganic forms.

Nitrification: This two-step aerobic process involves ammonia-oxidizing bacteria (AOB) like *Nitrosomonas* and

nitrite-oxidizing bacteria (NOB) like *Nitrobacter*. Recent findings have highlighted the role of ammonia-oxidizing archaea (AOA), especially in low-nitrogen soils (Leininger et al., 2006).

Denitrification: Facultative anaerobes such as *Pseudomonas* and *Paracoccus* reduce nitrate (NO_3^-) to gaseous nitrogen (N_2), returning nitrogen to the atmosphere. This process, while essential for nitrogen balance, can also lead to nitrogen losses from agricultural systems (Knowles, 1982).

Phosphorus Cycle

Phosphorus is a key macronutrient often immobilized in insoluble forms. Microorganisms improve its bioavailability through several mechanisms:

Phosphate Solubilization: PSMs, including *Pseudomonas*, *Bacillus*, and *Aspergillus*, secrete organic acids (e.g., gluconic acid, citric acid) that chelate cations and release bound phosphate (Rodríguez & Fraga, 1999).

Organic Phosphorus Mineralization: Enzymes like phytases and phosphatases, produced by bacteria and fungi, decompose organic phosphorus compounds into orthophosphate.

Mycorrhizal Fungi: AMF extend their hyphae into the soil, facilitating phosphorus uptake from beyond the depletion zones of plant roots.

Potassium and Micronutrient Mobilization

Potassium (K) and trace elements are often bound in soil minerals and thus not readily accessible to plants.

Potassium Solubilizing Microorganisms (KSM): Species such as *Bacillus mucilaginosus* and *Frateuria aurantia* release acids that solubilize K-bearing minerals like feldspar and mica (Sharma et al., 2013).

Micronutrient Chelation: Microbes produce siderophores – small, high-affinity iron-chelating compounds – that bind and mobilize iron, manganese, zinc, and copper for plant uptake. *Azotobacter*, *Pseudomonas*, and other PGPRs are common siderophore producers.

5. Symbiotic Relationships in Nutrient Cycling

Microbes form mutualistic relationships with plants that significantly enhance nutrient acquisition and efficiency. These symbioses are particularly critical in nutrient-poor soils.

Rhizobia-Legume Symbiosis

Rhizobium, *Bradyrhizobium*, and other rhizobia infect legume roots, leading to the formation of root nodules. Within these nodules, nitrogenase enzymes catalyze the conversion of atmospheric nitrogen to ammonia, providing a nitrogen source for the plant while receiving carbon compounds in return (Sprent, 2009).

Mycorrhizal Associations

Arbuscular mycorrhizal fungi (AMF) form endosymbiotic relationships with the roots of most terrestrial plants. They increase the surface area for water and nutrient absorption, particularly phosphorus and micronutrients. In forest ecosystems, ectomycorrhizal fungi enhance nitrogen cycling and organic matter decomposition (Smith & Read, 2008).

Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR are free-living soil bacteria that colonize root surfaces and interiors. They promote plant growth by producing phytohormones (e.g., indole acetic acid), enhancing nutrient uptake, and protecting against soil-borne pathogens. Common genera include *Pseudomonas*, *Azospirillum*, and *Bacillus* (Vessey, 2003).

Endophytes and Rhizosphere Interactions

Endophytic microbes inhabit internal plant tissues without causing harm. They often contribute to nitrogen fixation, hormone modulation, and nutrient solubilization. In the rhizosphere, complex signaling between plants and microbes regulates nutrient flow and microbial recruitment (Hardoim et al., 2015).

6. Microbial Interactions and Soil Structure

Soil structure directly influences water retention, aeration,

root penetration, and microbial habitat. Microorganisms play a crucial role in stabilizing soil structure through:

Biofilm Formation: Microbes form biofilms—aggregates encased in extracellular polymeric substances (EPS)—on root surfaces and soil particles. These biofilms trap nutrients and moisture, aiding microbial persistence and nutrient exchange.

EPS Production: Exopolysaccharides contribute to soil aggregation by gluing soil particles together, thereby enhancing soil porosity and resistance to erosion (Chenu, 1995).

Organic Matter Transformation: Microbial decomposition results in the accumulation of humic substances, which improve soil texture and cation exchange capacity (Six et al., 2006).

Carbon Sequestration: Microbial biomass and residues contribute significantly to soil organic carbon pools, which is essential for long-term soil fertility and mitigation of atmospheric CO₂ levels.

7. Environmental and Edaphic Factors Affecting Microbial Nutrient Cycling

The efficiency and composition of soil microbial communities are shaped by various biotic and abiotic factors:

Soil pH: Strongly influences microbial diversity and enzymatic activities. Bacteria dominate neutral to alkaline soils, while fungi are more prevalent in acidic environments (Rousk et al., 2010).

Moisture and Temperature: Affect microbial metabolism and community dynamics. Moisture stress limits microbial activity, while temperature controls enzymatic reactions.

Organic Matter Content: Acts as both energy source and nutrient reservoir for microbes. Higher organic matter fosters microbial diversity and activity.

Land Use and Management: Practices such as tillage, crop rotation, and organic amendments alter microbial habitats and functional capacities.

Pollution and Contaminants: Heavy metals, salinity, and pesticide residues negatively impact microbial growth and enzymatic function (Giller et al., 1998).

8. Role in Sustainable Agriculture

Soil microbes offer sustainable alternatives to synthetic inputs by enhancing nutrient efficiency and soil resilience.

Biofertilizers: Inoculants containing beneficial microbes such as rhizobia, PGPRs, AMF, and phosphate solubilizers are increasingly used in various cropping systems (Malusá & Vassilev, 2014).

Integrated Nutrient Management (INM): Combines organic, inorganic, and microbial sources of nutrients. INM promotes synergistic interactions between soil biota and nutrient sources, optimizing nutrient cycling.

Organic and Conservation Agriculture: Practices like composting, mulching, and reduced tillage conserve microbial habitats and support functional diversity.

Climate-Smart Agriculture: Microbial functions like nitrogen fixation, carbon sequestration, and stress mitigation support climate-resilient cropping systems (Schmidt et al., 2011).

