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INNOVATIVE FARMING | SUSTAINABLE PRACTICES | AGRI TECHNOLOGY | FARMER EMPOWERMENT | BETTER SOIL BETTER FUTURE

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EDITOR-IN-CHIEF

Dr. Balveer Singh
SMS-Agronomy
Krishi Vigyan Kendra, Hathras, Rati ka nagle,
Sikandrarao Road Hathras (Hathras) (U.P.), INDIA, PIN – 204 101

✉ Email: bvs955rajpoot@csauk.ac.in

🌐 Institutional Profile Link: https://mahamayanagar.kvk4.in/staff-strength.php

☎ Mobile: 9411259853

MEMBERS

Meet Our Dedicated Team

1 **Dr. Asha Upadhyay**
Assistant Regional Director
Regional Centre Jammu of IGNOU,
Aurobindo Block, Canal Road, Jammu-180001 (J&K), India
✉ ashaupadhyaya@ignou.ac.in
🌐 http://rcjammu.ignou.ac.in/aboutus/employee
☎ +91-9419263473

2 **Dr. Ashoka, P**
Professor and Head
Agricultural Reaserch station
Hanumanmatti(p) Ranebennur(tq) ,
Haveri 581 115 Karanataka
✉ ashokap@uasd.in
🌐 https://ach.uasd.edu/index.php/department-of-agronomy/
☎ +91-9686609363

3 **Dr. Lalit Upadhyay**
Senior Scientist, Agroforestry
KVK Reasi SKUAST-Jammu
Pin: 182301
✉ lalitkvkr@skuastj.org
🌐 https://kvkreasi.in/aboutus.html
☎ +91-9419215594

4 **Dr Sumit Rai**
Sr. Scientist, Centre for Environment Assessment &
Climate Change GB Pant National Institute of
Himalayan Environment Kosi-Katarmal,
Almora-263643, Uttarakhand
✉ rai.sumit@gbpihed.nic.in
🌐 https://gbpihed.gov.in/CEA&CC.php
☎ +91-7379738892

5 **Dr. Manish Singh**
Scientist-C, Centre for Environment Assessment &
Climate Change GB Pant National institute of
Himalayan Environment Kosi-Katarmal,
Almora-263643, Uttarakhand
✉ manish.singh@gbpihed.nic.in
🌐 https://gbpihed.gov.in/CEA&CC.php

Few Words

Welcome to the inaugural edition of **Kheti Vigyan e-magazine!** As the Editor-in-Chief, it is an absolute honor to introduce a digital platform dedicated entirely to **bridging the gap** between scientific laboratory research and practical, on-field farming. The landscape of agriculture is evolving at an unprecedented pace, facing the dual challenges of climate resilience and a rapidly growing population. In this dynamic era, traditional practices alone are no longer sufficient to sustain productivity. Our mission with Kheti Vigyan is to **empower farmers, extension workers, researchers, and agritech enthusiasts** with data-driven insights, advanced cultivation techniques, and smart technologies. We are committed to delivering timely, actionable scientific knowledge directly to your screens, translating complex research into simple, localized, and profitable solutions.

* * *

A primary focus of this e-magazine is the promotion of **sustainable agriculture and modern resource management.** We firmly believe that the future of farming lies in enhancing **nutrient use** efficiency and prioritizing **soil health management.** Through our upcoming editions, readers will find comprehensive coverage on **precision agriculture, integrated nutrient management, resource-conserving technologies,** and the revolutionary impact of **nano-fertilizers** in modern crop production. Additionally, we aim to spotlight **climate- resilient crops, biofortification strategies,** and **diversified farming systems** that secure both income and nutrition for the farming community. Kheti Vigyan is designed to be more than just a publication; it is a collaborative digital space where scientific expertise meets grassroots farming realities, fostering a community dedicated to innovation and environmental stewardship.

* * *

We extend our heartfelt gratitude to the scientists, contributors, and field experts whose valuable research and insights shape these pages. Most importantly, we thank you, our readers, for joining us on this digital journey toward a **smarter, greener, and more food-secure future.** We hope Kheti Vigyan e-magazine serves as your trusted knowledge partner, inspiring you to adopt scientific innovations that transform agriculture from a means of livelihood into a highly sustainable and prosperous enterprise.

Happy reading!

(Balveer Singh)

Editor-In-Chief

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Kheti Vigyan *e*-Magzine

Article ID: KVM0001/26 **Popular Article**

Soil Carbon Sequestration: A Powerful Tool in the Fight Against Climate Change

[1]Sulochna and [2]Shashidhar, K. S.

[1]*Assistant Professor-cum-Junior Scientist Faculty of Agriculture Department of Agronomy Agriculture College Garhwa Bishunpur, Piprakala, Garhwa-822114 Birsa Agricultural University, Jharkhand*

[2]*Assistant Professor and Course coordinator, B.S. (Hons.) Agriculture, Rajiv Gandhi South Campus, RGSC, Banaras Hindu University, Barkachha, Mirzapur, 231307*

***Corresponding Author**

Shashidhar, K. S.

✉ **: Shashi81@bhu.ac.in**

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Abstract:- The carbon sequestration in soil is natural climate solution that cannot be over-emphasized because it has huge potential of reducing the CO2 levels in the atmosphere, and at the same time improve the agricultural performance of the soil and ecosystem stability. This is a thorough review of the processes, application and international possibilities of soil carbon storage in different ecosystems. As we have the current rates of sequestration, management methods, and technology, we will obtain solutions to have the maximum possible amount of carbon in the agricultural and natural lands. The article makes comparisons of the region-specific strategies particularly to the Indian agriculture systems, and takes into consideration the economic incentives, policy frameworks, and the monitoring issues. We have determined that it is possible to achieve a maximum of 2-5 PgC/per year of soil sequestration and help mitigate climate and enhance soil health and food security.

Keywords: Soil Carbon, Climate Mitigation, Agricultural Management, Ecosystem Service, India.

Introduction:- Carbon sequestration in soil has been cited as among the most promising nature-based ways of dealing with the two issues of climate change and food security. It is estimated that the world soil bank has approximately 2,500 PgC in the top 3 meters of soil which exceeds the amount of carbon in the atmosphere and in vegetation on the earth (Neve & Sachs, 2020). This massive reservoir poses the greatest opportunity of curbing climate through encouraging the best management practices that improve organic storage of carbon and improve soil fertility and agricultural production.

The present alarming need to lower global warming to 1.5 ^{0}C above the pre-industrial temperature aggravates the immediate need to adopt several measures aimed at mitigating global warming (Asghar *et al.*, 2024). The sequestration of carbon in the soils is a highly accessible and affordable means, and which could be implemented immediately in the agricultural farms around the globe. Smallholder farmers are capable of adopting soil management techniques using the existing equipment and knowledge systems unlike other technological solutions which might require the development of a massive infrastructure in relation to the smallholder farming, particularly in developing nations like India where smallholder farming system is the prevailing system.

The agricultural sector in India has a vast potential in terms of carbon sequestration, having more than 600 million farmers, and a land area of 157 million hectares (Sarto & Ozili, 2025). The agro-ecological diverse nature of the nation such as the Indo-Gangetic plains and the Western Ghats provides numerous opportunities in terms of the implementation of the context-specific sequestration plans. However, over 30-50 years of intensive cultivation systems, excessive use of chemicals, and poor handling of organic material have depleted the carbon content of the soil in most regions (Raghav *et al., 2025)*. Such lessons may be applied in the formulation of particular interventions that can yield the best sequestration and co-benefits like increasing water capacity, cycling nutrients and resistance to climate extremes in crops (Asghar *et al.*, 2024).

Mechanisms of Soil Carbon Sequestration

Biological Processes

Carbon sequestration in the soil mainly depends on the proportion of the carbon input into the soil by the plants during the photosynthesis process and the carbon output of the microbes during the decomposition process. The major source of soil organic carbon that is used to bury 40-60 percent of the photosynthetically fixed carbon in plants is root biomass and rhizodeposition (Lv *et al.*, 2024). Root exudates are sources of energy to the microbial communities, which are energy sources through containing sugars, amino acids, and organic acids that promote carbon cycling. The effectiveness of the carbon delivery of the plants to the stable soil organic matter is determined by several factors such as the plant species composition, the root morphology and mycorrhizal association.

Mycorrhizal mycorrhizae, especially the arbuscular mycorrhizae which are linked with 80% of land plants are also important in carbon sequestration. These symbiotic fungi form networks of hyphae in the soil aggregates and they transfer photosynthetic carbon deep into the soil profiles and produce glomalin-related proteins which stabilize soil aggregates (Mathur *et al.*, 2025). It has been established that carbon produced by mycorrhizals has a long existence in soil compared to carbon produced by roots due to chemical recalcitrance and physical entrapment in aggregates.

In soils, carbon turnover takes place through microbial degradation of organic matter through the action of enzymes. Bacterial and fungal biomass has a direct effect on the formation of soil organic matter by necromass, contributing up to 50 percent of total soil organic carbon (Lv *et al.*, 2024).

Chemical Stabilization

The chemical processes conserve organic carbon by preventing its degradation by a number of bonding reactions with the soil minerals. The preponderant long-term carbon stabilization process in the majority of soils is organo-mineral associations, especially with clay particles and metal oxides (Basile-Doelsch *et al.*, 2020). These interactions are formed through ligand exchange, cation bridging and van der Waals forces and they form stable complexes which are not easily attacked by microbes. The soils with a great quantity of clay and the reactive surfaces of minerals demonstrate a great prospect of carbon sequestration due to the fact that they experience a better protection in the form of chemical one.

The composition of organic inputs has a molecular structure, which defines their persistence in the soil. Long aliphatic chains, functional groups of compounds with nitrogen, and aromatic structures are more difficult to decompose (Courtier-Murias *et al.*, 2013). Nevertheless, new studies question the conventional paradigm of recalcitrance indicating that environmental factors and accessibility of microbes and not the chemical properties are the main determinants of decomposition rates. This understanding makes the management focus on creating a state that can support organo-mineral contacts as an alternative to simply adding recalcitrant materials.

Physical Protection

Aggregation of soils offers physical security of organic carbon by restricting the access of microbes and lowering the supply of oxygen. The fungal hyphae, roots and organic binding agents are used to bind together micro-aggregates and primary particles to form the macro-aggregates (>250 5m). In such aggregates, the particulate organic matter gets clogged forming anaerobic microsites that delay decomposition. In the aggregate hierarchy concept, progressive stabilization is defined as the movement of organic matter to less free particulate forms to less vulnerable pools in smaller (Devine *et al.*, 2014).

Table 1: Soil Carbon Pools and Residence Times

Carbon Pool	**Size Range**	**Residence Time**
Dissolved organic carbon	<0.45 µm	Days to weeks
Particulate organic matter	53-2000 µm	Months to years
Microbial biomass	1-10 µm	Weeks to months
Mineral-associated carbon	<53 µm	Decades to centuries
Pyrogenic carbon	Variable	Centuries to millennia
Occluded particulate	53-250 µm	Years to decades
Deep soil carbon	>30 cm depth	Centuries

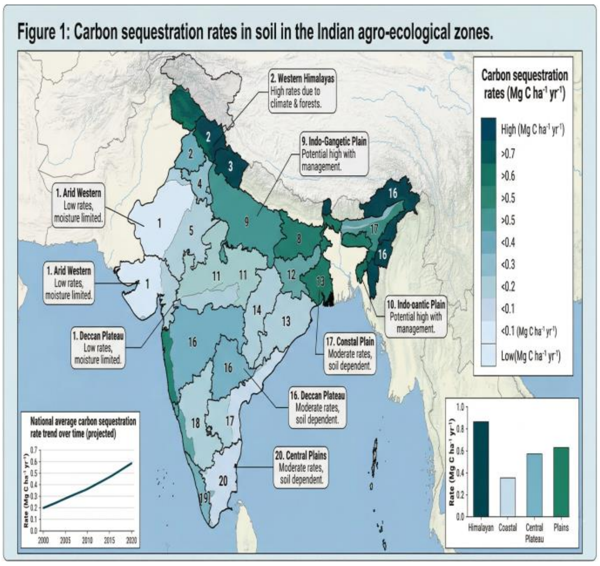
Global and Regional Carbon Sequestration Potential

Global Assessment

The global estimates of the potential of soil to sequester carbon have wide ranges with assumptions made on matters relating to land use change, intensity of management, and implementation timescales. It has been estimated conservatively that through better management practices agricultural soils can eliminate 0.4-1.2 PgC/yr (Alexander et al., 2015). Positive ones, massive adoption of best practices, land use changes that involve transformation to sequestration rates of 2-5 PgC/per annum. Such rates would offset 10-30 per cent of current anthropogenic emissions and would provide energy systems transitions with necessary time.

The fastest sequestration potentials are found in croplands which cover a total of 1.5 billion hectares of land globally because of the easily practiced methods. Agricultural soils that are in place have lost half to three quarters of their initial carbon stocks and this presents a massive potential of restoration (Zomer *et al.*, 2017). The grasslands and rangelands, which occupy 3.5 billion hectares, have a high sequestration potential since there is improved grazing practices as well as regeneration of the damaged land. Forest soils are not in most cases known to contain much more carbon potential sequestration than the current stocks, even though their stocks of carbon are significant.

Figure 1: Carbon sequestration rates in soil in the Indian agro-ecological zones.



Indian Context

There are varied possibilities of carbon sequestration in the agro-ecological regions in India depending on climate, nature of soil and the current management systems. The carbon depletion that has been as a result of burning the residues and over tillage has struck a blow to the Indo-Gangetic Plains which is the home of intensive rice-wheat system on 13.5 million hectares. The studies indicate that conservation agricultural practices can sequester 0.5-1.0 MgC/ha/year and at the same time be productive in these systems. The Deccan Plateau of 100 million hectares that is semi-arid has lower sequestration rates (0.2- 0.5 MgC/ha/year) yet of high areas to be applied (Kumar *et al.*, 2020).

Sequestration has much potential in coastal regions and the western ghats since the regions receive good rainfall and temperature. Traditional agro forestry systems in these regions already possess high levels of soil carbon compared to the mono culture agriculture (Jaisridhar *et al.*, 2025). The northeastern states which have altered cultivation patterns present unique challenges and opportunities of carbon management in relation to enhanced management of fallow and agro forestry integration (Sahoo *et al.*, 2021).

Management Practices for Enhanced Sequestration

Conservation Agriculture

Conservation Agriculture: Conservation agriculture is a practice that has been put in place to increase carbon sequestration of the soil by ensuring minimal disturbance of the soil, covering the soil and crop diversity. Soil systems with low or no-tillage reduce the oxidation and erosion of carbon and soil structure as well as maintain the biological activity (Khan & Wang, 2023). Meta-analyses show that no-till can captivate 0.3-0.5 MgC/ha/year of top 30 cm soil, and to a greater extent in cooler and damper climates. The carbon deposition is however normally concentrated at the surface and full profile procedures are to be taken into consideration.

Cover cropping and left behind of residues contain colossal amounts of carbon and serves as a deterrent measure in the fight against soil erosion, low and high temperatures. The cover crops will produce 1-3 Mg/ha of biomass per year and the leguminous species which carry the nitrogen will enhance the primary crop production (Singh & Pandey, 2024). Various root network, residue characteristics and rhizosphere correlation improve the carbon storage in plant rotation and diversification. Planting of deep rooted plants such as the pigeon pea (*Cajanus cajan*) or the perennial grasses enhances more carbon to be added to deeper parts of the soil where stabilization ability is deeper (McCauley & Barlow, 2023).

Organic Amendments

This is attributed to the fact that carbon is directly added to soils by addition of organic amendments such as compost, farmyard manure and vermicompost and enhances physical, chemical and biological characteristics of soils. Well composted materials have efficiencies of carbon sequestration 10-30% and are further enhanced by minerals associations and aggregate formation (Sahu *et al.*, 2021). There is also the possibility of converting the biomass to biochar which is a by-product of pyrolysis biomass and it has a high carbon sequestration capacity because of its recalcitration and 100 years permanence. Ten to thirty Mg/ha sequestration potentials have the ability to remove 5-15 MgC/ha, and enhance the soil to retain water and nutrients (Yadav *et al.*, 2017). Some other waste management in the Indian situations is biochar that is generated through the assistance of agricultural residues that produce carbon credits. The implementation issues are however the cost of production, availability of feedstock and application logistics.

Table 2: Carbon Sequestration Potential of Management Practices

Practice	Sequestration Rate	Implementation Cost
No-till agriculture	0.3-0.5 MgC/ha/yr	Low-moderate
Cover cropping	0.2-0.4 MgC/ha/yr	Moderate
Agroforestry	0.5-1.5 MgC/ha/yr	High initial
Biochar application	0.5-2.0 MgC/ha/yr	High
Compost addition	0.3-0.7 MgC/ha/yr	Moderate
Rotational grazing	0.2-0.5 MgC/ha/yr	Low
Wetland restoration	1.0-3.0 MgC/ha/yr	Very high

Agroforestry Systems

Agro forestry is a combination of trees and shrubs with crops or livestock to form multi-strata systems that would capture carbon best above and below ground. Such systems are able to trap 0.5-1.5 MgC/ha/year of the soil and other carbon contained in woody biomass (Selley & Sonnenberg, 2022). Successful cases of agroforestry systems which integrate carbon sequestration and food production include the use of agro forestry systems such as home gardens in Kerala, and khejri (*Prosopis cineraria)* systems in Rajasthan which are traditional Indian agro forestry systems.

Figure 2: Integrated Management System for Carbon Sequestration

The trees have their roots deeper down into the soil layers to the nutrients and water and store the carbon when the roots are broken and exuded. Leaf litter will provide an uninterrupted supply of organic matter and the decomposition rate will vary with the composition of the species (Adombire *et al.*, 2024). Nitrogen fixing trees, such as the *Gliricidia sepium* and *Leucaena leucocephala* allow the system to be more productive and the amount of fertilizer to be decreased. The shade and micro climate changes that trees may have are able to make crops more resistant to climatic extremes (Vira *et al.*, 2015).

Integrated Nutrient Management

The natural and artificial fertilization contributes to the stability of the harvest of the plants and the inputs of carbon without the harm of the soil. Excessive nitrogen fertilization can enhance the breakdown of organic matter as a result of priming effects but lack of nutrients suppresses the growth of plants and fixation of carbon. Soil-based nutrient management through nutrient site testing guarantees the best proportions of the nutrient ratios which make the most out of carbon sequestration without ecological wastage (Yousra et al., 2025).

Organic materials that are easily decomposed e.g. sesbania aculeata, crotalaria juncea are incorporated to enhance microbial activity and their cycling. They are especially applicable to the case, when the Indian rice systems are in use, when there is an opportunity to manufacture green manures in the fallow periods. Biofertilizers which harbor beneficial microorganisms increase the accessibility of nutrients besides, the biofertilizers also supply soil carbon through microbial biomass and metabolites (Sravan & Murthy, 2018).

Table 3: Soil Carbon Monitoring Technologies

Modeling and Decision Support Systems

Technology	Spatial Scale	Accuracy	Cost Level
Wet chemistry	Point	Very high	High
Vis-NIR spectroscopy	Point to field	Moderate-high	Moderate
Remote sensing	Landscape	Moderate	Low per area
Eddy covariance	Field	High	Very high
Soil respiration	Point	High	Moderate
Digital mapping	Regional	Moderate	Low-moderate
Isotopic analysis	Point	Very high	Very high

With the advancement of the remote sensing technology, it is now possible to track the dynamics of carbon in soil in large amounts at a greater accuracy and resolution. Multispectral data used to measure vegetation indices, soil moisture, and land use change which determine carbon sequestration are available through satellite-based sensors such as Sentinel-2 and Landsat (Chen *et al.*, 2021). The hyperspectral imaging is capable of delivering detailed spectral patterns which are related to soil organic carbon and can be used to analyze a wide terrain within a relatively limited period of time.

Digital soil mapping is an intertwining of remote sensing data, ground monitoring data, environmental covariates, and machine learning algorithms in order to predict the distribution of carbon in the soil. Deep learning and random forest models are highly effective in predicting the carbon stocks of soils when they are trained on large data (Chen *et al.*, 2024). Such approaches permit setting the priorities spheres in the context of the interventions in sequestration and tracking the progress over time.