9. Advances in Microbial Ecology and Technology

Technological innovations have expanded our understanding of microbial roles in nutrient cycling:

Metagenomics and Next-Generation Sequencing (NGS): Enable identification of unculturable microbes and their functional genes from environmental DNA (Prosser, 2015).

Stable Isotope Probing (SIP): Traces nutrient fluxes through microbial communities by incorporating labeled isotopes into biomass (Dumont & Murrell, 2005).

Synthetic Biology: Involves engineering microbial strains with enhanced metabolic capabilities for targeted nutrient transformations.

Microbial Consortia: Custom-designed microbial formulations combining nitrogen fixers, PSMs, and PGPRs

exhibit synergistic effects on plant growth and nutrient availability.

Soil Biosensors and Omics Platforms: Integrate genomics, transcriptomics, proteomics, and metabolomics to monitor microbial activity and soil health indicators.

10. Challenges and Future Directions

Despite growing recognition of microbial roles in nutrient cycling, several challenges remain:

Microbial Diversity Loss: Monoculture farming, excessive agrochemicals, and soil degradation reduce microbial richness and resilience.

Lab-to-Field Gap: Field performance of microbial inoculants often falls short due to complex soil-environment interactions.

Regulatory and Policy Barriers: Lack of standardized guidelines for microbial product registration and quality control limits widespread adoption.

Farmer Awareness and Training: Adoption of microbial technologies is constrained by knowledge gaps and limited extension services.

Research Gaps: Need for systems-level understanding of microbial networks, long-term monitoring, and integration with precision agriculture.

Future research should focus on unraveling microbe-soil-plant interactions, formulating robust microbial consortia, and designing adaptive soil management practices that harness microbial functions for ecological and agricultural sustainability.

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Unravelling Acid Sulfate Soils: Challenges and Strategies for Sustainable Management

Ramit Raj Halder, Parijat Bhattacharya*

*Department of Agriculture, Swami Vivekananda University,
Barrackpore 700121, Kolkata, West Bengal, India*

**Corresponding author: parijatb@svu.ac.in*

Abstract:

Acid sulfate soils (ASS) are a complex soil type characterized by the presence of iron sulfides, predominantly pyrite (FeS_2). These soils are typically found in coastal and estuarine environments, wetlands, and floodplains. The inherent properties of ASS can lead to the development of acidic conditions upon disturbance, resulting in the mobilization of toxic metals such as aluminum and iron. This mobilization poses significant threats to aquatic ecosystems, contributes to infrastructure corrosion, and diminishes agricultural productivity. Effective management strategies for acid sulfate soils are crucial to mitigate their negative impacts. Key approaches include avoiding soil disturbance to prevent oxidation, implementing water management techniques to maintain stable conditions, and applying lime to neutralize acidity. Additionally, establishing vegetative covers can help reduce soil erosion and further protect these vulnerable environments. Understanding the dynamics of acid sulfate soils is essential for developing sustainable land use practices and preserving ecosystem health. Continued research is necessary to refine management techniques and assess the long-term effects of various interventions on soil chemistry and ecology. This review aims to synthesize current knowledge on the formation, impact, and management of acid sulfate soils, providing a comprehensive resource for researchers, policymakers, and land managers engaged in coastal and wetland conservation efforts.

Keywords: Acid Sulfate Soils, Environment, Reclamation Strategies, Agricultural Sustainability.

1. Introduction

Acid sulphate soils are one of the problematic characters of soil. These are problematic due to their potentiality of releasing acidity in case of exposure to air, which leads to widespread soil degradation. These types of soils are commonly found in coastal and estuarine regions. These soils causes significant challenges for agricultural productivity and environmental health.

Acid Sulphate Soil (ASS), introduced by Chenery et al, (1954) are characterized by drained soils with absorbed sulphate and low pH (<4.0) when in water.

In India ASS are primarily found in coastal saline soil zones which covers 0.26 million hectares. West Bengal's Sundarbans, Andaman and Nicobar island and Kerala's coastal areas contains most of the acid sulphate soil of India.

Formation process of ASS

Acid sulphate soils forms in coastal and estuarine areas which contains oxygen-deficient condition.

Seawater or sulphate rich ground water provides sulfate ions (SO_4^{2-}) and iron, released from weathering of rocks or sedimentation, produces Iron-sulphides which is also termed as pyrite (FeS_2).

Oxidation process

Due to some natural processes and human works pyrite gets exposed to air. After getting exposed to air pyrite goes through oxidation, forming sulfuric acid (H_2SO_4), which make the soil pH low and releases some metals like iron and aluminium.

Pyrite oxidation reaction: $4\text{FeS}_2 + 15\text{O}_2 + 8\text{H}_2\text{O} \rightarrow 4\text{Fe}^{3+} + 8\text{SO}_4^{2-} + 16\text{H}^+$

Impacts of ASS in agriculture

Soil acidification: sulfuric acid which is produced due to oxidation of pyrite, lowers soil pH.

low soil pH reduces soil fertility and kills beneficial microbes

Release of Toxic Metals: ASS releases toxic metals like aluminium, iron and arsenic which directly put impacts on plants, mostly affects root growth and nutrient uptake.

Nutrient deficiency and imbalance: essential nutrients becomes less available in acidic soil, which affects in plants growth and yield.

Poor soil structure and drainage: Acid sulphate soil often form hard and compacted layers, reducing water infiltration and root penetration.

Contaminated Water Supply: Acid Runoff from ASS pollutes irrigation water and affects plant growth.

Economic Loss: Due to negative impact of ASS in crops and soil, it ultimately impacts as Economical loss.

Management of Acid sulphate soil

Controlled use of groundwater: Maintained use of groundwater reduces exposure of pyrite to oxygen.

Use of Lime: Use of lime (Calcium Carbonate) can neutralize the acidic condition

Chemical Treatments: Iron chelating agents and specific buffering agents can be used to treat affected soils, stabilizing iron and preventing its solubility. These treatments are typically more expensive and often reserved for smaller, highly affected areas. Bandopadhyay (1989) and Mongia and Bandopadhyay (1993) have also reported beneficial effects of liming, leaching and MnO₂ application singly and in combination in improving acid sulphate soils.

Use of Organic Amendments: Organic materials, like compost and manure, can buffer the acidification effects of ASS. These amendments add organic matter, increasing microbial activity that can help restore soil health and reduce acidity.