Proximal Sensing Technologies

Field-based sensing technologies Field-based (non destructive) methods of measuring soil carbon provide a rapid non-destructive technique of soil carbon measurement that requires only a small amount of sample preparation. The Visible and near-infrared (Vis-NIR) spectroscopy is a technology that enables the measurement of carbon in situ by the use of portable equipment which saves on laboratory analysis cost and time (England & Rossel, 2018). Mid-infrared spectroscopy is more precise in the determination of carbon and the fractionation of carbon. Laser-induced breakdown spectroscopy (LIBS) is a technique of instrumentation that offers elemental analysis which includes carbon contents and can be deployed in the field.

Process-based models are used to model the carbon cycling in the soil through the simulation of the key biogeochemical processes, i.e., decomposition, humification, and stabilization. Models like RothC, Century and DNDC have been able to calibrate on Indian conditions and this enables prediction of carbon sequestration under different conditions of management. Such tools facilitate the decision making process as they are used to estimate the long term impacts of management impacts and climate variability on solid carbon stores (Jensen & Eriksen, 2022).

Decision support system is the integration of the economic and environmental study coupled with modeling in order to find the optimal management

approach. COMET-Farm instrument is an instrument used in measuring the potential of carbon sequestration in accordance with greenhouse gases and economic returns. Mobile applications are soon to provide site-specific recommendations of carbon management to farmers based on the soil type, climate, and the cropping system (Morgado & Esteves, 2014).

Table 4: Economic Analysis of Sequestration Practices

Practice	Initial Investment	Annual Cost	Carbon Revenue
Conservation tillage	$200-500/ha	$50-100/ha	$30-75/ha
Cover cropping	$100-200/ha	$80-150/ha	$20-60/ha
Agroforestry	$500-1500/ha	$100-200/ha	$75-150/ha
Biochar	$1000-3000/ha	$50-100/ha	$100-300/ha
Organic amendments	$200-400/ha	$150-300/ha	$45-105/ha
Integrated systems	$800-2000/ha	$200-400/ha	$100-250/ha

Economic and Policy Aspects

Incentive Mechanisms and Carbon Markets

New carbon markets provide financial incentives on carbon sequestration of soil which may change the economy of agriculture. The voluntary carbon markets currently command prices of between 10-50/ton CO_2 equivalent and this price is expected to go up as the demand increases (Cerqueira *et al.*, 2023). However, the cost of measurement, permanence conditions, and the verification of additionality are the problems that limit the involvement of the smallholders. The aggregation techniques that unite two or more farms lower the transaction costs but yet access the markets.

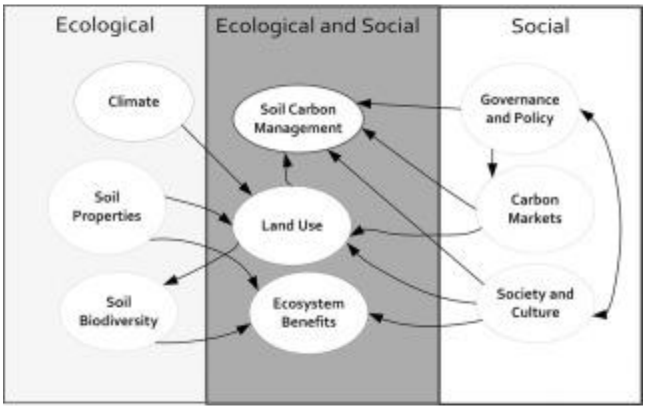
PES schemes are the other forms of incentives that compensate farmers on carbon seclusion and other environmental advantages. The National Mission of Sustainable Agriculture of India has provisions to help in the practices which are climate smart but this has not been realized extensively yet (Manjula *et al.*, 2019). The program at the state-level such as the Zero Budget Natural Farming program, in Andhra Pradesh, shows that it can be adopted on a large scale with proper policy backing.

Institutional Support and Policy Frameworks.

Appropriate policy frameworks are likely to support the process of scaling the sequestration of soil carbon in the agricultural landscapes. Paris Agreement on national determined contributions (NDCs) is acknowledging soil carbon potential increasingly, and individual countries have their climate plans which include soil management. The NDC of India involves the establishment of more carbon sinks of 2.5-3.0 billion tons CO_2 equivalent in 2030, which will necessitate a significant increase in soil carbon (Dey *et al.*, 2024).

Knowledge transfer and technology adoption is facilitated by institutional support using extension services, research organization and farmer cooperatives. Indian Council of Agricultural Research (ICAR) has come up with climate-resistant agriculture initiatives, which promote the application of carbon sequestration (Suresh & Viswanathan, 2022). However, there is no co-ordination between agencies and also between connecting carbon management with the existing agricultural programs (Jat *et al.*, 2022).

Figure 3: Policy Framework for Soil Carbon Management



Challenges and Barriers to Implementation

Technical and Scientific Challenges

Technological issues of precise measurements and verification of carbon variation of the soil are rather challenging. The spatial and temporal changeability of soil carbon requires intensive sampling in order to determine variations that have been caused by management as well as the background variation (Conant *et al.*, 2010). Carbon build up, at an average rate of 0.1-0.5/year, needs to be monitored over an extended period to demonstrate any significant changes. The processes of erosion and deposition need to be paid attention to in order to distinguish between the redistribution of carbon and real sequestration (Quijano *et al.*, 2021).

Table 5: Barriers to Adoption and Solutions

Barrier Category	Specific Challenges	Impact Level
Economic	High upfront costs	Very high
Knowledge	Technical complexity	High
Institutional	Weak extension	High
Cultural	Traditional practices	Moderate
Market	Price uncertainty	High
Policy	Unclear regulations	Moderate
Environmental	Climate variability	High

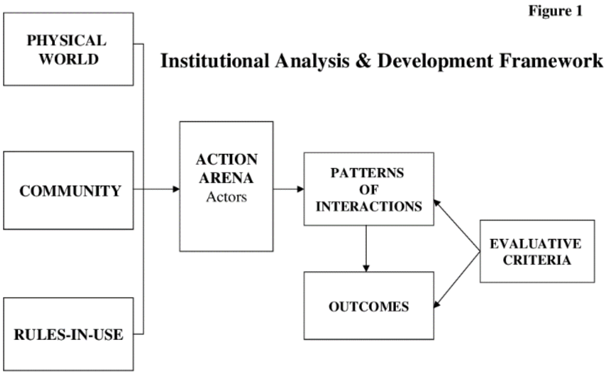
The long-term sequestration predictions are limited by the knowledge of the dynamics of the carbon saturation. The process of saturation of soils to carbon is an asymptotic process in which a management intervention has a diminishing effect over time. Temperature sensitivity of carbon in the soil raises a concern on permanence during climatic change particularly in the tropical regions where decomposition occurs at a very high rate.

Socio-economic Barriers

Carbon sequestration practices are hindered by many socio-economic factors especially in smallholder farmers. The price of equipments and inputs is high and limits the capacity of farmers who have limited resources to adopt (Mills *et al.*, 2019). This insecurity of tenure has the negative impact of reducing long-term investment in the soil especially in those activities that bear slow payoffs. Cultural tastes and customs might resist the changes in the management.

The reason why practice will not be adopted is because of the risk aversion of farmers on uncertainty in yield and market volatility. The cash flow issues are caused by the time lag between the implementation costs and the benefits of the carbon (Phelan *et al.*, 2023). Scaling is constrained by restricted credit and insurance products that are specifically designed to meet sustainable agriculture. The disparity in terms of access to resources and the right to make decisions also affects the adoption practice, since women farmers tend to be not taken into consideration in terms of extension services and support programs.

Figure 4: Institutional Framework for Implementation



Co-benefits and Synergies

Soil Health and Productivity

The co-benefits that are realized through the practices of soil carbon sequestration render the field of agriculture more sustainable than climate mitigation. Increasing the soil organic matter also enhances the soil structure, through greater aggregation and distribution of the pore space, which enhances the water infiltration and retention (Selley & Sonnenberg, 2022). This was discovered as the augmented water holding capacity which is increased by a percentage of 15-20 with 1 percent increase in organic carbon is critical resilience in drought stress. Higher cation exchange capacity brought about by organic matter enhances nutrient retention and availability as well as reducing the requirements of 20-30 percent of fertilizers.

The soils containing carbon are beneficial in increasing the level of biological activity leading to the improvement of nutrient cycling as well as preventing soil-borne pathogens. Diffuse microbial communities which thrive on organic matter generate antibiotics and are in competition with pathogens (Kiprotich *et al.*, 2025). The carbon management of mycorrhizal networks enhances the capacity to obtain phosphorus and drought resistance. These biological benefits are demonstrated to yield 10-30 percent increase in depleted soils and most in stress-prone soils.

Water Resources and Biodiversity

The carbon enriched soils are more beneficial in watersheds and agricultural production as they have a greater water management capacity. Increased infiltration reduces by 50-80 percent surface runoff and erosion to protect water quality in streams and reservoirs (Mrabet *et al.*, 2023). Improved water storage capacity saves 15-25 percent of irrigation demands and saves on the limited water resources. Carbon containing soils cause the moderation of water flow which ensures that streams have base flow during dry seasons.

Sequestration operated systems of carbon sequestration either in soil microorganisms or in above-ground fauna encourages biodiversity. There are agro forestry and other types of cropping systems that enable the settlement of useful insects, birds and small mammals. Carbon-based management improves the biodiversity of earthworms, arthropods and microorganisms in the soil by 30-70 percent. Such ecosystem services as pest control, pollination, and decomposition are among the biodiversity services that are appreciated at a rate of 150-500/ha/year (Karlen & Rice, 2017).

Conclusion

Carbon sequestration in soil is found to be a natural climate solution with a complementary implementation potential and a large set of co-benefits relevant to both agricultural sustainability and rural livelihoods. The scientific basis is a clear indication that a high carbon amount can be sequestered through optimized management practices, which would make a meaningful contribution to the climate mitigation goals. Carbon sequestration in India has enormous potentials due to the large agricultural land with practices that are context-specific and suited to the various agro-ecological contexts. Achievement necessitates concerted efforts that involve scientific innovation, favorable policies, proper funding, and empowering the farmers..

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Article ID: KVM0002/26 **Popular Article**

Water Quality Management in Fish Aquaculture Systems

[1]Indranil Ghosh and [2]Biplab Das

[1]*Subject Matter Specialist (Fishery Sciences), West Bengal University of Animal and Fishery Sciences, Ramshai-, Jalpaiguri, WB*

[2]*Senior Scientist & Head, Jalpaiguri Krishi Vigyan Kendra, West Bengal University of Animal and Fishery Sciences, Ramshai- 735219, WB*

***Corresponding Author**

[1]Indranil Ghosh

✉ : *wbuafs@gmail.com*

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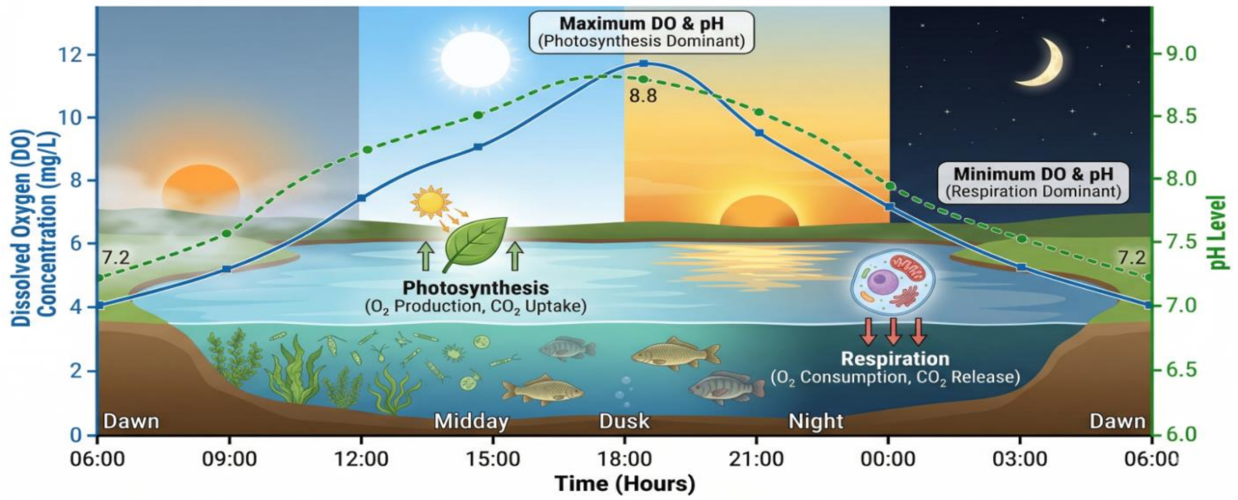
Abstract:- Water quality management is crucial for sustainable fish aquaculture systems, impacting fish health, growth performance, and the economics of production. This chapter highlights the importance of the most significant water quality parameters (dissolved Oxygen, temperature, and pH ammonia, nitrite, nitrate, and turbidity), and their interactions in aquaculture. Detailed treatment of fundamental water chemistry, biogeochemical cycles and how they affect fish physiology. An integrated evaluation based on water quality methods as per its current definition using physical, biological and chemical treatment options. All in the same place, water use and relevant environmental conditions which is recirculating aquaculture systems (RAS), biofloc technology or constructed wetlands. It discusses the monitoring technologies, remediation techniques and preventive management protocols with respect to Indian aquaculture. As these challenges, such as climate change impacts, disease management, and checking regulatory compliance appear, close study is attracted.

Keywords: *Dissolved Oxygen Dynamics, Ammonia Toxicity Management, Biofloc Technology Systems, Recirculating Aquaculture Systems, Water Quality Monitoring Protocols*.

Introduction:- Aquaculture is among the most rapidly expanding food production sectors globally and is essential to nutrition security, and rural employment and economic development. Fish farming in India has seen an unprecedented burst of growth, leading to the country being ranked globally the second largest fish producer, with an output of 7.96 million tonnes during 2022-23 (Sundaray *et al.*, 2025). However, this growing dynamic creates significant challenges in environmental sustainability and water management. Thus, the except quality of water management in aquaculture as the number one factor that would directly influence fish survival in culture systems, growth performance, feed conversion efficiency, as well as its trait to flare up diseases together with its economical aspects in its production (Olanubi *et al.*, 2024).

Figure 1: Diurnal Cycles of Dissolved Oxygen and pH in a Typical Aquaculture Pond



The aquatic environment provides fish with an interface for oxygen acquisition, waste disposal, and general physiological homeostasis. In this case, salmon and all other fish are similar to livestock in that they cannot flee from deteriorating environmental conditions and avoid, for example, toxic substances, particulates or pathogens. Subtle deviations in a variety of key parameters, such as dissolved oxygen (DO), pH, temperature, or concentrations of nitrogenous compounds can however induce stress, develop signs of immuno-suppression, even fish kill events (Carmichael et al. These challenges are compounded by the relatively closed or semi-closed nature of most aquaculture systems, wherein the metabolic wastes and other organic matter (uneaten feed, decaying organic matter) continue to accumulate to lead to gradually deteriorating water quality (Li *et al.*, 2024).

Indian aquaculture is one of the most diverse having its root from traditional extensive ponds and rice-fish integrated system to intensive recirculating aquaculture system (RAS) and cage culture. Furthermore, the local stocking density, feeding regimes, water exchange rates and climate all impact how water quality is managed and cared for, making each system have different challenges. In addition, the Indian climate is primarily tropical and sub tropical with elevated temperature and monsoon rainfall yielding higher metabolic rates, faster decomposition of organic matter in biogeochemical systems. Seasonal variations are also very pronounced, which modify different parameters related to water quality (Alkhadher et al., 2025).

Fisheries management practices are underpinned by an understanding of the fundamental principles regulating water chemistry, biogeochemical transformations, and physiological responses in cultured species (Zhang *et al.*, 2024). This chapter, being very comprehensive, covers numerous water quality parameters relevant to aquaculture along with the methods for their sampling and monitoring, treatment technologies, and the integrated management strategies for Indian aquaculture practitioners regarding harnessing optimum productivity per unit of this most precious resource, without compromising environmental sustainability (Yusoff *et al.*, 2024).

Significance of Major Water Quality Parameters

Dissolved Oxygen

Among the environmental parameters affecting fish health and growth, dissolved oxygen (DO) is arguably the most important in aquaculture systems because fish depend entirely on extracting oxygen from water passing over their gills (Hambali *et al.*, 2024). The physiological stress due to DO level below 3 mg/L most of the cultured species suffer, whereas the optimal values for most of fish are generally between 5-8 mg/L, but the Indian major carps (*Labeo rohita*, *Catla catla*, *Cirrhinus mrigala*) are relatively better low DO tolerant than the exotic species (*Pangasianodon hypophthalmus and Oreochromis niloticus*) (Mariu *et al.*, 2023).

As governed by Henry's Law, solubility characteristics of oxygen in water are inversely correlated to temperature and salinity. At 20 °C, 9.1 mg/L of oxygen is saturate in freshwater which decreases to ~7.5 mg/L at 30 °C (Iswantari *et al.*, 2023). Temperature-related solubility leads to important issues in the tropical Indian conditions as the water temperatures often crosses 30 °C in the summer months. Apart from this, since Q_{10} relationships suggests that the rate of oxygen usage can increases exponentially with temperature, such added demand for oxygen during warmer period will compounds the problem (Szewczyk *et al.*, 2023).

The great majority of aquaculture ponds are characterized by the daily cycle of oxygen input from photosynthesis during the day that evolves into output by respiration overnight (Ramesh et al., 2024). The role of biological processes in regulating conditions in the deep ocean: The balance of daytime oxygen supersaturation, produced by phytoplankton photosynthesis, and of nighttime respiration, which slowly reduces high concentration attained in the late afternoon into almost anoxia just prior to dawn, These dynamics are intensified within eutrophic systems that experience thick phytoplankton blooms, which may result in severe hypoxic episodes during extended periods of cloud cover or algal crash scenarios (Znachor *et al.*, 2023).

Temperature

Temperature is the foremost environmental factor affecting nearly all physiological, biochemical and ecophysiological processes in aquatic systems (Theodorou *et al.*, 2025). Since fish are poikilothermic creatures, they are unable to control their body temperature autonomously from the environment surrounding them and therefore, metabolic rates correspond directly to the ambient water temperature. Various species are known to have favourable temperature ranges for growth, feed conversion, and reproduction, and alter their physiological and behavioural activity as ambient water temperature varies.; 32-26 °C for Indian major carps and 28-30°C for Pangasianodon hypophthalmus (Debnath & Mahanta, 2023).

Oxygen solubility, ammonia toxicity, pathogen proliferation and feeding behavior are all temperature dependent processes. While bacteria are dissolving metabolic waste more quickly at these higher temperatures, the very same temperature limits oxygen availability – a vital physiological concern. Summer temperatures in shallow ponds used in intensive Indian aquaculture systems often exceed 35°C, close to upper lethal limits for most species . Winter temperatures in northern India, on the other hand, can fall below 15°C (such temperatures are shown to reduce feeding and growth rates dramatically) (Bhuiya *et al.*, 2023).

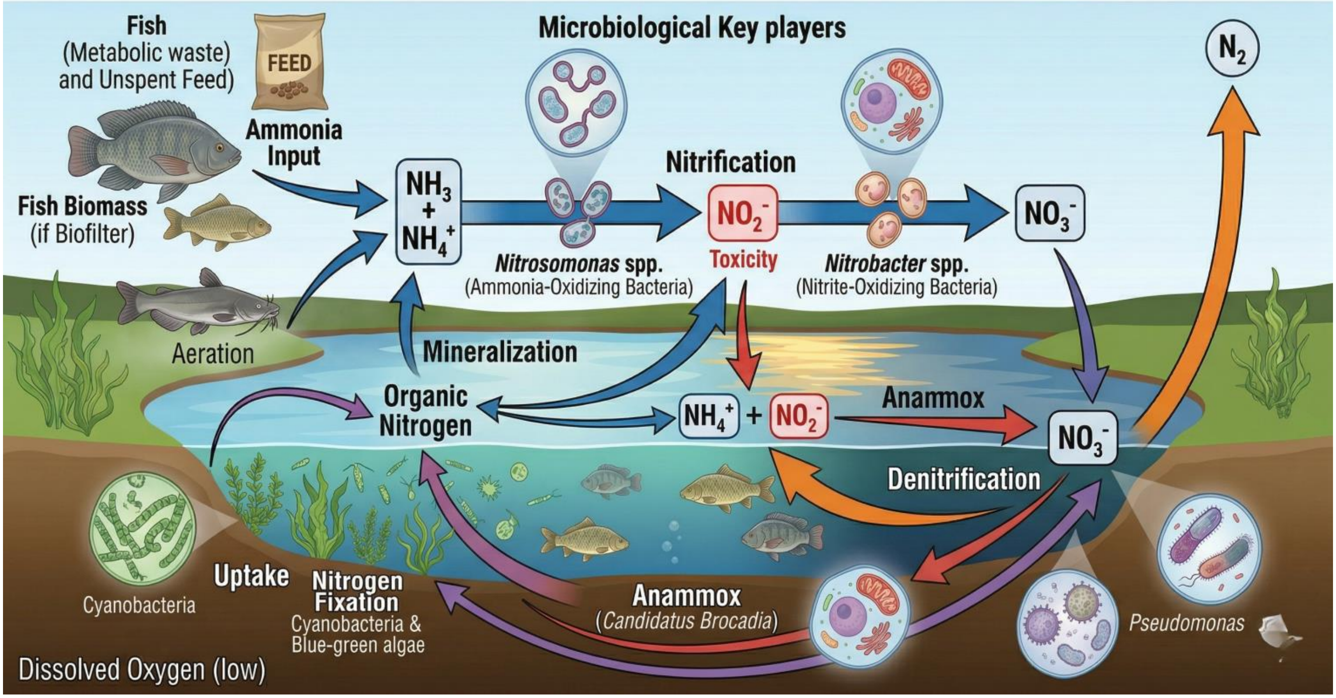
Another important temperature-related phenomenon (especially in the deeper ponds and reservoirs) is the thermal stratification. During warm seasons, the surface layers of water heat up quickly but the bottom remains cold, so that three temperature layers become evident (epilimnion, metalimnion and hypolimnion) (Ma *et al.*, 2024). Such stratification prevents vertical mixing leading to bottom water oxygen depletion, with an accumulation of nutrients potentially triggering harmful algal blooms or fish kills during rapid overturn events (Ma *et al.*, 2024).

Table 1: Optimal Water Quality Parameters for Major Cultured Species in India

Parameter	**Indian Major Carps**	***Pangasianodon hypophthalmus***
Dissolved Oxygen	4.0-8.0	5.0-8.0
Temperature	26-32	28-30
pH	6.5-8.5	6.5-8.0
Total Ammonia-N	< 1.0	< 0.5
Un-ionized Ammonia	< 0.02	< 0.01
Nitrite-N	< 0.5	< 0.2
Nitrate-N	< 100	< 50
Alkalinity	75-200	80-150
Hardness	50-300	75-200

The pH scale is a logarithmic scale from 0-14, that is a measure of hydrogen ion concentration or acidity (or basicity) of water. For most of cultured fish optimum pH range is 6.5-8.5 (may be 6.0-9.0 for Indian major carps). Effects of pH on fish physiology including osmoregulation, blood chemistry and gill function directly affect fish, whereas toxicity of various compounds (even toxicity of ammonia and heavy metals) is also pH-dependent (Mariu et al., 2023).

Figure 2: The Biological Nitrogen Cycle and Microbial Transformations in Aquaculture Systems



In the carbonate and bicarbonate ions, we have a natural pH buffering system. Total Alkalinity is measured as concentrations of carbonate (CO$_3^{2-}$) and bicarbonate (HCO$_3^-$) and is the measure of pH buffering against pH changes. The dashboard/Biodegraduable alkaline of Indian aquaculture ponds typically 9.0) za_taraecd the equilibrium of soluble/ferrous and ferric iron high level of NH$_4^+$ and toward unexcited NH$_3$, pose toxicity- risk significantly (Siew *et al.*, 2023). The relationship between pH and the fraction of un-ionized ammonia speciation follows the Henderson-Hasselbalch equation (pKa 9.25), showing an increasingly large exponential rise of un-ionized ammonia fraction above pH 8.0 (Naji *et al.*, 2025).

Table 2: Water Quality Testing Frequency and Methods for Intensive Aquaculture

Parameter	**Testing Frequency**	**Method**
Dissolved Oxygen	Daily	Electrochemical
Temperature	Daily	Thermometric
pH	Twice daily	Potentiometric
Ammonia-N	Weekly/Daily	Spectrophotometric
Nitrite-N	Weekly	Colorimetric
Nitrate-N	Bi-weekly	Cadmium reduction
Alkalinity	Bi-weekly	Titrimetric
Hardness	Monthly	Titrimetric
Transparency	Daily	Secchi disk

Nitrogenous Compounds

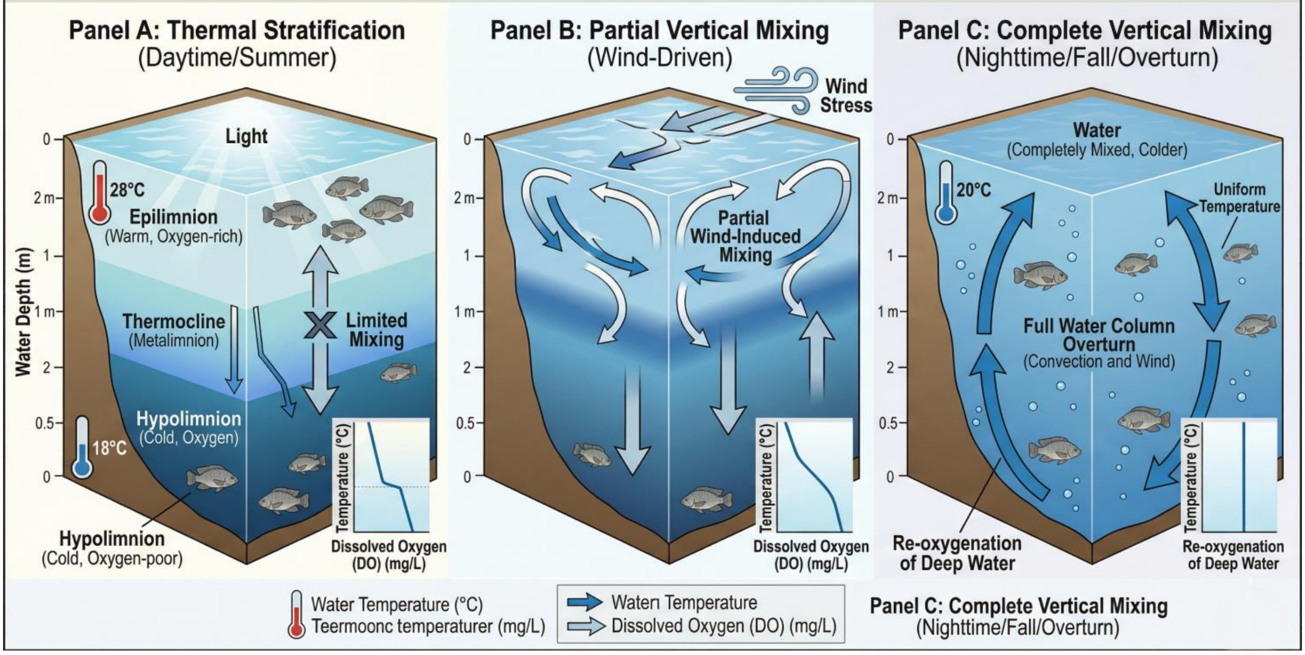
Out of several components that influence aquaculture water quality, metabolism of nitrogenous waste is particularly challenging (Lal *et al.*, 2024). The major metabolic end product excreted by fish is ammonia which is predominantly lost across the gill membranes. Intensive culture systems quickly lead to the accumulation of ammonia owing to the practices of high density stocking, heavy feeding and protein-rich diets. In addition, bacteria decompose uneaten feed, feces and dead organic matter and produce large amounts of ammonia (Zhang *et al.*, 2022).

Ammonia is present in aqueous equilibrium between toxic un-ionized ammonia (NH$_3$) and relatively nontoxic ionized ammonium (NH$_4^+$). This equilibrium is highly pH and temperature-dependent, with the un-ionized fraction increasing with higher pH and temperature. Chronic exposure to NH$_3$ concentrations higher than 0.02 mg/L induces physiological stress and immunosuppression and stunts growth, while acute levels of approximately

0.1 mg/L are lethal for more sensitive species (Miramontes *et al.*, 2020).

The nitrogen cycle, which involves three major stepwise microbial transformations, is the basis of many aquaculture systems, the oxidation of ammonia to nitrite (NO_2^-) by Nitrosomonas species; and all the oxidation of nitrite to nitrate (NO_3^-) which is mediated by the Nitrobacter species (energy used to supports a growing population) (Jifiriya *et al.*, 2025). This process requires oxygen, alkalinity and sufficient populations of bacteria. Intermediate metabolite nitrite is a highly toxic but powerful enzyme preparation, as it oxidizes hemoglobin to methemoglobin, which does not carry oxygen. The toxicity of nitrite correlates with chloride concentrations, because of competitive inhibition at gill surfaces, yet safe nitrite concentrations stay below 60 cm) and very low (< 15 cm) transparency are indicative of extremely low productivity and worms, low oxygen depletion risk ranges or very dense algal blooms associated with high supply and clay turbidity, respectively (Baker *et al.*, 2022).

Figure 3: Thermal Stratification and Vertical Mixing Dynamics in Deep Fish Ponds



Clay turbidity — associated with new ponds or monsoons (or both) — interferes with the processes of photosynthesis and gill function as well as feeding efficacy. Flocculation of clay particles are also achieved by gypsum ($CaSO_4 2H_2O$) 200-400 kg/ha. In contrast, natural turbidity caused by high-density phytoplankton blooms is much harder to control and can require reductions in feeding, water exchange or the use of algaecides in extreme cases (Kashem *et al.*, 2023).

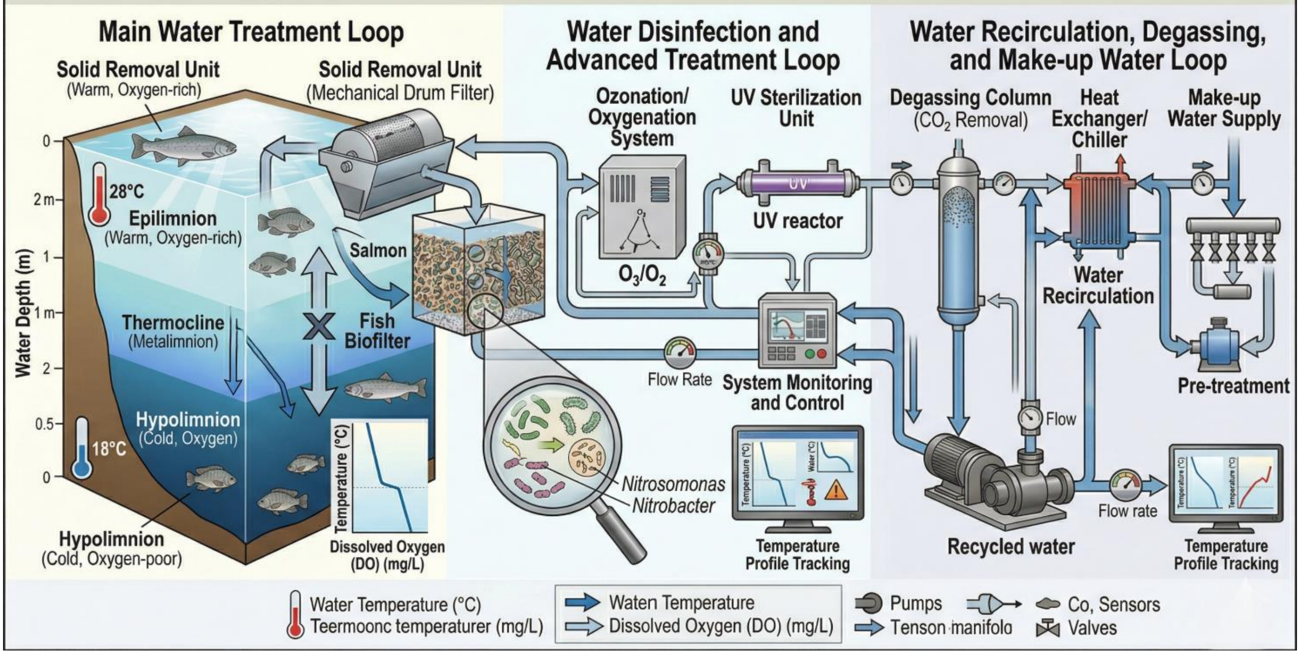
Water Quality Monitoring Strategies

Physical and Chemical Testing Methods

Timely and robust measurements of key water parameters are essential for comprehensive monitoring of water quality. Dissolved oxygen and temperature should be monitored on a daily basis, particularly during critical periods early in the morning (5-7 AM) when minimum concentrations are recorded. Optical or electrochemical sensors are portable meters that enable rapid and accurate measurements: only a regulart calibration (which is fundamental) is needed for reproducibility (Lal *et al.*, 2023).

pH monitoring: electronic pH meters or colorimetric test kits are used, generally twice daily (morning and afternoon) to capture the influence of diurnal variation. Once fully established, ammonia, nitrite and nitrate were tested spectrophotometrically or with kits weekly although this could be daily or every other day with high rates of feed or during disease high pressure or water quality crises (Sarker *et al.*, 2024). These different methods employ for ammonia Nessler, and for nitrite N-(1-naphthyl)-ethylenediamine, and in comparison to other methods tested such as ion chromatography, or spectrometry, they have the potential for inexpensive and accurate analysis, and visible results at the farm level (Gregucci *et al.*, 2025).

Figure 4: Schematic Architecture of a Modern Recirculating Aquaculture System (RAS)



Titrimetric alkalinity and hardness tests are performed once every 2 weeks or once a month because these parameters exhibit chronic rather than event-driven temporal dynamics, i.e., they do not respond at the moment lime is annually applied or when heavy rain events occur. Based on this, we can estimate phytoplankton density and general water clarity from Secchi disk transparency as a marker of turbidity, which we can perform rapidly and relatively inexpensively each day. In more sophisticated aquaculture operations, automated continuous-monitoring systems are increasingly placed, and real-time measurements of DO, pH, temperature and Oxidation-Reduction Potential (ORP) are transmitted to ensure rapid intervention while parameters deviate from their target ranges (Puangsuwan *et al.*, 2025).

Biological Indicators and Fish Behavior

Fish behaviour is a unique real-time indicator of water quality. Fish in good health will exhibit normal swimming and feeding responses and coloration. The early indicators of poor water quality different types of pre-spawning species, such as the Pacific salmon, is through surface gasping (hypoxia) loss of equilibrium lethargy reduced feeding unusual coloration and congregating near gates/ aerators. At dissolved oxygen below 2.5 mg/L, the gaping of Indian major carps is actually observed which requires immediate aeration action (Wang et al., 2023).

Chronic stress from water quality has slower growth rate, poor feed conversion ratio, lower disease resistance and higher mortality. Moreover, ecological assessments can also be implemented in addition to assessing growth performance quantitatively (i.e., through the decadal SGR and K) with regular sampling. Chronic ammonia exposure causes cellular damage to gill tissues, such as hyperplasia, lamellar fusion and epithelial lifting in histology (Li *et al.*, 2024).

Water Quality Management Technologies

Mechanical Aeration Systems

Mechanical aeration supplementation of oxygen is considered the most basic necessary intervention for intensive aquaculture systems. Different aerator configurations (e.g., paddlewheel, vertical pump, propeller-aspirator and diffused air systems) provide a range of efficiencies, power demand and applications. At shallow ponds (15°C and provides sufficient alkalinity (>100 mg/L as $CaCO_3$) to completely neutralizing acid production during nitrification (Sontheimer et al 1981) Surface area specifications do not accurately correlate with table 3 requirements as they typically range with temperature, feed rate and treatment efficiency (0.3–1.0 m^2/kg feed/d). On paper, biofilter maturation and stable-to-established bacterial populations can take 3–6 weeks, so managing startup of the system is one of the most important factors for the success of the facility (Gregersen & Pedersen, 2023).

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture systems (RAS) is the most modern technology applied in aquaculture concerning water conservation and environmental control. In these systems, 95–99% of the culture water is recycled, which includes treatments such as mechanical solids removal, biological filtration, aeration, adjustment of the pH and disinfection. This leads to stable yield throughout the year, control on environmental conditions with better biosecurity and reduced water consumption; Data regarding water availability regarding bioavailability is very important as most of the countries with such dishes are arid climates (Sil *et al.*, 2025).

. **Table 3: Comparison of Major Aquaculture Water Management Systems**

System Type	**Water Exchange Rate**	**Stocking Density**	**Capital Investment**
Extensive pond	High (10-20%/day)	Low (< 5,000 kg/ha)	Low
Semi-intensive pond	Moderate (5-10%/day)	Moderate (5,000-15,000 kg/ha)	Moderate
Intensive pond	Low-Moderate (2-8%/day)	High (15,000-50,000 kg/ha)	Moderate-High
Recirculating system (RAS)	Very low (< 5%/day)	Very high (50-150 kg/m³)	Very high
Biofloc technology	Minimal (< 1%/day)	High (20-40 kg/m³)	Moderate-High

The main elements of RAS are (1) culture tanks, with a correct hydraulic design that allows for self-cleaning, (2) solids removal (drum filter or settling tanks), (3) biofilters for nitrification, (4) aeration or pure oxygen injection systems and (5) Degassing units that will remove CO_2 and nitrogen; and finally quality assurance systems like UV sterilization or ozonisation. To avoid catastrophe, RAS systems require extensive monitoring and must be managed as continuously redundant power back up and aeration systems are essential (Gupta *et al.*, 2024).

Biofloc Technology

In Biofloc technology (BFT), a novel bioremediation process, the autotrophic and heterotrophic bacteria grow in the aquatic environment by converting ammonia to microbial protein through the manipulation of carbon: nitrogen ratio (Srimadhuri et al., 2024). Farmers add carbons sources (starch, wheat powder and molasses) maintaining C:N ratio between 10:1 to 20:1, stimulating heterotrophic bacteria; letting them dominate space against autotrophic nitrifiers for ammonia. These biofloc aggregates are a source of mostly non-competing protein (bacteria, algae, protozoa and detritus), thus they are a new feed, as well as improvement of water quality (Melaku *et al.*, 2024).

BFT biomasses have high respiration can be on the order of 0.3-0.5 kg O_2/kg feed, therefore requiring high aeration, and an extensive management regime is required with strict controls on settled biofloc volume (target 10-50 mL/L settled biofloc volume), and regular solids removal, necessary because accumulation will lead to a high exogenous respiration (Dheeran *et al.*, 2025). These most positive outcomes that can be inflicted include reducing water exchange, improved biosecurity, increased feeding and better nitrogen handling (Hosain *et al.*, 2025). Litopenaeus vannamei, *Pangasianodon hypophthalmus* and tilapia respectively also performed well in India, but only if properly managed so that rates of oxygen depletion, together with toxic floc accumulation, were not excessive (Joshna *et al.*, 2024).

Water Treatment and Remediation Techniques

Chemical Water Treatment

While chemical treatments can provide a rapid fix to a particular water quality problem, these should only be used as a complement to, not a substitute for, good management practices. Lime (calcium hydroxide, $Ca(OH)_2$) is applied at 100–500 kg/ha based on initial pH and buffering capacity, raising pH and alkalinity rapidly in acid waters. Calcium carbonate ($CaCO_3$) has a slower reaction to enhance alkalinity and substantial sudden pH overshoot is prevented (Apoliano *et al.*, 2023).