Conclusion

Acid sulfate soils pose serious environmental and agricultural

challenges due to their potential to generate extreme acidity and release toxic metals upon exposure. Their management requires a combination of preventive and remedial strategies, including controlled water use, liming, organic amendments, and chemical treatments. Sustainable handling of these soils is essential to protect ecosystems, ensure agricultural productivity, and minimize economic losses. Continued research and adaptive land management are key to mitigating the long-term impacts of acid sulfate soils.

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In vitro Mutation breeding in *Chrysanthemum*

Subham Ghosh, Suprabuddha Kundu

*School of Agriculture, Swami Vivekananda University, Barrackpore,
700121, West Bengal, India*

***Corresponding author:** suprabuddhak@svu.ac.in

Abstract:

Chrysanthemum (*Chrysanthemum morifolium*) is a globally significant ornamental plant valued for its diverse floral traits and adaptability. In vitro mutation breeding has emerged as a powerful tool for enhancing its genetic diversity and developing novel cultivars. This technique combines the advantages of tissue culture and induced mutagenesis to overcome the limitations of conventional breeding methods. Using physical mutagens (e.g., gamma rays) or chemical agents (e.g., ethyl methanesulfonate), targeted mutations can be introduced into explants such as shoot tips, petioles, or callus tissues under sterile conditions. Subsequent selection and regeneration in vitro facilitate the rapid screening of desirable traits, such as altered flower color, size, morphology, or improved abiotic and biotic stress tolerance. Advances in molecular markers and genomic tools have further streamlined the identification and characterization of mutations, enabling precision breeding. This approach not only accelerates the development of unique chrysanthemum varieties but also ensures sustainability by reducing dependency on natural resources. The integration of in vitro mutation breeding with advanced biotechnological methods holds immense potential for meeting market demands and addressing the challenges posed by climate change. Future research should focus on optimizing protocols, enhancing mutation efficiency, and exploring novel mutagenic agents for broader applications in chrysanthemum improvement.

Keywords: *Chrysanthemum*, in vitro mutation breeding, mutagenesis, biotechnology

1. Introduction

Chrysanthemum morifolium Ramat., a cornerstone of the global floriculture industry belonging to the Asteraceae family, is celebrated for its immense diversity in flower form, color, size, and flowering season. Conventional breeding, primarily reliant on interspecific hybridization and selection, has generated the vast array of existing cultivars. However, this approach faces significant constraints, including genetic barriers between species, linkage drag, prolonged juvenility periods, limited genetic variation for certain traits (especially novel flower colors like true blue), and the time-consuming nature of evaluating large seedling populations. In vitro mutation breeding has emerged as a powerful and indispensable complementary strategy to overcome these limitations (Datta, 2009; Shu et al., 2012). This technique involves the controlled application of physical or chemical mutagens to plant cells, tissues, or organs cultured under sterile conditions, followed by the regeneration, selection, and propagation of desirable mutant phenotypes. It offers a targeted method to broaden the genetic base, induce novel traits absent in the parental germplasm, and accelerate the development of commercially valuable chrysanthemum cultivars with enhanced ornamental appeal and agronomic performance (Mandal et al., 2000; Teixeira da Silva et al., 2013).

2. Principles and Advantages of In Vitro Mutation Breeding

The core principle involves inducing heritable changes (mutations) in the plant genome using mutagens. Physical mutagens, primarily ionizing radiation such as gamma rays (^{60}Co , ^{137}Cs), X-rays, and increasingly, ion beams (e.g., carbon, argon), cause DNA strand breaks and chromosomal aberrations. Chemical mutagens, including alkylating agents like ethyl methanesulfonate (EMS), methyl methanesulfonate (MMS), and sodium azide (NaN_3), or base analogues like 5-bromouracil, induce point mutations by modifying nucleotide bases or causing mispairing during DNA replication (Van Harten, 1998; Nagatomi & Degi, 2009). The choice depends on the desired mutation type, penetration efficiency, safety, and cost. Conducting mutagenesis *in vitro*

offers distinct advantages over *in vivo* methods. It allows for precise control over environmental conditions (temperature, humidity, light), handling of large numbers of uniform explants in minimal space, application of selection pressure directly in the culture medium for traits like disease resistance or salt tolerance, and significantly reduces the prevalence of chimeras (mosaics) compared to treating whole plants or cuttings (Predieri, 2001; Nakano et al., 2015). The sterile environment minimizes pathogen contamination during the critical post-mutagenesis recovery phase. Furthermore, the rapid clonal propagation capability inherent to *in vitro* systems facilitates the swift multiplication of selected mutants once identified.

3. Methodology: Explants, Mutagens, and Protocols

The success of *in vitro* mutation breeding hinges on careful selection of the explant and optimization of the mutagenesis protocol. Commonly used explants include shoot tips, axillary buds, nodal segments (each containing meristematic tissue), leaf discs, and to a lesser extent, callus or cell suspensions. Shoot tips and nodal segments are preferred for their genetic stability and direct shoot regeneration potential, reducing risks of somaclonal variation, but often result in chimeras initially. Mutagenesis using adventitious shoot regeneration systems (e.g., from leaf explants) offers a higher probability of obtaining solid (non-chimeric) mutants, as regenerants can originate from single mutated cells, though this carries an inherent risk of somaclonal variation (Zalewska et al., 2007; Miler & Zalewska, 2014). The mutagenesis process typically involves: 1) Establishment: Culturing uniform, healthy explants on a suitable medium (often MS-based supplemented with cytokinins like BAP). 2) Pretreatment (Optional): Some protocols include a brief culture period or osmoticum treatment to synchronize cell cycles or reduce endogenous water content for chemical mutagen penetration. 3) Mutagen Treatment: Exposing explants to a calibrated dose/concentration of the chosen mutagen for a specific duration. Physical mutagens are usually applied as acute doses, while chemical mutagens require immersion periods. 4) Post-treatment Washing: Essential for chemical

mutagens to remove residual mutagen, usually involving multiple rinses with sterile water or a neutralizing solution. 5) Recovery and Regeneration: Transferring treated explants to fresh regeneration or proliferation medium, often initially without selection pressure to allow recovery. 6) Subculture and Chimera Resolution: Propagating the M_1V_0 generation (first vegetative generation post-mutagenesis) repeatedly (M_1V_1 , M_2V_2 , etc.) to encourage segregation of mutated sectors and achieve genetically stable, homogeneous mutants (Broertjes & Van Harten, 1988; Jerzy & Zalewska, 1996).

4. Dose Optimization and Selection Strategies

Determining the optimal mutagen dose is critical and must precede large-scale experiments. This involves establishing a dose-response curve by treating explants with a range of doses/concentrations and assessing key parameters: survival rate (percentage of explants remaining viable), regeneration rate (percentage of explants producing shoots), growth reduction (e.g., shoot length, number), and observable damage (necrosis). The LD_{50} (dose causing 50% lethality) or GR_{50} (dose reducing growth/regeneration by 50%) are commonly used benchmarks for selecting the optimal treatment dose, aiming to balance sufficient mutation induction with acceptable regeneration capacity (Patil & Patil, 2015; Shao et al., 2019). Selection for desired mutants can be applied at different stages: *In vitro selection* involves incorporating selective agents into the culture medium. Examples include culture filtrates or toxins from pathogens (e.g., *Fusarium*, *Alternaria*) for disease resistance, NaCl for salt tolerance, herbicides, or altered levels of growth regulators or precursors to select for dwarfism or specific pigments (Datta et al., 2001). This allows screening large populations efficiently under uniform pressure. *Ex vitro selection* occurs after mutant shoots are rooted, acclimatized, and transferred to greenhouse or field conditions. This is essential for evaluating complex traits like overall plant architecture, flowering time, flower form, color expression under natural light, vase life, and field resistance to biotic/abiotic stresses. Phenotypic screening remains the primary method, but molecular markers are increasingly used for early detection and confirmation.

5. Major Achievements and Induced Traits

In vitro mutation breeding has yielded numerous successful chrysanthemum cultivars with novel and improved traits.

Flower Color: This is the most targeted trait. Mutagenesis has generated a wide spectrum of novel and altered colors, including various shades of pink, salmon, bronze, lavender, and deeper reds, yellows, and purples. Significant efforts focus on inducing blue/violet hues through mutations affecting the anthocyanin pathway, particularly the expression or activity of flavonoid 3',5'-hydroxylase (F3'5'H) to produce delphinidin derivatives, though achieving true blue remains challenging (Tanaka et al., 2009; Sasaki, 2010). Mutants exhibiting color breaks (stripes, spots, sectors), color intensification, or fading have also been obtained. **Flower Morphology:** Mutations have altered flower type (e.g., single to double, anemone, pompon, spider types), size (miniature or larger blooms), ray floret shape (e.g., tubular, spoon-shaped, quilled), and flower head structure (Misra et al., 2003). **Plant Architecture:** Induction of dwarf and compact mutants is highly valuable for pot plant production and landscaping, reducing reliance on chemical growth retardants. Mutants with altered branching patterns, leaf size, shape, and texture have also been developed (Wang et al., 2013). **Flowering Time:** Early and late flowering mutants extend the marketing period and adapt cultivars to different photoperiodic conditions. **Stress Tolerance:** Mutants exhibiting enhanced tolerance to abiotic stresses like salinity and low temperature, and biotic stresses like fungal diseases (e.g., powdery mildew, rust) or chrysanthemum stunt viroid have been selected, although *in vitro* selection for complex disease resistance remains difficult (Nakano et al., 2015). **Vase Life:** Mutations improving post-harvest longevity are commercially significant.

6. Role of Molecular Markers and Emerging Technologies

Molecular markers have become integral tools for enhancing the efficiency and precision of mutation breeding programs. Techniques like Random Amplified Polymorphic DNA (RAPD), Inter-Simple Sequence Repeats (ISSR), Amplified Fragment Length Polymorphism (AFLP), and more robustly, Simple Sequence Repeats (SSR) and Single

Nucleotide Polymorphisms (SNPs), enable the detection of DNA polymorphisms between mutants and the parental line (Thakur & Sood, 2006; Zhang et al., 2011; Shao et al., 2019). Applications include: 1) Early Detection: Identifying putative mutants at the DNA level before phenotypic expression, especially for recessive traits or traits expressed late in development. 2) Chimera Resolution: Tracking the segregation of mutant sectors through successive subcultures. 3) Genetic Fidelity Assessment: Distinguishing true induced mutations from background somaclonal variation arising from tissue culture. 4) Marker-Assisted Selection (MAS): Potentially selecting for traits difficult or costly to screen phenotypically, once marker-trait associations are established. 5) Diversity Analysis: Characterizing genetic diversity within mutant populations. TILLING (Targeting Induced Local Lesions IN Genomes): Although challenging in polyploids like chrysanthemum, TILLING adapted for vegetatively propagated crops offers a reverse genetics approach to screen mutant populations for lesions in specific target genes controlling desirable traits (Jain, 2010). Genome Editing (CRISPR-Cas9): This revolutionary technology offers the potential for targeted, precise modifications of specific genes, overcoming the randomness of conventional mutagenesis. While chrysanthemum's hexaploid genome and recalcitrance to transformation present hurdles, successful applications for modifying flower color (e.g., knocking out carotenoid cleavage dioxygenase 4 (CCD4) to enhance petal carotenoids) and other traits are emerging, representing the future frontier of precision breeding in ornamentals (Kishi-Kaboshi et al., 2018).

7. Challenges and Future Perspectives

Despite its successes, *in vitro* mutation breeding in chrysanthemum faces several challenges. Chimerism: Achieving genetically stable, non-chimeric mutants often requires multiple cycles of vegetative propagation, increasing time and cost. Randomness: The vast majority of induced mutations are deleterious or neutral, necessitating the screening of very large populations to identify rare beneficial mutants. Hexaploid Genome: The genetic buffering effect

of polyploidy can mask recessive mutations, making their phenotypic expression and recovery more difficult compared to diploids. Somaclonal Variation: The tissue culture process itself can induce genetic/epigenetic changes (somaclonal variation), which can confound the identification of true mutagen-induced variants and sometimes lead to undesirable off-types (Wang et al., 2013; Miler & Zalewska, 2014). Lack of Efficient *In Vitro* Selection Systems: Robust protocols for selecting complex traits like specific disease resistances or abiotic stress tolerances *in vitro* are limited. Genomic Complexity: Limited genomic resources and the genetic complexity of many ornamental traits hinder targeted approaches. Future research should focus on:

Optimizing Protocols: Developing methods for higher mutation efficiency and reduced chimerism, such as using single-cell cultures or optimized meristem treatment.