Table 4: Emergency Water Quality Interventions and Dosage Guidelines

Problem	**Intervention**	**Dosage/Application**
Low DO (< 2 mg/L)	Emergency aeration	Maximum aeration capacity
Low DO crisis	Hydrogen peroxide	25-50 mg/L
High ammonia	Zeolite application	100-200 kg/ha
High nitrite	Salt (NaCl)	1-3 ppt
Low pH (< 6.0)	Hydrated lime	100-300 kg/ha
Low alkalinity	Agricultural lime	200-500 kg/ha
Algal bloom crash	Water exchange	30-50% replacement
High organic load	Potassium permanganate	2-4 mg/L
Pathogen control	Chlorine dioxide	0.5-2 mg/L

This type of aluminosilicate zeolites having good cation exchange capacity is able to pull out dissolved ammonia through ion-exchange process. By the means of sequestering ammonium from the environment, the application rates of zeolite at 50–200 kg/ha may provide short-term ammonia control during acute events, but proven methods for removal or regeneration of zeolite are needed to counter the subsequent re-release of ammonium [215]. Scaling seawater to give 1–3 ppt salt (sodium chloride) follows competitive inhibition of nitrite uptake by gill chloride cells and acts as an emergency rescue during nitrite spikes (Mujahidah et al., 2023).

Which is $KMnO_4$ oxidizing organic matter in 2-4 mg/L, reducing chemical oxygen demand and controlling certain pathogens. Hydrogen peroxide (H_2O_2) acts as a "rescue" agent for both oxygenation and oxidation at emergency doses of 25-50 mg/L; nevertheless, over-doses are avoided by careful applicatons. Bacillus species, Lactobacillus and other beneficial microorganisms When supplemented daily to ponds (1–5 mg/L), probiotic bacterial preparations containing Bacillus species, Lactobacillus, and other beneficial microorganisms improve water quality through competitive exclusion, organic matter decomposition and pathogen control by antagonism (Das et al., 2024).

Integrated Water Quality Management Approaches

Best Management Practices (BMPs)

To address water quality on multiple fronts, best management practice protocols must feature multiple interacting strategies (Oduor et al., 2023). Healing is not as cheap nor easy as prevention. Core BMPs are (1) site selection (quantity and quality and use of water), (2) pond design (depth selected [1.5 m to 2.5 m], slope and outfall drainage) and (3) pond preparation (drying, liming and removal of detrital material after a crop (Sambu *et al.*, 2024).

In general, the stocking density management avoids development beyond limits of system carrying capacities and average biomass exceeded 5000 kg/ha in extensive systems but may be 5000–15000 kg/ha for semi intensive systems; analysis of intensive systems should limit biomass to 1515,000 kg/ha by continual monitoring. Feed management employees high-quality nutritionally-complete feeds15, at optimal feeding rates (2, 3, 4% BW/d, corrected for temperature and growth);multiple daily feedings minimize waste buildup and ensure food quality (Lal *et al.*, 2024).

In fact, fertilization strategies are applied in semi-intensive systems as phytoplankton are retain and natural productivity of food and oxygen in water is preserved. Split-dose organic inputs (cattle manure, poultry droppings) in the range of 5,000–10,000 kg/ha−1 were applied to improve bacterial decomposition and nutrients availability. The addition of nitrogen (urea 10–20 kg/ha) and phosphorus (single superphosphate 20–40 kg/ha) bi-weekly may promote balanced phytoplankton communities with inorganic fertilizer N:P∼10:1 (Kajgrová *et al.*, 2024).

Seasonal Management Considerations

Indian aquaculture has to manage between extremes in relation to seasons. Summer management (March-June) is when water temperature is most high and metabolic rates are raised and oxygen solubility is low. They confirmed capacity of aeration, limited stock density and controlled feed timings (morning and evening) have been found beneficial, maximum water depth should be maintained and shade trees may be planted around the ponds to control temperature (Khan *et al.*, 2025).

Heavy rains affect agriculture during the monsoon period (July–September) where it faces flooding or turbidity of runoff waters and grain spoilage and coastal areas experience abrupt salinity change and pond overflow. Proactive steps were strengthening of dykes, installing overflow ducts, creating settlement ponds for excess runoffs and low feeding rates during wet periods. The immediate post monsoon period (October-November) though provides maximum growth due to moderate temperatures and quality of water suitable for high feeding /growth (Khan *et al.*, 2025).

In particular, winter management (December-February) in northern India is challenged by reduced temperatures which limit feeding and growth. Potential strategies combine fast warming of shallow water, greenhouse covers (for small systems), low exchange rates and slow feeding with a feed regimen that mirrors the relative reduction in appetite as temperature decreases (Wang & Ôlsen, 2023). Fish are under the most environmental duress during temperature transition periods, and disease management ramps up during those periods .

Conclusion

Water quality management is the primary factor in the sustainability, profitability, and environmental stewardship of aquaculture systems. The complex interaction of physical, chemical and biological variables merits a comprehensive understanding as well as integrated management strategies. Key parameters such as dissolved oxygen, temperature, pH and nitrogenous substances need continuous monitoring and be maintained within species-specified optimal ranges.

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Kheti Vigyan e Magzine

Article ID: KVM0003/26 **Popular Article**

The Convergence of Biology and Business in Agriculture

Indranil Ghosh

Subject Matter Specialist (Fishery Sciences), West Bengal University of Animal and Fishery Sciences, Ramshai-, Jalpaiguri, WB

*Corresponding Author

Indranil Ghosh

✉ : *wbuafs@gmail.com*

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Abstract:- Together, they are radically restructuring conventional agriculture into high-tech, regulated enterprises, fusing biology and business practice at an unprecedented scale. It represents a fresh view to the future aqueous merchandise in addition to its blues; Acters with very alternative leather from your cellular biology, bud design, along with your agriculture comprise far more inside the promotion proven methods, let on, working out, as well as entrepreneurial stellar evolution. A whole new set of agribusinesses has emerged to maximise the input of crops and feed the hungry with a package of biotechnologies, precision agriculture and big data about weather, soil, farming and everything you can imagine. The next gen are about to innovate. of this convergence:of plant genomics,synthetic biology and bio–informatics and as these are appropriated for commoditisation to convert sustainable systems of agriculture. These issues cover the depth of agribusiness firms participation in research and development via advances in start-up firms associated with crop biotechnology to the cost-benefit effects of GM crops and bio-fortified crops.

Keywords: *Agribusiness Biotechnology Business Innovation Sustainable Agriculture Commercialization.*

Introduction:- The agriculture industry stands at a rare inflection point; an inflection point that is radically re-shaping food security and economic development worldwide converging biological innovations with advanced business models. Yet this convergence is far more than a matter of any recent technological advance -- it is a foundation for rethinking the structure and function of agricultural production, distribution, and consumption as part of the modern economy. The image of agriculture as a simple subsistence-oriented, labor-consuming activity — turning land, labor, and water into agricultural production — is being transformed at a rapid pace into a science-centered industry dedicated to discovering and using knowledge for economic profit — innovations that arise from scientific scholarship and the innovation of technology as the new commodity of commodities. This evolution includes the source of raw materials for a variety of non-food uses, such as energy, basic fibbers, construction materials, and biomaterials, which are progressively transformed into compounds with potential applications for medicines, flavours, and natural colors (Vargas-Canales et al., 2024.). These changes are in line with the holistic framework of bioeconomy, which focuses on the sustainable generation and use of biological resources, as well as conservation, to provide information, products, processes, and services in all economic sectors (Trigo et al., 2023). In the past 30 years the marriage of biology with business agriculture has exploded, housing a dynamic intersection between molecular biology, genomics, and biotechnology (Trigo et al., 2023; Wesseler et al., 2015).

Table 1: Major Genetically Modified Crops and Their Commercial Traits

Crop Species	Modified Trait	Target Pest/Stress
Gossypium hirsutum (Cotton)	Bt insect resistance	*Helicoverpa armigera* bollworm
Zea mays (Maize)	Bt and herbicide tolerance	Corn borer, rootworm
Glycine max (Soybean)	Herbicide tolerance	Broad-spectrum weeds
Brassica napus (Canola)	Herbicide tolerance	Competitive weeds
Gossypium hirsutum (Cotton)	Stacked traits Bt+HT	Multiple pests and weeds

Table 2: Precision Agriculture Technologies and Business Applications

Technology Category	Application Domain	Key Biological Parameters
GPS-guided equipment	Variable rate application	Soil nutrient variability
Drone-based imaging	Crop health monitoring	Chlorophyll, NDVI, thermal
Soil sensors	Irrigation management	Moisture, EC, temperature
Weather stations	Disease forecasting	Temperature, humidity, rainfall
Yield monitors	Productivity mapping	Grain flow, moisture
Satellite imagery	Field-scale assessment	Vegetation indices, biomass

Innovations in molecular biology, genomics, and then biotechnology have fueled an explosion of the biology–business interface in agriculture over the last 30 years. The entire genomes of numerous plants have now been sequenced, gene editing technologies (e.g. CRISPR-Cas9) oriented towards plants have been developed, and synthetic biology has fundamentally modulated diverse dimensions of plant-based products, and, these trajectories are now enabling the dawn of a new era for crop improvement and innovation in agriculture. Simultaneously, globalisation of food and ag markets, rising consumer demand for healthy and sustainable foods and the urgent need for addressing climate change are providing the market with a compelling business case to invest in biology R&D. Yet, integrating such biological advances into the agricultural landscape remains daunting, bolstering the arduous task of their development and adaption for agricultural utilization (Sameen & Khalil, 2025). Success in these technological developments requires a more thorough investigation into specific adoption variables and the corresponding incentives needed for entrepreneurs to innovate more strategically. Given this, we highlight focus ventures with awareness of specific innovation barriers, developing proactive strategies to navigate these buying behaviors through an innovation management lens (Dahabieh et al, 2018), especially for themotivaton, the food and agriculture biotechnology sector must address barriers such as specialized adoption uncertainty, complex product-market fit across convergent value chains to reach their full potential in addressing food security, and resource pathways challenges. The only way towards this bio-based production systems is based on the need for sustainable economy, fostering the conversion of biomass to food, energy, and industrial products; ensuring that the natural and economic pressures due to declining natural resources can be faced (Greblikaitė et al., 2020).

Table 3: Bio-fortified Crops and Nutritional Enhancement Strategies

Crop Species	Enhanced Nutrient	Target Deficiency
Oryza sativa (Rice)	Iron, zinc	Micronutrient deficiency
Ipomoea batatas (Sweet potato)	B-carotene	Vitamin A deficiency
Pennisetum	Iron	Anemia

glaucum (Pearl millet)		
Triticum aestivum (Wheat)	Zinc	Zinc deficiency
Oryza sativa (Golden Rice)	B-carotene	Vitamin A deficiency
Zea mays (Maize)	Lysine, tryptophan	Protein quality
Manihot esculenta (Cassava)	B-carotene, iron	Multiple deficiencies

Table 4: Sustainable Agriculture Business Models in India

Business Model	**Core Principle**	**Value Proposition**
Organic certification	Chemical-free production	Premium pricing
Biofertilizer manufacturing	Microbial inoculants	Input cost reduction
Integrated pest management	Ecological pest control	Reduced pesticide use
Contract organic farming	Supply chain integration	Market assurance
Agroforestry systems	Tree-crop integration	Diversified income
Conservation agriculture	Minimal tillage	Fuel and labor savings

India, which engages around 42% of The second potential is that the vibrant sector employs 50 percent of the country‘s population and contributes 18 percent of nation‘s GDP and is also undergoing transformation through use of biotechnologically improved crops, precision farming practices and digital agriculture platforms. Investment from corporate backed by agriculture on research & government driven initiatives for high throughput innovation show that a shift in agriculture is in the making as a nascent agri-tech start-up ecosystem emerges. This transition is rooted in the notion that agriculture is a knowledge-based industry in which biotechnology is an important contributor to innovation and economic growth (Khan et al. (2023); Thutupalli & Iizuka, (2016)) As long as the revolutionary power that the biotechnology is expected to wield through using gene codes of living beings drives a gene revolution and came to be ranked as one of key industry sector and key factors in attaining socio-economic development (Badiyal et al. (2024).

Biotechnology: The Cornerstone of Agribusiness

Biotechnology has led the way in innovations to the agsector via new ways to grow crops, manage pests, and farm sustainably, which all have changed the face of the current agribusiness landscape. These kinds of innovations take place at the intersection of traditional agriculture and the intersection of biology and business models to create productivity, resilience, and ultimately profit. Biotechnology is an umbrella term covering a wide range of technologies, with different commercial implications: genetic engineering, molecular breeding, tissue culture, bioinformatics. We can also utilise genetic engineering, which is the targeted alteration of plant genoms to improve yield, drought resistance or nutritional qualitiy. The selection cycle of the best varieties is shortened by molecular breeding (marker aided selection); tissue culture is the regeneration of healthy plants. Based on the physics of improvement, predictive modeling is aided by data-driven bioinformatics augmented by genomic data. These tools transformed agriculture from a labour-intensive activity to a knowledge-based one, within the general paradigm of the bioeconomy: sustainable use of biological resources for food, feed, chemical, energy, and industrial products (Greblikaitė et al., 2020; Trigo et al., 2023).

This is reflected by the commercialization of genetically modified crop which can also be considered as biotechnology on an industrial scale. Farmers across 29 countries and more than 190 million hectares annually plant GM (genetically modified organism) crops which possess stand-alone traits (such as insect-resistance and herbicide-tolerance events). The successful adoption of biotechnologies in these developing countries is an unmistakable signal of the role biotechnology will play in addressing the food security challenges of a burgeoning population and climate change. Recent breakthroughs such as the CRISPR-Cas9 technique for genome editing have supercharged the field, offering precise modifications to individual genes for climate resilient and nutritionally enhanced crops (Sameen & Khalil, 2025). At the same time, the advances of scientific progress in genetics and genome science, including its use in a wider number of applications, ranging from bio-enhanced crops to biofuels and bioproducts (e.g., from agricultural biomass Wesseler et al., 2015), have not only improved productivity, enabled the agribusiness to occupy the top of the bio-economy4 business chain. First, there is the impact of scientific and technological evolution [i] transforming the understanding of what the agri-food sector and the paradigm of employment were with regard to the parameters of what they consist of limited by alternative bioresources [ii] that can be integrated into some other products (Vargas-Canales et al., 2024).Agribusiness in India is a major sector where biotechnology can play an important role as it provide livelihood to 42% of population, and accounts for 18% of GDP. Specific example can be findings related with productivity increase and reduction of pesticide usage through adoption of Bt cotton, which seems to have been associated with the technology-led process of innovation development (Thutupalli & Iizuka, 2016).

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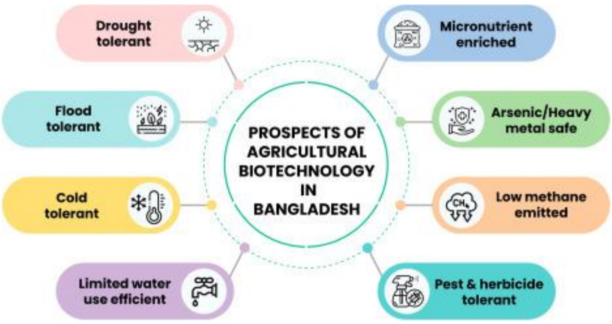
Figure 1: Value Chain of Agricultural Biotechnology



However, the full potential of biotechnology can only be realized through the alleviation of innovation constraints, which is present in the form of adoption uncertainties and intricate alignments within the value chain for food and agricultural biotechnology (Dahabieh et al., 2018). With a focus on technology-market fit, ventures can create value addressing global challenges like resource limitation and climate change adaptation (Dahabieh et al., 2018). From this foundation, advanced applications in precision sustainable models emerge, futureproofing agribusiness to be a foundational force for the bioeconomy it will propel. Strategically, the theoretical potential to scale-up cheap sustainable biomass (including flexi-crops and low-cost non-edible feedstock) via conversion through innovations such as GM microbial enzymes and advanced bio-refineries (Neimark & Healy, 2018) Precision agriculture utilizes data-driven technology and digital platforms to optimize resource utilization and decision-making, playing a vital role in the creation of innovative business models that increase productivity and farm profitability (Holloway et al., 2023; Shojaei et al., 2023).

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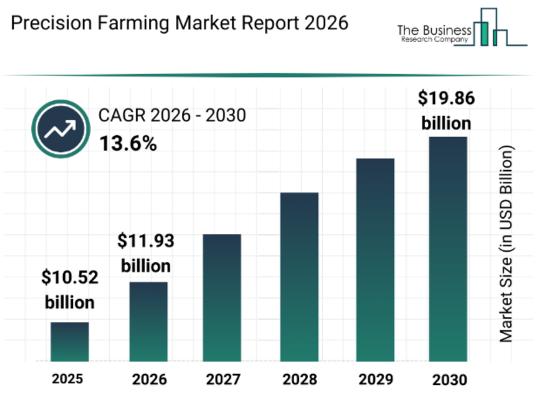
Figure 2: Precision Agriculture Adoption Curve Technology Space below the Threshold (TNaq) This segment of the Precision Agriculture maller.



Precision Agriculture and Data as an Enabler for Business Models

Precision agriculture is a game changer– from resource management efficiency and productivity improvement to displaying sustainability business models in the bioeconomy, high-end data technologies are being further utilized. Combining sensors, drones, satellite imagery, GPS, and artificial intelligences enables precision agriculture to provide real-time information about the condition of crops, soil and environmental factors. This granularity ensures minimization of inputs such as water, fertilizers and pesticides, maximizing yields, while simultaneously reducing costs as well as environmental impact. Data becomes the new commodity, and agribusiness turns from manual labor to a high-tech, knowledge-intensive business. For example, sensors linked to the Internet of Things (IoT) gathering huge amounts of data on soil moisture and nutrient content are being linked to predictive analytics to determine the right agronomy practices. This serves the bioeconomy idea of sustainable biomass utilization itself and generates additional revenue streams from data analytics services and precision input delivery (Greblikaitė et al., 2020; Trigo et al., 2023)

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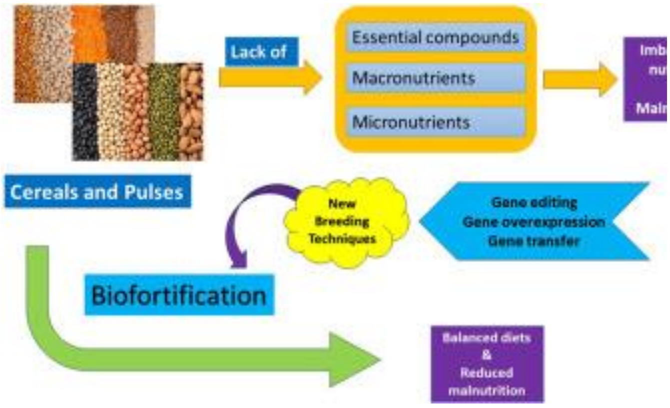
Figure 3: Model of the Bio-fortification Impact Pathway



Data serves as the foundation layer for innovative new business models that change agribusiness from product-centric to service-oriented business ecosystems. Microsoft FarmBeats or John Deere Operations Center, are platforms aggregating farm data into actionable insights — often offered as a subscription-based, recurring revenue. In India, for starters, firms like CropIn and DeHaat have created such digital providers starting from end-to-end—from crop advisory to provide chain administration—empowering the smallholder farmers and giving them AI-driven suggestions. Thus, these models provide equal access to advanced tools, and thereby have bridged the digital divide along with enabling inclusive & equitable growth. In addition, the use of anonymised insights into farm data also creates the emergence of data marketplaces, where data is traded for insights on market developments or climate resilience, similar to applications in bioinformatics in biotechnology (Wesseler et al., 2015). This is further catalyzed by government initiatives such as the Digital Agriculture Mission (Reshmitha et al., 2023) in India, which invests in AgriStack—an integrated digital architecture consisting of farmer registries, soil profiles, and business scaling innovations that can further be integrated with biotechnology innovations such as GM crops and microbiome technologies (Badiyal et al., 2024; Khan et al., 2023).

Even still, adoption challenges remain, particularly in developing markets such as India, where both small plot/farm sizes and limited digital skills slow down scale. Overcoming these challenges demands strategic open innovation and technology-market matching, as food and agricultural biotechnology literature has highlighted (Dahabieh et al., 2018). This requires tackling cross-jurisdictional data privacy and interoperability regulatory hurdles in order to increase trust and legitimacy. Fortunately, there are success stories like Bt cotton farmers using precision tools who have reported increases in yield by 30% with simultaneous reductions in pesticide use – enhancing the socio-economic impact of biotech (Thutupalli & Iizuka, 2016). Over 50 million hectares around the world are covered by precision agriculture, forecasting as a $12 billion market by 2027, which demonstrates its profit potential. Within the bioeconomy paradigm, it complements the synthetic biology missions that turn flexi-crops into food/fuel/biomaterials via data-aided bio-refineries (Neimark & Healy, 2018; Wang et al., 2022).