Advanced Screening: Integrating high-throughput phenomics and genomics (transcriptomics, metabolomics) for more efficient mutant identification and understanding mutation effects.

Robust Selection Systems: Creating reliable *in vitro* and molecular markers for key agronomic traits like disease resistance and stress tolerance.

Precision Breeding: Expanding the application of CRISPR-Cas9 and TILLING platforms for targeted trait modification.

Multi-Omics Integration: Utilizing genomics, transcriptomics, and metabolomics to decipher the genetic networks underlying key traits and identify prime targets for manipulation.

Combined Approaches: Integrating mutation breeding with other biotechnological tools (e.g., somatic hybridization/protoplast fusion) or conventional breeding for synergistic effects.

8. Conclusion

In vitro mutation breeding stands as a vital and proven technology for enhancing genetic diversity and accelerating cultivar development in chrysanthemum. By inducing

novel variation beyond the limits of conventional crossing, it has demonstrably contributed to the commercial release of cultivars featuring unique flower colors, novel floral forms, desirable dwarf habits, altered flowering times, and improved stress resilience. The inherent advantages of the *in vitro* system, particularly in reducing chimerism and enabling large-scale handling and selection, make it superior to *in vivo* methods for vegetatively propagated species. While challenges related to randomness, polyploidy, and efficient selection persist, the ongoing integration of molecular markers for early detection and fidelity assessment, coupled with the transformative potential of genome editing technologies like CRISPR-Cas9, promises to significantly enhance the precision, efficiency, and impact of mutation breeding. Continued research focused on protocol optimization, advanced screening methodologies, and understanding the molecular basis of traits will ensure that *in vitro* mutation breeding remains a cornerstone strategy for meeting the ever-evolving demands of the global floriculture market for innovative and superior chrysanthemum varieties.

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Integrated Pest Management: A Sustainable Approach to Modern Agricultural Challenges

**Priya Mandal, Rakesh Das*, Kaushik Pramanik and
Rakesh Das**

School of Agriculture, Swami Vivekananda University,
Barrackpore 700121, West Bengal, India

*Corresponding author: rakeshd@svu.ac.in

Abstract

Integrated Pest Management (IPM) is a sustainable approach to modern agricultural challenges, addressing pest control while minimizing environmental harm. Traditional reliance on chemical pesticides has led to pesticide resistance, biodiversity loss, and health risks. IPM integrates multiple strategies-cultural, biological, mechanical, and chemical methods-to manage pests effectively while reducing pesticide dependence. Key components of IPM include crop rotation, habitat manipulation, resistant crop varieties, and biological control using natural predators. Chemical pesticides are used only as a last resort, ensuring ecological balance and long-term sustainability. IPM enhances biodiversity, improves soil health, and promotes safer food production. Despite its benefits, IPM adoption faces challenges such as limited awareness, technical expertise, and initial costs. However, advancements in precision agriculture and decision-support systems are making IPM more accessible. Governments and agricultural organizations play a vital role in promoting IPM through policies, research, and farmer education. As modern agriculture strives for sustainability, IPM offers a practical and effective solution for ensuring food security, environmental protection, and human health. Its adoption is essential for a resilient and eco-friendly agricultural future.

Keywords: Integrated Pest Management (IPM); Sustainability; Biological Control; Pesticide Resistance; Precision Agriculture

Introduction

The Changing Landscape of Pest ManagementFor much of the twentieth century, pest management in agriculture was synonymous with the use of chemical pesticides. This “chemical paradigm” delivered dramatic short-term gains in crop yields but, over time, revealed a host of unintended consequences: pesticide resistance, resurgence of secondary pests, ecological imbalance, contamination of soil and water resources, and threats to non-target organisms—including pollinators, natural enemies, and even humans (Pimentel & Burgess, 2014; Pretty & Bharucha, 2015). Increasing globalization and trade further accelerated pest introductions and spread, intensifying biosecurity challenges (Barzman et al., 2015).

With mounting evidence of systemic failure in “spray and pray” methods, researchers and practitioners sought alternative frameworks. The emergence of Integrated Pest Management in the late 1960s and 1970s revolutionized thinking, placing priority on ecological processes, monitoring, and the integration of multiple pest control tactics (Kogan, 1998).

The Philosophy and Practice of IPM

Integrated Pest Management is not a single product, technology, or methodology. It is a science-driven philosophy—“a practical system of crop protection that uses a knowledge-based combination of biological, cultural, physical, mechanical, regulatory, and chemical methods in a coordinated way” (Ehler, 2006; Sparks & Nauen, 2015). IPM is adaptive: it relies on continual monitoring, considers economic, social, and ecological factors, and embraces innovation.

At its core, IPM involves the following principles:

- Prevention rather than cure.
- Use of natural biological controls wherever possible.

- Reliance on chemical pesticides only as a last resort, using targeted, minimally disruptive products guided by economic thresholds.
- Emphasis on the whole agroecosystem, not just the pest organism.
- Active participation by farmers and stakeholders at all stages.

Foundations of Integrated Pest Management

Historical Development and Conceptual Advances

The concept of IPM grew from the recognition that pests are a natural part of agricultural ecosystems and that total eradication is ecologically unrealistic and economically imprudent (Kogan, 1998; Ehler, 2006). During the initial phases of industrial agriculture, the “pesticide treadmill” effect became evident: increased use of potent synthetics led to resistance and non-target outbreaks, requiring yet more chemical use (Hill, 2008).

The 1967 United States National Academy of Sciences report, “Pest Control: Biological, Physical, and Selected Chemical Methods,” catalyzed IPM’s development by advocating for wider implementation of ecological knowledge, population dynamics, and integrated tactics.

The Science of Pest Ecology and Thresholds

At the heart of IPM is the understanding that pest populations fluctuate naturally and can be managed at levels that do not cause significant economic harm (Pedigo & Rice, 2014). Central concepts include:

- **Economic Injury Level (EIL):** The lowest pest population density that will cause economic damage.
- **Economic Threshold (ET):** The pest population density at which control measures should be applied to prevent reaching the EIL.

The deliberate economic foundation of IPM sets it apart from conventional prophylactic spraying. Tactics are implemented only when necessary—avoiding unnecessary costs and reducing risk to beneficial species (Naranjo et al., 2015).

Key Components of an IPM Program

Cultural Control: Re-Designing Agroecosystems

Cultural practices influence pest abundance, habitat, and community structure. Common techniques include:

- **Crop Rotation:** Interrupts pest life cycles by alternating non-host crops (Hill, 2008).
- **Intercropping and Cover Crops:** Increase plant diversity, reducing the likelihood of crop-specific pest outbreaks and supporting beneficial insects.
- **Altered Planting/Harvest Dates:** Escape windows for peak pest periods.
- **Sanitation:** Removal of plant debris and cull piles reduces overwintering sites.

Case Example: In rice cultivation, rotation with legumes has been shown to reduce stem borer and planthopper populations, while also enhancing soil nitrogen content (Pretty & Bharucha, 2015).

Biological Control: Harnessing Ecological Allies

Natural enemies—predators, parasitoids, and pathogens—regulate pest populations. Biological control operates through three channels:

- **Conservation:** Protecting habitats for native enemies (e.g., hedgerows for ladybeetles, floral strips for parasitoid wasps).
- **Augmentation:** Release of commercially-reared beneficials (e.g., *Trichogramma* wasps, predatory mites).
- **Classical Biological Control:** Introduction of natural enemies from the pest's native range, particularly effective against invasive species.

Modern advances include the use of microbial pesticides (e.g., *Bacillus thuringiensis*) and entomopathogenic nematodes, representing rapidly growing sectors in global pest control markets (Van Lenteren, 2012).

Mechanical and Physical Controls: Direct and Non-Chemical

Physical methods can reduce pest populations or prevent colonization:

- **Manual Removal:** Practical in smallholder and high-value cropping systems.
- **Trapping:** Pheromone, light, and colored sticky traps disrupt mating and reduce pest densities.
- **Barriers:** Nets, mulches, and plastic films physically exclude pests.
- **Soil Solarization:** Use of clear plastic to raise soil temperature and kill soil-borne pests.

Integrated with other methods, physical controls fill vital roles in IPM systems, especially in organic operations.

Chemical Control: Precision, Selectivity, and Responsibility

Chemical pesticides are not banished from IPM, but are tightly regulated in timing, choice, and method of application.

- **Threshold-Based Application:** Sprays are applied only when economic thresholds are met.
- **Selective Chemistry:** Use of products with reduced toxicity to non-targets, minimal persistence, and targeted action (Sparks & Nauen, 2015).
- **Rotational Strategy:** Alternating between chemicals with different modes of action to slow resistance development.

Case Example: The judicious use of growth regulators and biological insecticides has almost eliminated broad-spectrum organophosphates in Australian cotton cultivation, lowering environmental impact without yield loss (Barzman et al., 2015).

Pest Monitoring and Decision Support

A defining feature of IPM is its reliance on continuous field monitoring and risk assessment. Modern technologies enable:

- **Regular Field Scouting:** Systematic observation, pest counting, and damage assessment.

- **Pheromone Traps:** For early warning of insect emergence.

- **Remote Sensing and Sensor Networks:** Drones, satellite images, and IoT devices contribute real-time data on pest development, crop health, and weather patterns (Parsa et al., 2014).

Data-driven decisions maximize efficacy and cost-effectiveness while preventing accidental damage to beneficial species.

Benefits and Broader Impacts of IPM

Biodiversity Conservation

IPM reduces pesticide applications, protecting pollinators, decomposers, and non-target wildlife. Enhanced biodiversity, in turn, supports ecosystem stability, crop productivity, and resilience to pest invasions and climate variability (Letourneau et al., 2011; Gurr et al., 2012).

Human and Environmental Health

Limiting the use of hazardous chemicals lowers occupational health risks for farm workers and reduces pesticide residues on food and in the environment (Alavanja et al., 2013). Waterways, soils, and biota benefit from fewer contaminant inputs.

Economic Returns and Farmer Prosperity

Research consistently finds that IPM can deliver equal or higher net returns by reducing input costs, maintaining yields, and reducing losses from pest resistance (Pretty & Bharucha, 2015; Naranjo et al., 2015).

- Economic gains accrue not only from reduced pesticide expenditure, but also from greater market access (certified “IPM/organic” produce) and premium pricing (Barzman et al., 2015).

Case Studies in IPM Implementation

Rice IPM in Asia

A model of successful adoption, the Asia Rice IPM program leveraged extensive farmer training (“Farmer Field Schools”), participatory research, and coordinated regional efforts. Outcomes included a 50-80% reduction in pesticide use, increased natural enemy abundance, and equal or improved yields (Heong & Escalada, 1999).

Cotton IPM in Africa and India

African and Indian cotton farmers embracing IPM protocols — crop rotation, cultural and physical controls, and targeted biopesticides — saw significant drops in pest outbreaks and chemical dependency, with measurable environmental and health improvements (Kranthi et al., 2002).

Vegetable IPM in Europe

European greenhouse and field vegetable systems have integrated monitoring, biorationals, and beneficial insect releases. Government support, market certification, and traceability have accelerated the adoption of safe and effective IPM protocols, reducing chemical residues and supporting public trust (Barzman et al., 2015).

Challenges and Constraints in IPM Adoption

Knowledge, Training, and Perceptions

IPM requires new skills in pest identification, ecological processes, and monitoring. Lack of farmer education, insufficient extension resources, and entrenched “chemical-centric” mindsets are recurring barriers (Kogan, 1998; Barzman et al., 2015).

Economics and Policy Factors

Initial costs, particularly for biological agents and monitoring, can discourage adoption, especially among resource-poor smallholders. Policy incentives, subsidies, and infrastructure investments dramatically influence IPM uptake (Sparks & Nauen, 2015).

Institutional and Regulatory Barriers

National regulation of biocontrol agents, registration of low-toxicity chemicals, and integration into crop insurance and food safety programs all affect IPM deployment (Barzman et al., 2015). Fragmented supply chains and limited access to quality biocontrol products are acute constraints in developing countries.