Forward, precision agriculture allows for new resilient and circular business models equipped with genomics, AI and block-chain for traceability. Such innovations have the potential to increase GDP contributions and to address climate threats such as drought and salinity in India where agriculture already employs 42% of the workforce (Vargas-Canales et al., 2024). Agribusiness ventures could thus spearhead the "gene revolution" into the sustainable bioeconomy by unlocking big data for predictive breeding and resource-efficient farming. The transformation of data potential into shared wealth will hinge on pouring ideas into collaborative ecosystems of startups, corporations, and policymakers, ensuring that agriculture remains resilient and progressive as one of the cornerstones of national advancement. Molecular breeding and genomics enterprises are revolutionizing the agricultural landscape by employing pioneering biotechnological tools for a rapid throughput of developing adaptive, climate-smart, and high-yielding crop varieties (Amarasinghe et al., 2024; Riaz et al., 2025). They allow for specific, targeted changes to be made to improve stress tolerance, disease resistance, and nutritional content, among other traits (Riaz et al., 2025). These advances in CRISPR gene editing and transgenic approaches accelerate trait introgression, providing scalable solutions for bottlenecks ranging from seed production to food security with severe alteration of climate (Xie, 2025).

Conclusion

But, agriculture's fusion of biology and business is a radical change in how the life sciences and agribusiness intersect—which influences the global food system, how rural people make a living and how we can be good stewards of the environment. The stunning pace of progress in genomics, biotechnology and accessing and manipulating genetic information has transformed food and agriculture a new opportunity for agricultural innovation, but also a new set of challenges, namely issues of equity, sustainability and governance along a new scale of integrated food and agriculture. Plant science discovery, seen in the context of the work-to-benchtop pipeline, has spawned considerable economic investment in commercial application, and revolutionized agricultural productivity, new industries and jobs at every stage in the agricultural value chain.

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Open Access

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Kheti Vigyan e Magzine

Article ID: KVM0004/26 **Popular Article**

Black Soldier Fly Larvae Meal as an Alternative to Fishmeal in Aquaculture Nutrition: Opportunities and Challenges

Indranil Ghosh

Subject Matter Specialist (Fishery Sciences), West Bengal University of Animal and Fishery Sciences, Ramshai-, Jalpaiguri, WB

*Corresponding Author

Indranil Ghosh

✉ : wbuafs@gmail.com

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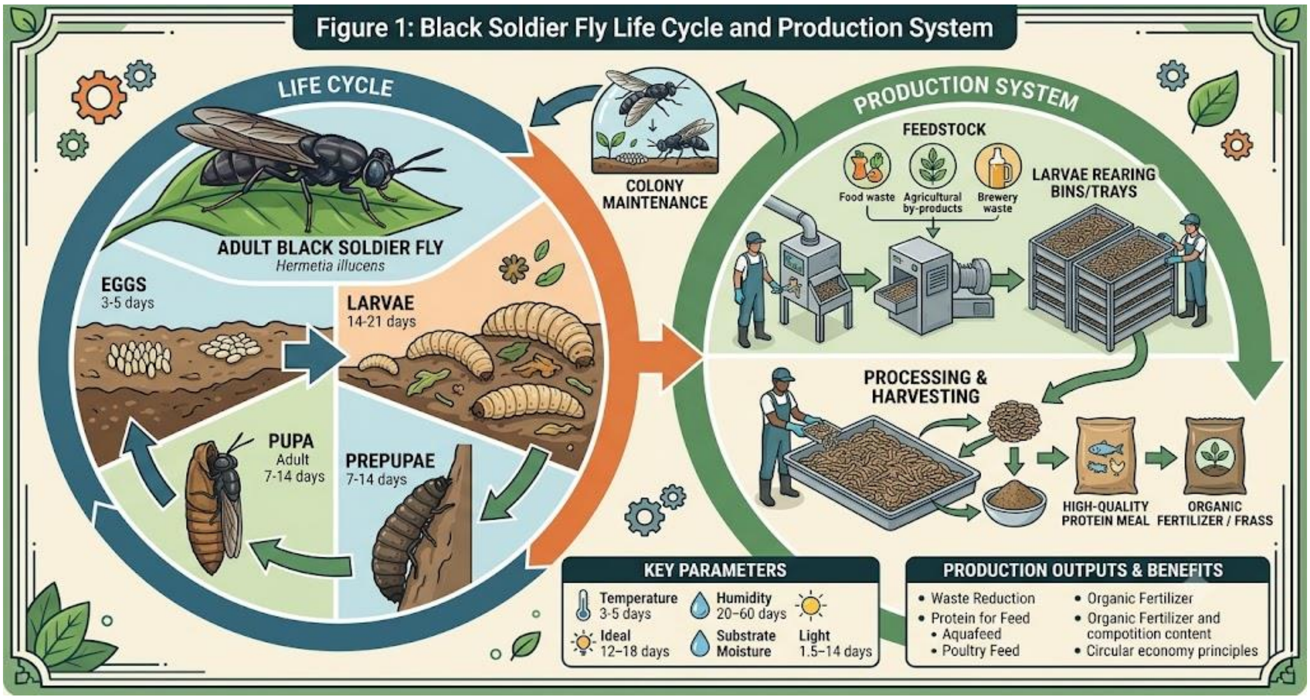
Abstract:- Production and the dwindling resources of fishmeal imply that the generation of other sources of protein is a significant matter. A possible alternative that might replace alfalfa meal is larvae meal (BSFLM) of black soldier fly (Hermetia illucens) as it contains a high protein level (40-45%), balanced composition of amino acids, and antimicrobial peptides. Regardless of the fact that such advantages are observed as waste valorization and low environmental footprint, where the challenges still exist in the framework of chitin digestibility, the calcium-phosphorus ratio, and prone to lipid oxidation, the regulatory frameworks to be considered. The formulated BSFLM to be included in commercial aquafeeds should be based on strategic processing methods and species-specific formulations and conventional manufacturing mechanisms.

Keywords: *Soldier Fly, Black, Aquaculture, Nutritional, Insect, Meal, Fishmeal, Substitutes, Sustainable, Protein*.

Introduction:- The world aquaculture sector has realized unprecedented growth in the last thirty years producing around half of the total fish output to human consumption and defining itself as the quickest expanding food manufacturing trade in the globe (Serra *et al.*, 2024). This tremendous growth however poses a big challenge concerning the sustainability of feed especially in the aspect of fishmeal which is the conventional protein base of aquaculture diet. Production of fishmeal depends profoundly on forage fish taken by wild methods and the amounts of forage fish taken per year are ranging between 16-20 million metric tons harvests, which is of great concern to marine ecosystem stability, overfishing, and future sustainability of the resources (Liu *et al.*, 2025). Aquaculture industry is already using approximately 70 percent of the world fishmeal production, and this puts a desperate need to find alternative sources of protein that are economically viable and environmentally sustainable.

Another innovative solution that is developed on the principles of the circular economy and transforms the streams of organic waste into high-quality protein, which can be used in animal feed, is black soldier fly (Hermetia illucens) larvae meal. Hillucens is native to tropical and warm temperate systems and has shown superior bioconversion efficiency converting a wide variety of organic substances such as agricultural residues, food waste, and animal manure into nutrient-rich biomass in 12-14 days (Wilson *et al.*, 2025). This extraordinary biological potential makes BSFLM one of the versatile resources that would solve three issues at the same time waste management, security of proteins and environmental sustainability. The larvae is rich in crude protein (40-45% on dry matter basis), with favourable amino acid composition that is similar to fishmeal and synthesizes antimicrobial peptides and lauric acid with reported health-promoting effects (Abdelmaksoud *et al.*, 2026).

Figure 1: Black Soldier Fly Life Cycle and Production System



Studies on the use of BSFLM in aquafeeds have continued to grow across the world, with a wide range of aquatic animals being targeted, including salmonids, tilapia, catfish, carp, shrimp, and marine finfish (Gadzama *et al.,* 2025). Initial results are promising with regard to growth and increase in feed efficiency, and enhancement of the immune system in various species when BSFLM is used to partially or fully replace fishmeal (Kariuki *et al.,* 2024). Nonetheless, there are still optimization issues available, among which are chitin-related anti-nutritional effects, mineral imbalances, alterations in the ratio of fatty acids, species-specific tolerance levels, and the need to standardize processing (Khan *et al.*, 2025). This will be a summary of the existing information on the BSFLM uses in aquaculture nutrition, their nutritional value, digestibility measures, growth and health performance, technological process pressing matters, economic viability, regulatory environment, and future research areas necessary in commercial-scale adoption of this feed in the Indian aquaculture and other places more generally (Kabir *et al.*, 2025).

Nutritional Composition of Black Soldier Fly Larvae Meal

Proximate Composition and Protein Quality

The black soldier fly larvae have a high level of nutritional variability that is determined by the composition of the substrates, the age of the larvae, methodology of processing, and environmental conditions during rearing (Ovie *et al.,* 2025). BSFLM is generally 40-45% crude protein on a dry matter basis though in literature it has been found to range between 35-55% depending on defatting methods (Pittarate *et al.*, 2026). The protein fraction has high biological value and the digestibility coefficients of the protein are over 85 percent of most aquaculture species. When compared to the plant-based alternatives that are usually low in restrictive amino acids, BSFLM offers balanced essential amino acid configurations that are extremely high in lysine (5.8-7.2% of protein), methionine (1.8-2.5%), and threonine (3.5-4.2%), which are close to the aquatic species needs (Zainorahim *et al.*, 2024).

Whole BSFLM lipids are ranged radically at

15-40% according to larval food source and extraction methodologies. Fatty acid profile illustrates the presence of saturated fatty acids especially lauric acid (C12:0) 30-60% of all the fatty acids when larvae fed on high-carbohydrate substrates (Gadzama *et al.*, 2025). Lauric acid is a gram-positive antimicrobial agent that has immunomodulatory effects in fish. Nonetheless, BSFLM usually has a smaller amount of long-chain polyunsaturated fatty acids (LC-PUFA), namely, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are necessary in the nutrition of sea fish. This imbalance requires nutritional supplementation or substrate alteration measures to normalize fatty acid profiles to meet particular aquaculture requirements (Khan *et al.*, 2025).

Amino acid Profile and Biological Value.

Thorough amino acid analysis shows that BSFLM is better than traditional plant proteins in terms of the availability of essential amino acids. Lysine levels (2.5 -3.2 percent DM) are much higher than those of soybean meal, and these values overcome an enormous constraint in plant-based aquafeeds. The combination of Methionine and cysteine gives up 1.8-2.4% of dry matter, which promotes growth, immune activities, and antioxidant-like production. The level of arginine (2.5-3.0) fulfills the effects of nitric oxide production and immune competence, and leucine, isoleucine, and valine meet the demands of branched-chain amino acids in protein synthesis and energy metabolism (Jha *et al.*, 2025).

Most of the aquaculture species have protein digestibility-corrected amino acid score (PDCAAS) of over 0.85, which denotes high protein quality, close to fishmeal standard (Petereit *et al.*, 2024). Nevertheless, chitin, a structural polysaccharide (5-8% of whole larvae dry matter) has the potential to decrease the digestibility of proteins and minerals in relation to chelation effects and physical encapsulation (Gadzama *et al.*, 2025). The age of the larva negatively correlates with the chitin content, and the younger instar larvae had a greater percentage of chitin. Anti-nutritional effects of chitin can be reduced by strategic timing of harvest and processing such as mechanical grinding, enzymatic hydrolysis or microbial fermentation without reducing the quality of protein (Abenaim & Conti, 2025).

Mineral Content and Bioavailability

BSFLM exhibits high mineral density especially in the aspects of calcium and phosphorus due to the exoskeletal chitin-calcium carbonate complex (Lv *et al.*, 2024). The level of calcium is 5-8 percent of dry matter, which is much higher than fishmeal (3-5 percent) and most vegetable products (less than 1 percent). But this high level of calcium causes unbalanced calcium to phosphorus ratios (3:1 to 8:1) in opposition to optimal aquafeed ratios (1:1 to 2:1). High amounts of dietary calcium may cause phosphorus to be precipitated by the calcium-phosphate complexes being insoluble in the digestive tract decreasing the phosphorus bioavailability and may even cause deficiency symptoms even with adequate total phosphorus (Khan *et al.*, 2025).

Table 1: Proximate Composition of Black Soldier Fly Larvae Meal Compared to Conventional Protein Sources

Parameter (%)	**BSFLM**	**Fishmeal**	**Soybean Meal**	**Poultry By-Product Meal**
Crude Protein	40-45	60-72	44-48	55-65
Crude Lipid	15-40	8-12	1-3	10-15
Crude Fiber	7-12	0-1	3-7	2-4
Ash	10-18	15-20	6-7	12-18
Chitin	5-8	0	0	0
Calcium	5-8	3-5	0.3-0.5	3-5
Phosphorus	0.8-1.5	2.5-3.5	0.6-0.7	2-3

Phosphorus in BSFLM exists mostly in organic forms that are related to protein and phospholipids, which has the greater bioavailability in comparison to phytate-phosphorus in plants. Iron levels (300-800 mg/kg) are significantly higher than those of fishmeal, which are beneficial in the production of hemoglobin and oxygen (Chhetri *et al.*, 2025). Zinc (150-300 mg/kg) and copper (20-50 mg/kg) are sufficient amounts of the cofactor of the enzyme and immune system support. Magnesium, manganese and selenium are in concentration that satisfies aquatic species needs, but bioavailability is dependent on interactions between diets and species-specific physiological adaptations (Kokkali *et al.*, 2023).

Antimicrobial Peptides and Bioactive Compounds.

In addition to traditional nutrients, BSFLM possesses a variety of bioactive compounds that have functional properties that can be applied in health management of aquaculture. Antimicrobial peptides (AMPs) such as cecropins, defensins, and attacins are broad-spectrum antimicrobial agents against pathogenic bacteria, fungi and some viruses (Saini *et al.,* 2026). It is these peptides that survive in part due to processing and by gastric digestion, which might alter the composition of gut microbiota, and increase resistance to disease. Studies have shown BSFLM supplementation helps to reduce colonization of pathogens in fish intestines and help preserve beneficial bacteria such as Lactobacillus and Bacillus species (Chen *et al.,* 2024).

Besides its antimicrobial effects, lauric acid has anti-inflammatory effects by regulating the production of eicosanoids. Chitin and its deacetylated analogue chitosan are immunostimulants and induce innate immune responses, such as phagocytosis, active lysozyme, and complement system components. Immunomodulatory effects can be attributed to these effects showing a greater resistance to disease in BSFLM-fed fish than would be predicted by nutritional composition alone. Also BSFLM consists of phenolic compounds, melanin precursors and carotenoids (in limited amounts) as part of antioxidant defenses, although the amounts remain significantly low compared to dedicated sources, such as algae or crustacean diet (Abdolmanafi *et al.,* 2025; Wang *et al.,* 2024).

Digestibility and Nutrient Bioavailability in Aquatic Species

Protein Digestibility Coefficients

BSFLM protein apparent digestibility Coefficients (ADC) across aquaculture species differ amongst species and thus represent differences in digestive physiology, capacity to produce enzymes and dietary adaptation (Zehra *et al.,* 2024). The rainbow trout (Oncorhynchus mykiss) has a protein ADC of 82-89% similar to or even greater than the digestibility of fish meal (85-92%). Salmon Atlantic salmon (Salmo salar) exhibit the same trends in digestibility with ADC values of 80-88 of BSFLM proteins. These carnivorous species have powerful protease systems that completely break insect proteins even though they have structural dissimilarity with fish proteins (Lv *et al.,* 2024).

BSFLM protein digestibility is also exceptional in omnivorous species like Nile tilapia (Oreochromis niloticus) in ADC of 88-93 (which may be greater than fishmeal in comparative studies). The digestive tract of the tilapia is long and the digestive environment is alkaline which leads to efficient hydrolysis and absorption of protein and amino acids (Munguti *et al.,* 2025). A high BSFLM protein digestibility (85-91%), which is also observed in the channel catfish Ictalurus punctatus, also warrants a large amount of fishmeal substitution without disrupting the growth performance. These results indicate that omnivorous freshwater species are the best candidates to include in BSFLM integration since they have a digestive physiological fitness with the insectaceous proteins (Mohammed *et al.,* 2025).

The number of patterns of digestibility among marine fish species is high. BSFLM protein ADC values in European seabass (Dicentrarchus labrax) lie between 75-85% which is a little below the fishmeal standards (Tefal *et al.,* 2023). This reduction may be linked to the chitin interference, variation in amino acid profile or evolutionary specialization of food on marine animals. Gilthead seabream (Sparus aureus) that displays a protein digestibility of 78-86% when fed BSFLM and whose digestibility improves after defatting and grinding of samples that reduces the particle size, and dislodges chitin-protein matrices are yet another economically valuable marine nutrient of interest (Basili *et al.,* 2024; Khan *et al.,* 2025).

Lipid Digestibility and Fatty Acid Absorption.

Most species of aquaculture (usually more than 85 per cent) can digest BSFLM lipid, attributed to the dominance of saturated fatty acids and the presence of phospholipids that allow the formation of emulsions and micelles. The absorption of BSFLM lipids by rainbow trout has an ADC of 90-95 that is similar to fish oil digestibility (Wang *et al.,* 2024). The beta-oxidation of the high percentage of lauric acid is a very efficient process which provides easy to spend energy and assists to enlarge provided the levels of dietary energy are optimum (Lv *et al.,* 2024).

The special fatty acid profile however has implications of tissue composition. Fish that had been fed BSFLM based diets have more saturated fatty acid deposition of flesh as well as less EPA and

DHA as compared to the fish meal fed counterparts (Zainorahim *et al.*, 2024). The effect illustrates the incorporation of dietary fatty acids in tissue lipids, which is a problem in the example of species that are sold to humans in which the composition of omega-3 LC-PUFA has an impact on the nutritional value and palatability to consumers. Modification of the fatty acid composition of tissues can be corrected using strategic supplementation with fish oil, algal oils, or genetically modified oilseeds without altering BSFLM as the main protein source (Su *et al.*, 2025).

Table 2: Apparent Digestibility Coefficients of BSFLM Nutrients Across Selected Aquaculture Species

Species	**Protein ADC (%)**	**Lipid ADC (%)**	**Energy ADC (%)**	**Phosphorus ADC (%)**
Rainbow Trout	82-89	90-95	85-90	70-78
Atlantic Salmon	80-88	88-93	83-89	68-75
Nile Tilapia	88-93	92-96	88-92	72-80
Channel Catfish	85-91	89-94	86-91	70-76
European Seabass	75-85	85-92	80-88	65-72
Pacific White Shrimp	78-84	82-88	78-85	62-70
Common Carp	86-92	90-95	87-92	74-82

The medium-chain fatty acids, particularly lauric acid, undergo selective oxidation as compared to the long-chain fatty acids, that is, they divert the energy to protein synthesis and growth, but not to lipid deposition. This metabolic characteristic is most likely causing the enhanced feed efficiency and reduced fat deposition which is favorable to the economics of aquaculture production. Nonetheless, in the context of BSFLM utilization in feeds at early life stages, species-specific fatty acid requirements that are vital to the maturation of the neurological and visual pathways of a variety of marine fish larvae will need to be put into careful consideration (Siddiqui *et al.*, 2024).

Mineral Bioavailability and Anti-Nutritional Factors

The interaction of the forms of nutrients, the effects of the dietary matrix and the interference of the anti-nutritional factors all demonstrates complex interactions between the bioavailability of minerals through BSFLM (Tura *et al.*, 2024).. The calcium-carbonate complex of exoskeletons is less soluble than calcium-phosphate salts and, therefore, may not be absorbed by species with acidic stomachs which stimulate the dissolution of minerals (Khan, 2023).

The phosphorus bioavailability of BSFLM (60-75%) is much higher than the plant sources of phytate-phosphorus (30-50% availability) and this is a huge plus on the reduction of inorganic phosphorus supplementation and the environmental pollution caused by aquaculture effluents. BSFLM grows the organic phosphorus and this is effectively hydrolyzed by endogenous phosphatases to aid skeletal growth, and energy metabolism and do not require microbial supplementation of phytases (Wang *et al.*, 2024).