Social and Cultural Context

Trust in extension advice, farmer networks, and perceived risk influence choices. Community-based approaches—incorporating participatory research and shared decision-making—are more likely to succeed than top-down prescriptions (Pretty & Bharucha, 2015).

Enabling Advances: Technology and Knowledge Integration

Digital Agriculture and Decision Support

Precision technologies enable more accurate pest monitoring, diagnosis, and threshold determination:

- Smartphone apps and online platforms connect farmers to diagnostic tools, forecasting, and markets (Parsa et al., 2014).
- Big data and AI algorithms are being explored for predicting pest outbreaks, optimizing spray schedules, and improving rapid response.

Genomics, Biotechnologies, and Microbials

Gene editing (CRISPR), molecular markers for pest and resistance monitoring, and introduction of genetically improved natural enemies/additional biopesticides herald a new era in smart IPM (Sparks & Nauen, 2015).

Participatory and Farmer-Led Innovation

Farmer Field Schools, research-for-development initiatives, and south-south cooperation have shown the power of bottom-up models for IPM adoption, adaptation, and scaling-up (Barzman et al., 2015; Pretty & Bharucha, 2015).

Policy, Institutions, and Global Partnerships

Governmental Roles

IPM adoption can be accelerated by:

- Policy frameworks prioritizing sustainable pest management.
- Support for extension, research, and farmer education.
- Incentive programs rewarding biodiversity enhancements, lower inputs, and environmental services.
- Market-based incentives and eco-labeling.

Value Chain and Market Engagement

Retailer standards, third-party certification, and consumer awareness are driving IPM adoption by linking sustainable production with market access, especially in high-value, export-oriented crops (Letourneau et al., 2011).

IPM and the Future of Sustainable Agriculture

Climate Change Adaptation

IPM, built on adaptive management, is exceptionally well-suited for the unpredictable challenges of climate change. The resilience conferred by biodiversity, reduced chemical dependency, and enhanced ecosystem services will be critical for future food security (Gurr et al., 2012; Barzman et al., 2015).

Integration with Agroecology and Regenerative Farming

IPM is increasingly converging with agroecological principles—diversification, soil health, resource recycling, and landscape-level management. Innovations such as push-pull technology, cover cropping, agroforestry, and polycultures are expanding the IPM toolbox (Altieri et al., 2012).

Conclusion

Integrated Pest Management is more than a technical solution; it is the embodiment of sustainability in crop production—a reflection of ecological literacy, stewardship, and long-range vision. Through synergy between research, technology,

policy, and farmer engagement, IPM offers a robust pathway toward resilient, climate-smart, and eco-friendly agriculture. Embracing IPM is a moral, economic, and environmental imperative for securing food systems and protecting earth's biodiversity for future generations.

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Exploring the Potential of Dragon Fruit (*Hylocereus spp.*) in Arid and Semi-Arid Regions

Arnab Ghosh and Tanmoy Sarkar

Department of Agriculture, School of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, 700121

Corresponding author: tanmoys@svu.ac.in

Abstract

Dragon fruit (*Hylocereus spp.*) has emerged as a promising crop for arid and semi-arid regions due to its exceptional drought tolerance and ability to thrive in harsh environmental conditions. This cactus species, known for its vibrant, nutrient-rich fruit, offers a sustainable solution to food security challenges in water-scarce areas. Its ability to survive with minimal irrigation, coupled with low soil fertility requirements, positions dragon fruit as an ideal candidate for cultivation in regions with limited water resources. Rich in vitamins, antioxidants, and fiber, dragon fruit is also a valuable crop for improving nutritional outcomes. Moreover, its economic potential, driven by increasing global demand, provides a lucrative opportunity for farmers in arid regions. Advances in agronomy, including optimized irrigation systems and soil conditioning techniques, have further enhanced its cultivation. By tapping into dragon fruit's potential, arid and semi-arid regions can diversify agriculture, improve livelihoods, and promote environmental sustainability.

Keywords: Drought tolerance; Economic potential; Arid and semi-arid regions; Sustainable agriculture; *Hylocereus spp.*

1. Introduction

Arid and semi-arid regions, characterized by low and unpredictable rainfall, high temperatures, and poor soil fertility, face significant challenges in sustaining conventional

agriculture. Climate change exacerbates these conditions, leading to increased water scarcity and land degradation, thereby threatening global food security (Reynolds et al., 2007). In this context, there is an urgent need to identify and promote crop species that are not only resilient to such abiotic stresses but also economically viable and nutritionally beneficial. Dragon fruit (*Hylocereus* spp.), a member of the Cactaceae family, has recently garnered international attention as one such candidate. Native to tropical regions of the Americas, this climbing cactus is now cultivated across Southeast Asia, the Middle East, and parts of Africa, demonstrating remarkable adaptability (Mizrahi et al., 2002). The plant's inherent drought tolerance, Crassulacean Acid Metabolism (CAM) photosynthetic pathway, and minimal agronomic requirements make it exceptionally suited for cultivation in marginal lands where traditional crops fail (Nobel & De la Barrera, 2003). This manuscript explores the multifaceted potential of dragon fruit, delving into its physiological adaptations, nutritional profile, economic viability, and optimized cultivation practices, arguing for its strategic integration into agricultural systems in arid and semi-arid regions to enhance resilience, nutrition, and farmer incomes.

2. Physiological Adaptations for Drought Tolerance

The success of dragon fruit in water-limited environments is fundamentally rooted in its unique physiological and morphological adaptations. As a CAM plant, dragon fruit opens its stomata at night to take in carbon dioxide, which is fixed into organic acids and stored in its succulent stems. During the day, when stomata are closed to prevent water loss, these acids are decarboxylated, and the released CO₂ is used for photosynthesis (Nobel, 2006). This mechanism drastically reduces transpirational water loss, allowing the plant to achieve a high water-use efficiency, a critical trait for survival in arid zones (Cushman, 2001). Furthermore, the plant possesses a shallow but extensive root system that efficiently captures light rainfall and dew, while its succulent, chlorophyll-rich stems serve as water reservoirs and the primary photosynthetic organs (Mizrahi, 2014). The

thick, waxy cuticle of the stems further minimizes water loss through evaporation. These combined adaptations enable dragon fruit to survive and produce fruit with significantly less water than conventional fruit crops like citrus or mango, requiring as little as 20-30% of the irrigation water (Weiss et al., 2010). This makes it a cornerstone for climate-resilient agriculture in areas facing increasing water scarcity.