Chelating ability of chitin can reduce bioavailability of zinc, iron as well as copper by creating a coordination complex. Practical feeding trials, in any case, barely report trace mineral deficiency syndrome in BSFLM-fed fish suggesting adequate bioavailability in physiological situations or adequate levels of dietary trace minerals that overcome the reduced absorption efficiency. Chitin molecular weight can be reduced by enzymatic or acid hydrolysis to reduce chelating capacity (without affecting protein integrity), and potentially enhance the overall mineral bioavailability of BSFLM-based aquafeeds (Pascon *et al.*, 2025).

Growth Performance and Feed Utilization Efficiency

Effects on Growth Rates and Body Weight Gain

The lack of research on different species of aquaculture demonstrates the potential of BSFLM to attain the same growth efficiency as fishmeal-based feeds with the best replacement ratios, and dietary frameworks. BSFLM as an alternative to fishmeal to a maximum of 50 percent in rainbow trout does not have any impact on growth rates, feed ratio (FCR) and protein efficiency ratio (PER) which are not statistically different when compared with controls.

Substitution of fishmeal (100 percent) has been found to be inconsistent depending on dietary formulation with certain reports indicating that 10-15 percent growth loss than others as they did well using amino acid supplementation and other cases using palatability enhancement (Chen *et al.*, 2024).

Nile tilapia is highly tolerant to high BSFLM inclusion rates where total fishmeal replacement offer the same level of growth performance as fishmeal controls and in some cases, even greater. Research records an increase in weight gain of 5-12% in tilapia juveniles fed on completely replaced diets of BSFLM when compared with traditional fishmeal diets because of elevated digestibility and health of the gut together with the benefits of antimicrobial peptides. The growth performance of channel catfish also does not decline with complete substitution of fishmeal with BSFLM, which makes them the ideal ones to be used in BSFLM-based feed plans (Mohammed *et al.,* 2025).

Atlantic salmon despite a good acceptance of BSFLM up to 60 percent fishmeal replacement performance is compromised at greater inclusion levels, unless dietary adjustments are made to offset amino acid ratios and fatty acid profiles. In the study where there is no strategic nutritional supplement, growth reduction of 8-18% with 80-100% replacement, nutrition-specific species requirement and dietary optimization are underlined. A majority of marine animals like European seabass and gilthead seabream can be replaced by 25-50 percent of fishmeal with BSFLM, and still be able to grow commercially, but total replacement usually involves a titanic change in diet (Khan *et al.*, 2025).

Feed Conversion Ratio and Efficiency of Protein.

The ratios of feeds are the indicators of feed per unit weight gain, which are the economic indicators that play a significant role in determining the profitability of the aquaculture. Other species Replacement 5-10% fishmeal with BSFLM inclusion to 40-60% does not alter FCR values more than 5-10. Rainbow trout fed half BSFLM replacement diets have FCR of 1.05-1.15 which is equal to fishmeal control FCR of 1.00-1.10. This low variability suggests that insect-based proteins are well metabolised, and their rate of energy use, along with their nutrient use, is minimal (Zainorahim *et al.*, 2024).

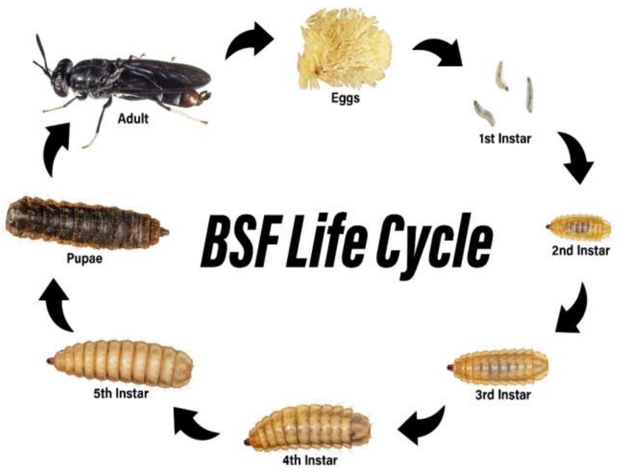


Figure 2: BSFLM Production Flow and Critical Control Points

Protein efficiency ratios (weight gain/grams of protein intake) are used to give an idea about the effectiveness of protein utilization. Normal values of PER in BSFLM based diets in carnivorous and omnivorous species are 2.0-2.8 and 2.5-3.5 respectively, which is similar or almost equal to fishmeal based diet performance. But when dietary inclusion is excessive of the tolerance levels in the species, it may decrease PER either by imbalances of amino acids, interference of chitin or due to palatability problems with the feed (Vu *et al.*, 2025).

The other key sustainability indicator that should be taken into consideration when environmental concerns arise on nitrogen pollution as a result of aquaculture can be stated as the nitrogen retention efficiency that is the percentage of ingested nitrogen that is retained in body tissue. The nitrogen retention rate of BSFLM-based diets is 30-45 percent depending on species and amount of dietary protein that is equal or even higher than that of fishmeal-based formulation. This type of efficiency presupposes the adequate balance of amino acids and protein values in favor of anabolic growth and low yield of nitrogen waste that is a significant advantage when it comes to creating environmentally friendly aquaculture (Vu *et al.*, 2025).

Feed Palatability and Acceptance

The growth performance is largely determined by the feed palatability which can be determined by its effects on voluntary feed intake in which BSFLM has been found to react speciesdependently. The palatability effect of many studies is neutral or positive, yet, there are species of which the BSFLM based diets are preferred to the traditional ones (Rawski *et al.,* 2024). Due to the presence of nucleotides, free amino acids and other flavor compounds in BSFLM, chemosensory stimulation and feeding motivation can go up. Rainbow trout and Atlantic salmon will tend to accept a BSFLM-based diet, although in other tests the diet has been lower at high levels of inclusion (more than 60 percent replacement) which may be due to altered flavor profile or altered texture(Siddiqui *et al.,* 2024).

Figure 3: Comparative Environmental Footprints of Protein Sources

Table 3: Growth Performance Parameters of Selected Species Fed BSFLM-Based Diets

Species	BSFLM Inclusion (%)	Weight Gain (g)	FCR	PER	Survival (%)
Rainbow Trout	0 (Control)	125±8	1.08±0.05	2.4±0.2	96±2
Rainbow Trout	50% Replacement	122±7	1.12±0.06	2.3±0.2	95±3
Nile Tilapia	0 (Control)	48±4	1.45±0.08	2.8±0.3	98±1
Nile Tilapia	100% Replacement	52±5	1.40±0.07	3.0±0.3	97±2
Atlantic Salmon	0 (Control)	285±18	1.05±0.04	2.6±0.2	97±2
Atlantic Salmon	60% Replacement	275±16	1.10±0.05	2.5±0.2	96±2
Channel Catfish	100% Replacement	156±12	1.52±0.09	2.7±0.2	96±3

Tilapia and catfish species are repeatedly portrayed to be highly tolerant to BSFLM-based feeds of all inclusion confusions and this validates the hypothesis that omnivorous species that have an evolutionary history of eating insects are more compatible with insect-based proteins. The gut analysis of wild tilapia resources also often contains microinsect larvae, which would suggest the possibility of natural exposure to the diet and hence would be physiologically and behaviorally tolerant to accept BSFLM (Kariuki *et al.,* 2024).

Conclusion

Black soldier fly larvae meal is a revolutionary innovation in aquaculture feeds, providing innovative and sustainable protein sources to solve major issues of fishmeal dependence, resource scarcity, and environmental sustainability,attractants and flavor enhancers. The crustaceans such as the Pacific white shrimp (Litopenaeus vannamei) will probably be satisfied with BSFLM to around 50 percent of fishmeal substitution and addition of the chitin that may potentially have a positive fiber effect to maintain the gut healthy and immunized, enhance growth performance, immune system, and economic production in a wide range of species. Unbiased studies reveal the nutritional sufficiency of BSFLM, which has 40-45 percent protein content and proportional amino acid ratios, which can substitute 25-100 percent of fishmeal based on the species, formulation approaches, and production level. In addition to traditional nutritional properties, antimicrobial peptides, immunostimulatory compounds, and lauric acid also have functional properties that increase resistance to disease and minimise medication needs, which would not otherwise be predicted by compositional analysis..

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Integrated Nutrient Management Strategies for Enhancing Crop Productivity and Soil Health Sustainability in Modern Agriculture

[1]Naushad Khan and [2]M.Z. Siddqui

[1&2]Professor, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology Kanpur

*Corresponding Author

Naushad Khand

✉ : ***naushadkhan.0000@gmail.com***

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Abstract:- Integrated Nutrient Management (INM) has developed as a crucial method to fill the gap between the high agricultural production and the environmental care. Through the synergy in application of chemical fertilizers, organic manures as well as bio-fertilizers, INM enhances the physical, chemical and biological nature of soil. This review will discuss the INM constituents, its influence on nutrient use efficiency (NUE), and how it relates to soil organic carbon sequestration. The results indicate that a balanced INM strategy can not only decrease the level of reliance on synthetic inputs by 25-50% but also the long-term food security of the Indo-Gangetic Plains and beyond through the preservation of the ecological balance of the Indo-Gangetic Plains.

Keywords:- *bio-fertilizers, yields, environmental, fertilizers, soil, food security.*

Introduction:- The current agricultural landscape is in a fundamental shift where there is the pressing need to have food security globally and to conserve the environment. With the world population growing to 10 billion by 2050, the strain on agricultural land has been increasing and this has seen the world heavily depending on high-input chemical agriculture. High-yielding varieties and synthetic fertilizers have helped the Green Revolution to avert famine, but the ecological price of this yield-at-any-cost strategy proved to be very expensive. The use of urea and other nitrogenous fertilizers in excess has interfered with the natural balance of nutrients in regions such as the Indo-Gangetic Plains leading to massive soil erosion (Ray *et al.*, 2024).

The effects of unbalanced fertilization are dire and complex. The prolonged use of high dosage chemicals that lack the ability to replenish the soil with organic matter has drained the soil of organic carbon, which forms the basis of soil fertility leading to compaction, low water-absorbing ability and shortage of micronutrients such as zinc, boron, and iron which reduce the nutritional value of crops. Additionally, traditional methods are also known to pollute the environment with nitrate leaching into groundwater and nitrous oxide emissions (Shah *et al.*, 2024).

Instead Integrated Nutrient Management turns out to be a scientifically sound, sustainable philosophy for 21st century agriculture, rather than a

Figure 1: Conceptual Framework of Integrated Nutrient Management (INM) Synergizing Synthetic, Organic, and Biological Inputs

mere alternative method. The ability of INM to maintain soil and plant nutrients at optimal levels has been demonstrated to sustain crop productivity (Yimer & Tarnawa, 2025). It ensures maximum advantages from all plant nutrient sources through judicious integration of chemical fertilisers, organic manures and bio-fertilizers.

While the former addresses the short-term nutritional needs of intensive cropping systems with mineral sources; the latter, through organic and biological inputs, can preserve the physical and biological integrity of soil, in the long term. INM increases nutrient use efficiency and reduces losses by synchronizing nutrient release with crop phenological stages. Application of nano-fertilizers or precision IoT-based soil monitoring/management techniques makes it possible (Ahmad *et al.*, , 2025). Here, we summarize the various dimensions in which INM can contribute to carbon sequestration potential, increased yield stability, and ecological balance restoration leading to sustainable intensification of agriculture.

This has further led to preparation of data tables requested for Integrated Nutrient Management (INM) and improved fertilization technologies:

Table 1: Nitrogen Loss Pathways and Mitigation via INM

Loss Pathway	Conventional Practice Loss (%)	INM Reduction (%)	Key Mitigation Mechanism
Volatilization	20–50	30–50	Slow-release organic buffering
Denitrification	10–30	25–40	Optimized aerobic pore space
Leaching (N)	15–35	20–40	Rhizosphere retention & synchronization
Runoff	10–25	20–35	Improved soil aggregate stability
Surface Erosion	5–15	40–60	Increased humic "microbial glues"
Ammonia Fixation	5–10	10–15	Organic acid chelation
Microbial Immobilization	10–20	15–25	Balanced C:N ratio management
Deep Percolation	10–30	25–45	Enhanced water-holding capacity

2. The Evolution of Integrated Nutrient Management

The history of nutrient management in agriculture is a story of the human development of a new relationship to the land-of natural balance, to active overexploitation and, ultimately, to a kind of scientific symbiosis. This development can be divided into three different historical stages (Samanta & Sengupta, 2024).

2.1 The Pre-Green Revolution Period: The Age of Organic Recycling.

Until the mid-20th century, agriculture was naturally integrated, by necessity. To fix atmospheric nitrogen, farmers were virtually the only source and used the circular flow of nutrients in the farm ecosystem, using farmyard manure, cattle dung, crop residues, and including legumes in rotations. Also considered a biological legacy but not a chemical input was soil fertility. Though this system was eco-friendly and supported high levels of soil organic carbon, it was low in productivity (Gopalakrishnan *et al.*, , 2023). The low rate of mineralization of organic matter was not up to the high caloric needs of the fast growing world population, and thus, food shortages were common.

2.2 The Green Revolution: The Chemical Shift.

The 1960s was a radical break with conventional ways. Nutrient demand per unit area due to the introduction of high-yielding varieties of wheat and rice changed the agricultural paradigm towards mineral nutrition. The use of synthetic fertilizers, mainly urea, diammonium phosphate and the muriate of potash, delivered instantaneous, high levels of N, P and K (Debnath *et al.*, , 2023).

Crop	Conv. Rate (kg/ha)	Nano Rate (L/ha)	Yield Increase (%)	NUE Improvement (%)
Paddy (Rice)	120	4–6	5–12	82
Wheat	100	3–4	6–10	85
Maize (Corn)	150	6–8	8–15	80
Cotton	80	2–4	7–14	88
Sugarcane	250	10–12	10–18	75
Mustard	90	3–5	5–9	83
Potato	180	5–7	12–20	78
Chili	100	4–6	10–15	81
Soybean	40	2–3	6–12	90

This period was successful when it came to food production and the countries such as India became the bread baskets and not the begging bowls. However, the "more is better" mentality marginalized organic sources (Sapkota & Sıngh, 2025). The effects became felt by the 1980s and 1990s: partial factor productivity of fertilizers started to decrease, and farmers had to use ever more fertilizer each year to keep production at current levels-so-called soil fatigue.

2.3 The Contemporary Age: The INM Synergy is Born.

In the late 20th century, scientists theorized Integrated Nutrient Management after realizing that existing systems based on organic or chemical management were unsustainable. Fertilizers made of chemicals are the source of the so-called speed required by high yields, organic manures are the source of the so-called stamina to keep the soil healthy in the long run (Samanta & Sengupta, 2024).

Contemporary INM involves the integration and equal use of various sources of nutrients. It has progressed to simple combinations such as manure plus urea to more advanced structures using:

●**Bio-fertilizers:** Strains of microbes to release nutrients in the atmosphere and soil.

●**Accurate equipment:** Soil health cards and leaf color charts to avoid over-fertilization.

●**Nano-technology:** Nano-urea and nano-zinc to high-efficiency nutrition with the least environmental impact.

3. INM basic elements.

An effective Integrated Nutrient Management plan is based on the combination of four main pillars. They each have their own physiological and ecological functions, providing the best nutrition to the plants and leaving the soil as a dynamic, productive ecosystem (Samanta & Sengupta, 2024; Yadav *et al.*, , 2023).

The Immediate Nutrition Source:

3.1 Chemical Fertilizers.

The strength of intensive agriculture is chemical fertilizers, which are rich in nutrients and can dissolve quickly. In an INM system, the urea, DAP, and MOP are used based on the principles of the 4R Stewardship: the Right Source, Right Rate, Right Time, and Right Place. These provide rapid-growing nitrogen, phosphorus and potassium at crucial growth periods such as tillering and flowering (Bhattarai *et al.*, , 2024). They can be used in combination with other sources to reduce chemical inputs by 25-30% without yield loss (Alvi *et al.*, , 2025).

3.2 Organic Sources: Soil Health Builders.

Farmyard manure, vermicompost, and green manures (e.g., dhaincha or sunnhemp) are organic manures that are slow-release sources of nutrients (Xu *et al.*, , 2025). In addition to providing NPK, they improve:

- **Soil structure:** through enhanced granulation and aeration of roots;
- **Cation exchange capacity:** increasing the capacity of the soil to store and release minerals;
- **Water retention**: behaving as a sponge to relieve stress on drought.

3.3 Bio-fertilizers: The Biological Catalysts

Bio-fertilizers are harbored with living cells of effective microbial strains (Shahzad *et al.*, , 2025). These agents do not directly provide nutrients, but rather increase their availability by natural processes.

Table 2: Impact of Nano-Urea and Nano-DAP on Crop Performance

- **Nitrogen fixers** (e.g. Rhizobium, Azotobacter or Azospirillum) transform atmospheric nitrogen to forms that are usable by plants;
- **Solubilizers** (e.g., phosphate- or zinc-solubilizing bacteria) produce organic acids to dissolve insoluble soil minerals;
- **Mobilizers** (e.g., arbuscular mycorrhizal fungi) stretch hyphae to access phosphorus in far-off regions of soil.

3.4 Nano-Nutrients: The Precision Revolution.

The most recent addition to INM toolkit is nanotechnology. Nano-urea and nano-DAP represent the shift in the paradigm of nutrient delivery, due to their small size of particles and large ratio of surface and volume (Dhiman *et al.*, , 2025). When used as foliar sprays they are directly absorbed by plant leaves through the stomata resulting in:

- **Hyper-efficiency:** only 500 ml bottle of nano-urea is needed to substitute a 45 kg bag of traditional urea;
- **Environmental safety:** steep declines in nitrogen leaching and emissions of nitrous oxide;
- **Specificity**: direct delivery of micronutrients such as nano-zinc and nano-copper to the metabolic sites, attacking its hidden hunger.

3. Chemical Fertilizers: function and environmental limitations.

Chemical fertilizers are the first responders in the hierarchy of Integrated Nutrient Management. Although organic and biological sources are sure to provide stability over time, synthetic mineral fertilizers are created to provide specific, concentrated, and directly available nutrients to support the metabolic needs of the high yielding types of crops (Zhang *et al.*, , 2025).

Parameter	**Conventional Change**	**INM Change**	**Physiological Benefit**
Bulk Density	Increases (Compaction)	Decreases (10–15%)	Easier root penetration
Porosity	Decreases	Increases (20–30%)	Improved soil aeration
Water Retention	Low	High (25–40% increase)	Alleviates drought stress
Aggregate Stability	Poor (Structural collapse)	High (Humus binding)	Prevents soil erosion
Infiltration Rate	Decreases	Increases	Reduced surface runoff
Soil Temperature	Fluctuates highly	Buffered/Moderated	Optimal root metabolism
Resilience to Tillage	Low	High	Sustained friability
Crusting Propensity	High	Low	Improved seedling emergence

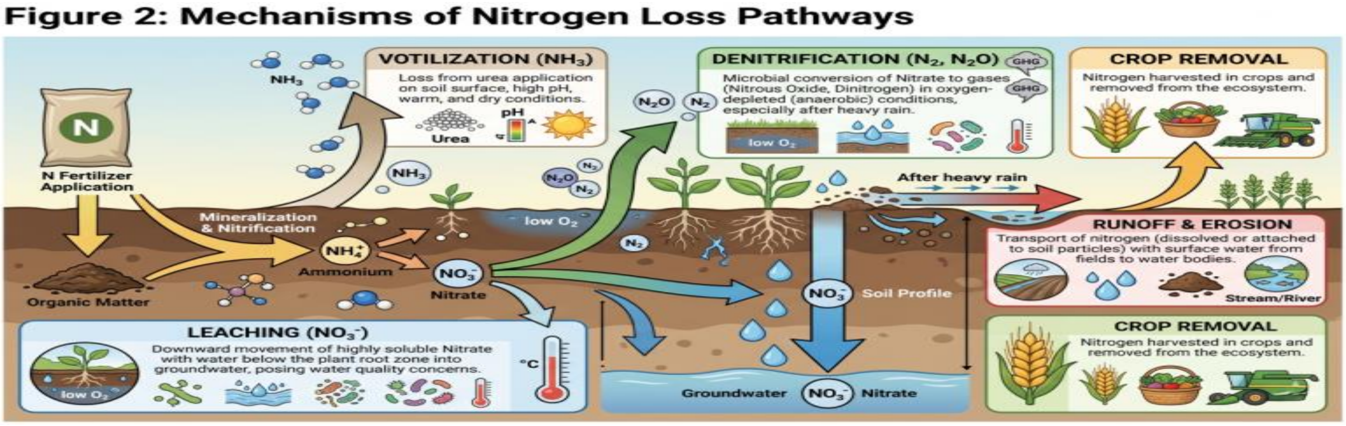

Figure 2: Mechanisms of Nitrogen Loss Pathways

VOTILIZATION (NH$_3$)
Loss from urea application on soil surface, high pH, warm, and dry conditions.

DENITRIFICATION (N$_2$, N$_2$O)
Microbial conversion of Nitrate to gases (Nitrous Oxide, Dinitrogen) in oxygen-depleted (anaerobic) conditions, especially after heavy rain.

CROP REMOVAL
Nitrogen harvested in crops and removed from the ecosystem.

RUNOFF & EROSION
Transport of nitrogen (dissolved or attached to soil particles) with surface water from fields to water bodies.

CROP REMOVAL
Nitrogen harvested in crops and removed from the ecosystem.

LEACHING (NO$_3^-$)
Downward movement of highly soluble Nitrate with water below the plant root zone into groundwater, posing water quality concerns.

3.1 Scientific Necessity of Immediate Gains of Yield.

Fertilizers based on chemicals, specifically nitrogen (N), phosphorus (P) and potassium (K), bypass slow rates of mineralization of organic material.

●**Nitrogen** plays a vital role in chlorophyll production and vegetative growth; in the absence of mineral N, plants tend to have sluggish growth in a critical period of tillering.

●**ATP** production and root development is dependent on phosphorus. Since P is often fixed in insoluble forms in soils, fertilizers that are soluble in water attract early-stage vigor.

●**Potassium** controls stomatal opening and enzyme activations, which promotes resistance to biotic and abiotic stress.

3.2 Environmental limitations and Degradation of the chemical.

Although efficient, the sole and overuse of chemical fertilizers causes a series of "second-generation" issues that undermine the soil they are supposed to feed (Vindena *et al.*, , 2023).

Table 3: Soil Physical Property Improvements under INM

A. Soil Acidification and Structural Collapse

The constant use of the ammonium-based fertilizers emits H+ ions during the nitrification process.:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O/NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

C. Eutrophication and Atmospheric Pollution

The runoff of phosphatic and nitrogenous residues into water bodies by surface runoff provokes eutrophication, explosive growth of algae that destroys dissolved oxygen and kills aquatic life (Liu *et al.*, , 2023). In the atmosphere, excess nitrogen is denitrified to produce nitrous oxide (N 2 O), a greenhouse gas with almost 300 times the global warming capacity of CO 2 (Chatterjee *et al.*, , 2023).

3.3 The INM Balance

Scientific opinion in INM is that chemical fertilizers are not pollutants when used properly. The idea is to shift toward uneven fertilization (which is usually biased towards Urea) to a balanced one whereby chemical feeds are balanced by organic matter (Samanta & Sengupta, 2024). Organic fertilizers enhance the buffering capacity of the soil, cushioning variations in the pH, and bio-fertilizers enhance the effectiveness of the chemicals used in improving their recovery, thus reducing the environmental footprint (Dahunsi *et al.*, , 2025).

4. Soil Conditioning Properties of Organic Manures.

Organic manures play the role of soil conditioners and not a source of nutrients in the context of the Integrated Nutrient Management (Singh *et al.*, , 2020). Although chemical fertilizers stimulate the short-term growth of plants, the organic manure develops the so-called engine of the soil, increasing the physical, chemical, and biological characteristics of the soil to form a stable medium to develop roots (Acar *et al.*, , 2025).

Manure Type	Avg. NPK Content (%)	Primary Role	Decomposition Rate
Farmyard Manure	0.5 : 0.2 : 0.5	Humus formation	Moderate
Vermicompost	1.5 : 1.0 : 1.5	Growth regulators	Fast
Green Manure	2.5 : 0.5 : 2.0	In-situ revitalization	Very Fast
Poultry Manure	3.0 : 2.5 : 1.5	High nutrient pulse	Fast
Sheep/Goat Dung	3.0 : 1.0 : 2.0	Dry-land conditioning	Moderate
Pressmud	1.2 : 2.0 : 0.5	P-enrichment	Moderate
Biochar	0.1 : 0.1 : 0.2	Carbon sequestration	Very Slow
Bone Meal	3.0 : 20.0 : 0	Phosphorus supply	Slow

Table 4: Biological Catalysts (Bio-fertilizers) and Their Roles

Inoculant Type	Primary Mechanism	Target Nutrient	Typical Nitrogen Fixation
Rhizobium	Symbiotic fixation	Nitrogen (Legumes)	50–100 kg N/ha
Azotobacter	Free-living fixation	Nitrogen (Cereals)	20–30 kg N/ha
Azospirillum	Associative fixation	Nitrogen (Grass/Corn)	25–40 kg N/ha
PSB (Bacteria)	Organic acid secretion	Phosphorus	15–20% P mobilization
AM Fungi	Hyphal extension	Phosphorus/Zinc	Enhanced uptake area
KMB (Bacteria)	Mineral weathering	Potassium	Improved K availability
ZSB (Bacteria)	Chelation/Acidification	Zinc	Combats "hidden hunger"
NPK Consortia	Multi-strain synergy	N, P, and K	Balanced plant nutrition

Table 5: Integration of Organic Manures in INM Systems

4.1 Farmyard Manure: The Traditional Workhorse.

The most commonly used organic amendment is farmyard manure, which is a decomposed mixture of cattle dung, urine, and litter (Howe *et al.,* , 2024). It provides multipronged advantages to soil health:

●**Nutrient Profile:** FYM provides small amounts of N, P, and K (usually 0.5:0.2:0.5%) and a complete range of micronutrients that is usually lacking in synthetic fertilizers.

●**Humus Formation:** Its decay results in humic and fulvic acids that are natural chelators that enhance the plant availability of minerals.

●**Biological Activation:** FYM is a carbon-rich substance that enhances the populations of soil macro- and micro-fauna, such as earthworms and biomass of microorganisms.

4.2 Vermicompost: The Bio-Amendment of Nutrient-Rich.

Vermicompost is produced through the process of decomposition of organic waste through the use of earthworms, which is in turn more nutrient dense and active than normal compost (Sharma, 2025).

●**Enzymatic Activity:** It has abundant plant growth regulators such as auxins and gibberellins, which enhances seed germination and root growth.

●**Microbial Diversity:** It serves as a bio-inoculant, introducing beneficial bacteria and fungi that suppressing the pathogenic bacteria present in the soil.

4.3 Green Manuring: The "In-Situ" Soil Revitalizer

Green manuring involves planting succulent, leafy plants, like Sesbania aculeata or Crotalaria juncea, and putting them into the soil when green (Gaspar *et al.,* , 2024).

●**Nitrogen Fixation**: Leguminous plants fix 60-100 kg N/hA, which decreases the basal urea requirement.

●Nutrient Scavenging: Their deep roots extract nutrients in the subsoil layers and when they decompose, the nutrient is sent back to the topsoil.

4.4 Impact on Soil Physical Properties

Organic manures have the greatest impact on soil physical health in three important indicators:

A. Decrease in Bulk Density.

Large bulk density hinders penetration and aeration of roots. Organic manures hold particles together in crumbs, reduce bulk density to be easily tilled and provide a friable soil by promoting stable aggregates by releasing microbial glues during decomposition (Majamo *et al.*, , 2025).

B. Improving the Water-Holding Capacity.

The organic matter acts as a sponge and retains multiple times its weight of water. It reduces the runoff and percolation by increasing surface area and pore space, which helps crops to survive long dry spells between irrigations or rains (Zgallai *et al.*, , 2023).

C. Enhancing Soil Aeration and porosity.

These modifications form a balanced set of macropores, and micropores, which provide sufficient oxygen to roots and prevent anaerobic environments, which promote root rot and denitrification. These conditioning effects render organic manures a living system that maintains soil as a dynamic, vibrant system that can support intensive agriculture in the long-term (Wei *et al.*, , 2025).

5. Bio-fertilizers: Biological Engine of INM.

Bio-fertilizers are the biological engine when the chemicals fertilizers supply the fuel and the organic manures are the chassis in the Integrated Nutrient Management system. They do not have any nutrients as opposed to traditional fertilizers (SG, 2025). Instead, they are carrier-based preparations which contain living or dormant cells of efficient microbial strains that colonize the rhizosphere or invade plant tissues. These microorganisms can be described as the living factories that convert the unavailable nutrients, which are not easily taken up by plants, into forms that are easily absorbed by plants (Arora and Mishra, 2024; Santos *et al.*, , 2024).

Table 6: Comparison of Precision Tools in Nutrient Management

Tool / Innovation	**Application Focus**	**Goal**	**Primary Benefit**
Soil Health Card	Basal application	Correction of deficits	25-50% less synthetic use
Leaf Color Chart	Real-time N top-dress	Nitrogen efficiency	Prevents over-fertilization
IoT Soil Sensors	Continuous monitoring	Precision irrigation/NPK	Dynamic stress response
Variable Rate Tech	Site-specific needs	Spatial uniformity	Optimized input costs
Remote Sensing	Field-scale mapping	Biomass estimation	Large-scale management
Deep Placement	Fertilizer placement	Reduced NH_3 loss	Increased recovery rate
Foliar Nano-Sprays	Stomatal delivery	Rapid metabolic fix	Hyper-efficiency
ZBNF Principles	Natural recycling	Zero synthetic cost	Ecological restoration

5.1 Nitrogen-Fixing Bacteria: Tapping the Reservoir of the Air.

The most limiting nutrient in agriculture, nitrogen, is 78 percent of the atmosphere. This can be filled in by bio-fertilizers through the process of biological nitrogen fixation (Koushal *et al.*, 2025).

Rhizobium: adapted to leguminous crops, Rhizobium forms symbiotic root nodules and transforms the N 2 in the atmosphere to ammonia using the nitrogenase enzyme. This has the potential to provide 50100 kg N/ha and can be sufficient to meet the total nitrogen requirement of the crop (Shahzad *et al.*, 2025).

Azotobacter: It is adapted to non-legumes such as wheat, maize, and mustard and fixes nitrogen on its own in the soil. It is also a source of growth promoters like thiamine and riboflavin, which promote seed germination.

Azospirillum: It is a symbiotic microorganism that associates with cereal and millet roots, fixes nitrogen and increases the root surface area to enhance water and nutrient intake.

5.2 Phosphate-Solubilizing Bacteria: Release of Bound Phosphorus.

Phosphorus often represents a "bottleneck" in soil fertility; even after applying phosphatic fertilizers, up to 80% becomes fixed in insoluble complexes with aluminum, iron, or calcium. Phosphate-solubilizing bacteria, including Bacillus polymyxa and Pseudomonas striata respond to this by secreting organic acids that reduce local pH and chelate binding cations, releasing "locked up" phosphorus into the soil solution to be taken up by plants. PSB usage has the ability to cut down on the 20-25 percent of phosphatic fertilizer requirements.

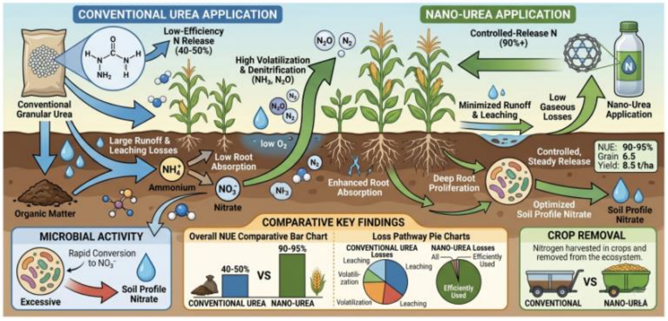

Figure 3: Comparative Analysis of Nutrient Use Efficiency (NUE) between Conventional Urea and Nano-Urea Applications

5.3 Mechanisms of Enhancing Nutrient Availability

In addition to the conversion of nutrients, these bio-inoculants use advanced processes:

●**Siderophore Production:** They produce siderophores-iron-binding compounds which supply iron to plants and deny soil pathogens, a natural biocontrol.

●**Hormonal Stimulation:** They produce phytohormones such as indole acetic acid, gibberellins and cytokinins that stimulate the growth of root hair and increase soil-root contact.

●**Soil Aggregation:** Extracellular polysaccharides are a biological glue, creating stable micro-aggregates that increase the rhizosphere to be able to diffuse nutrients.

5.4 Integration in the INM Framework

Bio-fertilizers provide a cost-efficient, environmentally friendly supplement, preferably given through seed treatment or seedling root dips, in a properly controlled INM system. They maintain the populations of microbes which increases the efficiency of chemical fertilizers, reduces the environmental loss of nutrients and keeps the soil in its living condition.

Table 7: Environmental Footprint: Conventional vs. INM

Indicator	Conventional Impact	INM Impact	Mitigation Factor
Nitrous Oxide (N_2O)	High (Emission pulse)	Low (30–45% reduction)	Synchronized release
Nitrate Leaching	High (Groundwater risk)	Minimal	Organic-mineral buffering
Carbon Footprint	High (Energy intensive)	Low (Offset by C-seq)	Organic recycling
Eutrophication	Severe (Runoff/P)	Controlled	High aggregate stability
Soil Micro-fauna	Declining	Flourishing	C-rich energy source
Heavy Metal Risk	Potential (P-sources)	Diluted	Phyto-remediation crops
Soil Acidification	High (H^+ release)	Buffered	Increased CEC
Ecosystem Services	Degraded	Restored	Holistic biological health

6. Impact of INM on Soil Organic Carbon (SOC) Sequestration

Integrated Nutrient Management of organic and inorganic inputs has a tremendous impact in increasing the soil organic carbon sequestration, to restore lost carbon stocks by incorporating more biomass, stabilizing humus, and decreasing mineralization frequencies. This dual-action plan not only helps curb climate change, by sequestering atmospheric CO 2 into stable soil fractions at rates that are faster than those of sole chemical fertilization but also rejuvenates soil microbial communities and enzyme functions, which are crucial in nutrient cycling and long-term agroecosystem stability.

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Heavy Metal Risk	Potential (P-sources)	Diluted	Phyto-remediation crops
Soil Acidification	High (H^+ release)	Buffered	Increased CEC
Ecosystem Services	Degraded	Restored	Holistic biological health

7. INM Effects on Nutrient Use Efficiency (synergistic effects).

Integrated Nutrient Management is a powerful approach to increasing nutrient use efficiency, with synergistic effects that combine organic manures, bio-fertilizers, and inorganic fertilizers, resulting in much higher NUE compared to single chemical treatments (Yimer *et al.*, 2025; Zahoor *et al.*, 2025).

7.1 Mechanisms of Nutrient Loss Reduction

INM reduces losses through various inter-linked channels:

Nutrient Supply and Demand: Organic manures and bio-fertilizers have slow-release nutrient that is synchronized to crop uptakes, so the nutrient is not accumulated when the demand is low. This decreases by 30-50 per cent the volatilization of NH3 in urea (up to 50 per cent loss in conventional systems) and by 20-50 per cent the loss in denitrification (N_2O, N_2) owing to the encouragement of aerobic solutions by enhancing soil structure (Paramesh *et al.*, 2023).

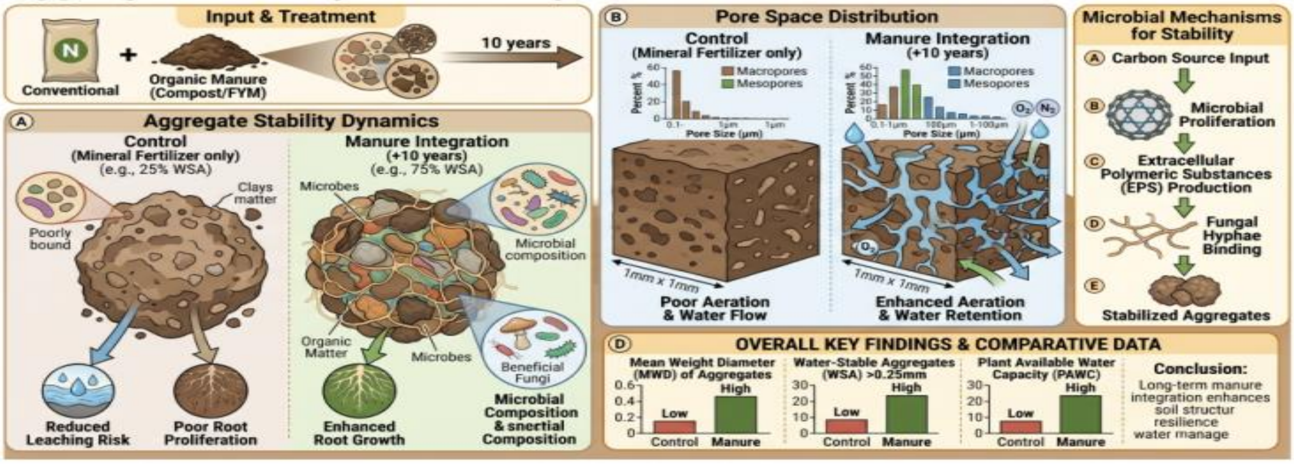
Increased Microbial Activity: Phosphate-solubilizing microbes and nitrogen-fixers expand the nutrient range in the rhizosphere, reducing fixation and leaching. Research indicates 2540% phosphorus runoff and nitrogen leaching reductions under INM (Khan *et al.*, , 2023; Samanta and Sengupta, 2024)

Enhances of Soil Structure: Organic amendments enhance aggregation, which reduces 2035% of nutrients lost due to erosion and increases water retention to curb percolate (Zahoor *et al.*, 2025).

These savings not only increase NUE to 6080% but also decrease GHG emissions by 1525, promoting climate-smart agriculture (Khan *et al.*, , 2023; Yimer and Tarnawa, 2025).

INM maintains soil organic carbon, microbial biomass, and enzymatic activities, which prevents climate variability resilience (Paramesh *et al.*, , 2023; Zahoor *et al.*, 2025). The holistic approach (Paramesh *et al.*, 2023; Zahoor *et al.*, 2025) can be used to achieve the sustainable development goals and minimise fertilizer use by 20-25 per cent, increasing profits (Samanta and Sengupta, 2024). Moreover, the effective deployment of this framework will require a strategic change towards precision agriculture, where frequent soil testing and balanced fertilization instructions will be strictly followed to meet the site-specific nutrient demands (Samanta & Sengupta, 2024)

Figure 4: Impact of Long-term Organic Manure Integration on Soil Aggre'gate Stability and Pore Space Distribution



8. Enhancing Crop Quality and Biofortification

In addition to yield, this heading will discuss how INM enhances the nutritional quality of produce, namely, protein levels and micronutrient density (Zinc, Iron, and Boron). This is largely due to the increased metabolic routes and translocation of nutrients facilitated by bio-inoculants that catalyze the production of high-value proteins and essential minerals in edible plant tissues (Yadav and Yadav, 2024). Moreover, this balanced strategy guarantees the steady absorption of the necessary components by dealing with the latent nutrient shortages, which tend to restrain crop metabolic potential, hence enhancing the nutritional value of the crop in the long term (Kumar & Chaudhary, 2018). This specific improvement of produce quality can be effective in the case of the problem of hidden hunger in agrarian societies because the optimization of nutrient management pathways leads to the systematic retention of the necessary vitamins and minerals in the edible plant biomass (Hasanain *et al.*, , 2025), (Yimer and Tarnawa, 2025). Moreover, this approach will help to reduce the dependency on chemical fertilizers, since optimized nutrient cycling will reduce the environmental degradation caused by intensive synthetic inputs (Paramesh *et al.*, , 2023; Samanta and Sengupta, 2024).