3. Nutritional and Health Benefits

Beyond its agronomic resilience, dragon fruit is a powerhouse of nutrition, offering significant health benefits that can address micronutrient deficiencies in vulnerable populations. The fruit, which comes in varieties with white, red, or purple pulp, is low in calories but rich in essential nutrients. It is an excellent source of vitamin C, antioxidants like betalains (in red-pulped varieties) and flavonoids, and dietary fiber (Jamilah et al., 2011). The betalain pigments, responsible for the vibrant red and purple hues, possess potent antioxidant and anti-inflammatory properties, which are linked to reduced risk of chronic diseases such as cancer and cardiovascular disorders (Wu et al., 2006). The high fiber content aids in digestion and helps regulate blood sugar levels, making it a valuable dietary component (Stintzing et al., 2002). Additionally, the fruit contains prebiotic oligosaccharides that promote the growth of healthy gut bacteria (Wichienchot et al., 2010). The seeds, which are edible, provide a good source of omega-3 and omega-6 fatty acids (Ariffin et al., 2009). Introducing this nutrient-dense fruit into local diets can therefore play a crucial role in improving public health outcomes in arid regions, where access to a diversity of fresh fruits is often limited.

4. Economic Viability and Market Potential

The cultivation of dragon fruit presents a compelling economic opportunity for farmers in arid and semi-arid regions, driven by rising global and domestic demand. Often marketed as a “superfruit,” dragon fruit commands premium prices in international markets, particularly in Europe, North America, and the Middle East (Lichtenthäler et al., 2005). Its long harvesting period, often spanning several months, provides farmers with a continuous source of income rather

than a single seasonal payout, which enhances financial stability (Hoa et al., 2006). The crop begins yielding within one to two years of planting and can remain productive for over 20 years, ensuring a long-term return on investment. Furthermore, dragon fruit plants can be intercropped with other drought-resistant species or integrated into agroforestry systems, providing additional income streams and enhancing farm biodiversity (Nobel, 2002). Value-added products such as jams, jellies, wines, and natural colorants extracted from the fruit peel and pulp can further augment profitability (Wu et al., 2006). For rural communities, the establishment of dragon fruit cooperatives can facilitate access to larger markets, improve bargaining power, and create local employment opportunities, thereby fostering holistic rural development (Mercado-Silva, 2018).

5. Agronomic Practices and Cultivation Management

To fully realize the potential of dragon fruit in arid regions, the adoption of specific agronomic practices is essential. While the plant is adaptable, optimal growth and yield are achieved through careful management. Dragon fruit prefers well-drained, sandy loam soils with a slightly acidic to neutral pH, but it is highly tolerant of poor and saline soils, a common feature in arid areas (Castellanos et al., 2009). Due to its climbing habit, it requires a supporting structure or trellis system, which facilitates aeration, pest management, and efficient harvesting (Trindade et al., 2011). Although drought-tolerant, strategic irrigation is critical during the flowering and fruit development stages to ensure good fruit size and quality. Drip irrigation systems are highly recommended as they deliver water directly to the root zone, maximizing efficiency and conserving scarce water resources (Weiss et al., 2010). Nutrient management should focus on organic amendments like vermicompost and farmyard manure, which improve soil structure and water-holding capacity while providing a slow-release source of nutrients (Bartholomew et al., 2020). Integrated Pest Management (IPM) strategies should be employed to control common pests like stem borers and ants, as well as diseases like anthracnose, with an emphasis on biological controls to maintain the crop's organic credentials (Masyahit et al., 2009).

6. Conclusion

Dragon fruit (*Hylocereus* spp.) stands out as a paradigm of a sustainable and climate-resilient crop perfectly suited for the challenges of arid and semi-arid agriculture. Its exceptional physiological adaptations for water conservation, coupled with its low input requirements, position it as a key species for combating desertification and promoting agricultural productivity in marginal environments. The significant nutritional benefits of the fruit offer a direct pathway to improving health and combating hidden hunger in these regions. Economically, its high market value and long productive lifespan provide a viable and lucrative alternative for farmers, contributing to poverty alleviation and economic diversification. The successful establishment of dragon fruit cultivation, supported by appropriate agronomic research and extension services, can transform barren landscapes into productive orchards. Therefore, governments, agricultural researchers, and development agencies should prioritize the promotion of dragon fruit through farmer training, the development of improved cultivars, and the creation of robust market linkages. By embracing the potential of this remarkable cactus, arid and semi-arid regions can build more resilient, profitable, and sustainable agricultural systems for the future.

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Contributors

Dr. Tanmoy Sarkar

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Sudip Sengupta

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Suprabuddha Kundu

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Rakesh Das

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Parijat Bhattacharya

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Tanmoy Majhi

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Ria Mukhopadhyay

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Animesh Ghosh Bag

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Sayani Bhowmick

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Mahafuzar Rahaman

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Anirneeta De

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Mr. Kaushik Pramanik

Assistant Professor,

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24

Parganas, West Bengal 700121, India

Dr. Nitin Chatterjee

Department of Agricultural Chemistry and soil science BCKV,
Mohanpur

Abhinaba Samanta

UG Student, School of Agriculture, Swami Vivekananda
University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Biswadeep Mazumder

UG Student, School of Agriculture, Swami Vivekananda
University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Ramit Raj Halder

UG Student, School of Agriculture, Swami Vivekananda
University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Rick Banerjee

UG Student, School of Agriculture, Swami Vivekananda
University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Kankana Panda

UG Student, School of Agriculture, Swami Vivekananda
University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Subham Ghosh

UG Student, School of Agriculture, Swami Vivekananda University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Dipanwita Manna

UG Student, School of Agriculture, Swami Vivekananda University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Sneha Nandi

UG Student, School of Agriculture, Swami Vivekananda University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Priya Mandal

UG Student, School of Agriculture, Swami Vivekananda University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India

Arnab Ghosh

UG Student, School of Agriculture, Swami Vivekananda University, Telinipara, Barrackpore,

North 24 Parganas, West Bengal, India