9. Nano-Fertilizers integration into INM Frameworks.

Nano-fertilizers can be seen as a paradigm shift in Integrated Nutrient Management, which provides specific and targeted nutrition using nanotechnology and reducing the environmental impact of traditional fertilizers. Their encapsulation of nutrients (1-100 nm) in nano-sized particles increases nutrient solubility, controlled release, foliar uptake and bioavailability, and the nutrient use efficiencies of these formulations can be up to 80 percent compared

9.1 Nano-Urea: The Game Changer of Nitrogen.

Nano-Urea: A 4% w/v suspension of nitrogen in nano-droplets stabilized with a polymer matrix allows a hectare-dose of 20-40 kg N/ha by spraying foliar nano-Urea that is 50% less than granular urea requirements (Book Overview, 2024). This reduces the loss of NH 3 (cut down by 90 percent) and N_2O, which are important in curbing climate (Yimer and Tarnawa, 2025).

These experiments, across various agro-climatic regions, claim an average yield increase of 8-12 percent with reduced N application, and 20-30 percent of less global warming potential (Paramesh *et al.*, , 2023; Yimer and Tarnawa, 2025).

9.2 Nano-DAP: Accurate Phosphorus Supply.

Nano-Diammonium Phosphate is a solution to P-fixation problems because it offers nano-crystals that chelate the cations in the soil and increases the available P by 25-40 percent. Used as foliar/soil amendments (2-4 kg/ha equivalent), it reduces superphosphate use by 40-50, promoting root growth and energy metabolism in crops (Book Overview, 2024).

In soybean: 15% yield gain, 30% P savings (“Book Overview,” 2024).
Groundnut: 12 percent higher pods, less fixation losses (Khan *et al.,* 2023).
Potato: Enhanced tuber size by 18%, PUE to 35% (Zahoor *et al.*, 2025).

The enhancement of its effects with phosphate-solubilizing bacteria is consistent with the biological engine developed by INM (Samanta and Sengupta, 2024).

9.3 Fighting Hidden Hunger.

Nano-Zn (nano-zinc oxide/sulphate 150-500 kg/ha foliar) corrects the shortages of Zn in 50% of Indian soils to enhance enzyme activity, photosynthesis and biofortification. Research indicates that there are increases in yield of 10–25 percent in cereals/legumes and 50–75 percent reduced doses of Zn compared to conventional (Book Overview, 2024).

The main results of field assessments:
Rice: 14% yield, 20% grain Zn content (Khan *et al.*, , 2023).
Chickpea: 16% pods, drought resistance (Yimer & Tarnawa, 2025).
Maize: 22% biomass, alleviated deficiency symptoms (Zahoor *et al.*, , 2025).

9.4 Synergies and Challenges in INM

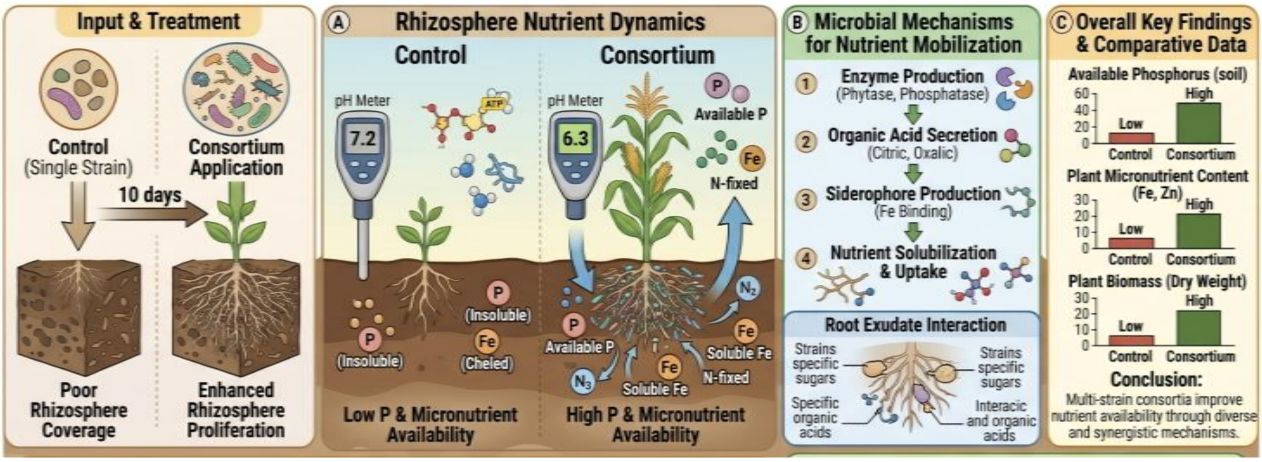
Nano-fertilizers enhance INM through a sustained release and microbial priming process by matching organic inputs, which requires scaling, increased cost (2030 higher) and regulation (Blesh *et al.*, , 2022). Long-term studies of over 20 affirm 15-25% overall N/P/Zn savings, 10-20% increase in yield, and preservation of soil health (Book Overview, 2024; Yimer and Tarnawa, 2025).

10. Socio-Economic Benefits and Farmer Adoption Hurdles

Integrated Nutrient Management brings about significant socio-economic benefits to the smallholder farmers especially in terms of better cost-benefit ratio. In the long-term, the adoption of INM can increase crop yield and profitability in resource-constrained agriculture systems, i.e. by providing balanced nutrient supply, reducing fertilizer cost by 20-25% and raising yields by 10-20 percent relative to traditional methods (Yimer and Tarnawa, 2025; Zahoor *et al.*, , 2025) e.g., These advantages are consistent with the overarching sustainability objectives, such as improved food security and compatibility with UN SDGs (“Contents, 2024).

Nevertheless, barriers to adoption still remain, such as the time-consuming process of applying organic manure and the lack of technical knowledge of smallholders. A shift to INM would necessitate participatory research on-farm to make sure that the numerous socioeconomic factors affecting the adoption of farmers are considered, including availability of quality bio-inputs and education (Blesh *et al.*, , 2022). These barriers need to be overcome by increasing extension services, subsidies on the production of bio-inputs, and awareness campaigns to scale up INM (Khan *et al.*, , 2023).

Figure 5: The Role of Bio-fertilizer Consortia in Rhizosphere Nutrient Mobilization and Solubilization



Finally, it is also important to institutionalize them by shifting the policy frameworks towards long-term food security and ecological sustainability in the form of an innovative scaling up based on the nutrients in the soil (Harnessing Dividends from Drylands: Innovative Scaling up with Soil Nutrients, 2016). The need of the moment in future research should focus on the establishment of uniform, localized management guidelines to maximize the synergistic effects of organic, inorganic and biological inputs (Samanta & Sengupta, 2024).

11. Precision Tools and Site-Specific Nutrient Management (SSNM).

Understanding how Soil Health Cards and IoT-based sensors could be used to fine-tune INM recommendations to fit various agro-climatic regions. Through these data-driven solutions, farmers will be able to optimize the timing and placement of nutrient application to find a more optimal balance that will reduce the environmental footprint and guarantee food security in the long run, (Kushwah *et al.,* , 2023). Moreover, this localized calibration can reduce the nutrient inflow-outflow disparity, so the fertilization rates can be accurately reflective of the spatial heterogeneity of native soil fertility (Paramesh *et al.,* , 2023).

This high-resolution method is able not only to maximize resource productivity but also to be combined with new nanotechnology-enabled delivery systems, which enable precise nutrient release to minimise leaching and improve the overall uptake efficiency (Book Overview, 2024). This combination of the accuracy of sensing and nano-scale delivery systems leads to maximum resource utilization, which contributes to the growth of agricultural output and systemic resilience to the environment (Zahoor *et al.,* , 2025). These sophisticated systems cannot be implemented successfully without the solid policy development and regulatory assistance to scale-up adoption to eventually attain global sustainability goals and targets such as the UN SDGs in agricultural practices (“Contents, 2024).

12. Future Research Directions and Policy Implications.

A prospective research direction including the necessity of the field experimentation in the long-term and government subsidies to encourage bio-input production. The regulatory framework to control the quality of bio-input needs to be strengthened to promote producer confidence and guarantee the long-term effectiveness of such integrated systems (Samanta & Sengupta, 2024). Finally, the shift to a more resilient agricultural paradigm requires a partnership between policymakers, agricultural extension agencies, and researchers to intensify these practices of integration in different agro-ecological environments (Khan *et al.,* , 2023; Paramesh *et al.,* , 2023).

The key to the successful implementation of these frameworks at scale is the success of ensuring long-term agricultural productivity and ensuring an effective reduction of the environmental externalities of conventional intensive farming (Paramesh *et al.,* , 2023; Yimer and Tarnawa, 2025). The next stage of the development of this paradigm is interdisciplinary, cross-scale research that would embrace the myriad socioeconomic and biophysical factors that contributed to farmer transitions to ecological nutrient management (Blesh *et al.,* , 2022).

13. Conclusion

Conclusively, the best and soundest approach to attaining sustainable intensification of agriculture is through Integrated Nutrient Management. Combining organic manures, bio-fertilizers, and prudent chemical inputs in a synergetic manner, INM does not only maintain high yields in crops, by 1020 percent higher than when used alone with chemical fertilizers, but also recovers soil organic carbon pools, increases the efficiency of nutrient use through synchronized release, and reduces environmental losses such as leaching and volatilization. Moreover, the combination of innovative solutions, including nano-fertilizers, precision sensors, and site-specific management, tackles the current issues, enhancing the quality of crops, bio-enhancing them, and increasing their resistance to variations in climate conditions. Smallholder adoption challenges notwithstanding, the socio-economic advantages, such as cost savings and less dependency on inputs, are overwhelming, which underlies the transformative nature of INM. To achieve food security and steward planetary health, policymakers and farmers should focus on long-term field tests, bio-input subsidies and awareness to take INM to scale globally.

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Kheti Vigyan e Magzine

Article ID: KVM0006/26 **Popular Article**

Biochar: Enhancing Soil Health and Climate Resilience

[1]M.Z. Siddqui and [2]Naushad Khan

[1&2]Professor, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology Kanpur

***Corresponding Author**

M.Z. Siddqui

✉ : *zafarallahabadi@gmail.com*

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Abstract:- Biochar is a complex phenomenon on which sustainable agricultural practices and mitigation of climate change are built. Biochar is an ideal solution in converting the wastes in agriculture to a high quality amendment to soil with the twin threats which are soil degradation and growth of atmospheric CO_2.

The discussion elaborates on how biochar is porous and therefore can be used to enhance the soil fertility by enhancing cation exchange capacity (CEC) and reducing nutrient leaching which directly correlates to high yields of crops, particularly in the tropics with acidic or depleted soils. Other than agronomic properties, we also discuss how biochar can be used in carbon sequestration; the sequestration of carbon into a solid material centuries old in effect locks CO_2 out of the biological cycle. The researchers conclude that biochar is not a silver bullet, but that a combination of biochar in regenerative agricultural practices presents a multi-benefit, scalable process to both long-term food security and environmental stewardship.

Keywords:- *Biochar, Carbon Sequestration, Soil Fertility, Pyrolysis, Sustainable Agriculture, Climate Change Mitigation, Nutrient Cycling, Regenerative Farming.*

Introduction:-

The pursuit of sustainable agricultural systems is more than ever before in an era where climate change is escalating and the world is increasingly straining its food systems (Saldarriaga & Lopez, 2025). Nearly 33% of global soils are affected by soil degradation, resulting in a decrease in productivity, loss of biodiversity, and increased susceptibility to extreme weather conditions (Timilsina *et al.*, 2025). At the same time, the levels of carbon dioxide (CO_2) in the atmosphere have exceeded 420 ppm, pushing the global temperatures to the limits of disastrous levels (Wydra *et al.*, 2023). It is on this background that the idea of biochar as a solution with transformative potential emerges, as a constant, carbon-rich substance generated during the pyrolysis of biomass that can be a pathway between the restoration of soil health and climate mitigation (Shyam *et al.*, 2025). This model employs the pyrolysis technique to convert the biomass waste to a robust carbon sink, which also helps mitigate the dire demands of regenerative soil management and drawdown of carbon in the atmosphere (Kefalew *et al.*, 2025; Shyam *et al.*, 2025).

The production of biochar involves heating organic substances, e.g., agricultural residues, wood chips, or manure, in the low-oxygen atmosphere at temperatures of approximately 35070 ^{0}C (Saldarriaga & Lopez, 2025). The result of this thermochemical process is a porous recalcitrant char that exhibits high physicochemical characteristics: high surface area (up to 1000 m 2 /g), high alkalinity, and cation exchange capacity of over 50 cmol/kg in certain feedstocks (Souza *et al.*, 2025). These properties allow biochar to mitigate several constraints in soils at a time (Varkolu *et al.*, 2025). Biochar helps to improve nutrient retention in nutrient-poor tropical soils, which are common in regions such as sub-Saharan Africa and southeast Asia, by adsorbing nitrogen (ammonium), phosphate, and micronutrients, and reducing losses due to leaching by 2050 percent (Rizwan *et al.*, 2023). This leads to better crop production; meta-analyses show that on average maize, rice and wheat produce 13-20 percent higher under biochar amendment. Moreover, the amendment helps to reduce the dependence on synthetic fertilizers by maximizing nutrient uptake and reducing the leaching of nitrogen, which consequently reduces the level of greenhouse gas emissions (Ali *et al.*, 2025; Bo *et al.*, 2023).

In addition to agronomy, biochar as a form of negative emissions technology is due to its carbon sequestration capacity. The aromatic structure of biochar is not degradable by microbes, unlike labile organic amendments, and half-lives of biochar range over centuries to millennia. The scale of CO_2^- eq/ha/year (0.1-0.5 t) that can be sequestered using 1-5 t/ha can offset 12% of the global agricultural greenhouse gas emissions when used at scale(Weng and Cowie, 2025). Furthermore, it also reinforces synergies when implemented in regenerative farming, including through conservation agriculture and agroforestry, which helps to improve nutrient cycling and disease resistance (Vejendla *et al.*, 2025; Yogender, 2026). Moreover, biochar can be a highly effective immobilized medium to remove heavy metals and organic pollutants and, therefore, recover polluted waters and soils (Kannan *et al.*, 2024).

Table 1. Physical Properties of Biochar by Feedstock Type

Feedstock Source	Surface Area (m^2/g)	Porosity (%)	Average Pore Size (nm)
Rice Husk	150	45	12
Wheat Straw	210	50	15
Poultry Litter	45	30	25
Hardwood (Oak)	380	65	8
Softwood (Pine)	320	60	10
Coconut Shell	450	70	5
Corn Stover	180	48	18
Sewage Sludge	35	25	30

2. The Science of Pyrolysis: One of the advantages of the pyrolysis process is that it can convert many biomass feedstocks, such as agricultural wastes and wood chips to biochar, a carbon-rich and high-stability compound that is created to be robust and useful. Pyrolysis, which occurs in low oxygen (35070 ^{0}C) depolymerizes lignocellulosic structures to recalcitrant aromatic polycyclic structures, slowing down the mineralization speed and ensuring carbon retention in soils over centuries to millennia. It is not an accidental byproduct of heat; it offers a good source of 30%-60% of feedstock carbon in a form which is both lowly biodegradable, far more so than the labile amendments like compost and it does provide a scientifically proven form of carbon sequestration in addition to the biochar preparation with an improved interaction between employed soil which occurs in the following subsections. The functional properties of the material, the developed surface area and the arrangement of functional groups determined are the most important factors that determine the individual ability of the material in stabilizing the pH of the soil and in engaging into complex ion-exchange reactions (Roy *et al.*, 2025). Internal structural properties are also used to control the potential development of the pore size distribution and bulk density of the soil to construct a robust physical environment that allows useful soil biota to colonize (Vijay *et al.*, 2021).

3. Physicochemical Properties:

Hierarchical porosity, large surface area and high cation exchange capacity are physicochemical characteristics that make biochar a strong scientific basis of the agronomic superiority. The pyrolysis engineering produces a multiscale pore structure (micro-, meso-, and macropores) with volumes of up to 1.0 cm 3 /g and Brunauer-Emmett-Teller surface areas in the 300-1000 m 2/g range that is orders of magnitude larger than untreated soils or composts (<10 m 2/g). It is the huge surface between the soils, which causes multiple functional benefits: better water retention (volumetric capacity improves 15 to 30 percent), multimicrobial colonization (up to 10-fold growth of beneficial rhizobacteria), anion/cation adsorption, and bypassing leaching of nutrients by 20 to 60 percent in sandy or acidic soils The presence of oxygen-containing functional groups and mineral forms leads to values of CEC (usually 50-150 cmol/kg) approaching those of nutrient-rich soils (e.g. 5-40 cmol/kg), which enable a strong attachment of NH 4 +, PO 4 -, and K + and heavy metals- directly proportional to higher crop yields in meta-analyses of. Moreover, the specified physicochemical properties enable the controlled delivery of the required nutrients, thus ensuring the timely match of the nutrient supply with the demand of crops and reducing the reliance on intensive synthetic fertilization (Farooqi *et al.*, 2018; Shyam *et al.*, 2025).

4. Soil Fertility Restoration:

The biochar is a restorative catalyst that can increase cation exchange capacity, which greatly exceeds 50-150 cmol/kg due to the oxygen-rich functional groups and mineral phases (Rahim *et al.*, 2023) and improves the bioavailability and retention of crucial macro-nutrients, including phosphorus (via ligand exchange and precipitation) and potassium, thereby enhancing Field experiments verify that these effects would translate to 20-60% decreases in leaching losses, 13-25% increases in crop yields and 20-30% decreases in fertilizer needs in nutrient-depleted tropical soils. Moreover, biochar can also improve the chemical environment of nutrient uptake by neutralizing soil acidity and enhancing electrical conductivity that, in many cases, limits root development in highly weathered soils (Kannan *et al.*, 2024).

Table 2. Chemical Composition and Nutrient Content

Biochar Type	pH Value	Carbon Content (%)	Nitrogen (%)
Dairy Manure	9.2	42	2.10
Bamboo	8.5	82	0.45
Corn Cob	7.8	70	0.80
Switchgrass	7.4	75	0.65
Green Waste	8.1	55	1.20
Nut Shells	8.9	78	0.35
Bagasse	7.2	68	0.50
Bone Meal	10.5	25	4.50

Nutrient Retention and Bioavailability: The remarkable nutrient retention of biochar is based on its outstanding physicochemical characteristics, especially the cation exchange capacity of over 50-150 cmol/kg that is attributed to oxygen functional groups and natural mineral phases. This ability enables intense adsorption of important nutrients- NH_4^+, K^+, Ca_2^+, Mg_2 +, and micronutrients - through electrostatic binding and van der Waals forces, and phosphate (PO_4^-) immobilization through ligand exchange, surface precipitation (e.g., Ca-P complexes) and increased uptake by microbes. Biochar amendments reduce the losses by 20-60 percent in the acidic, sandy tropical soils subject to 50-80% nutrient leaching during rainfall, according to a plethora of field studies and meta-analyses, which guarantees the long-term nutrient bioavailability and prevents excessive runoff to the environment.

Table 3. Impact of Pyrolysis Temperature on Biochar Stability

Temperature (°C)	Biochar Yield (%)	Fixed Carbon (%)	H/C Molar Ratio
300	65	35	0.85
400	45	52	0.60
500	35	68	0.45
600	28	75	0.30
700	22	82	0.20
800	18	88	0.12
900	15	92	0.08
1000	12	95	0.05

5. Microbial:-

It is optimally engineered with pyrolysis to increase its hierarchical porosity, high surface area (3001000 m 2/g), and pore size distribution. All these traits create a potent physical shelter to advantageous soil microorganisms and favor microbial colonization and activity compared to untreated soils or unstable amendments (Roy *et al.*, 2025; Vijay *et al.*, 2021). These physicochemical properties as well lower bulk density and enhance water-holding capacity. Consequently, biochar develops safe habitats that protect microbes against drying up and predation. Besides that, its oxygenated functional groups and elevated pH support various bacterial and fungal communities which are necessary in the process of nutrient cycling (Kannan *et al.*, 2024; Rahim *et al.*, 2023). Field experiments also demonstrate that biochar enhances the biomass and biomolecular activity of microbes. This is beneficial in making the soil healthier and nutrient-rich. It is also involved in crop yield improvements of 1325% with synergistic interactions between plants and microbes, which in most instances outcompete traditional methods (Roy *et al.*, 2025; Vijay *et al.*, 2021)..

6. Water Security:

Biochar has a great contribution to water security in arid and semi-arid soils. Hierarchical porosity, high surface area (typically 300 1000 m 2/g) and maximized pore size distribution increase water-holding capacity. These properties form multiscale reservoirs that store moisture and minimize the losses of evaporation and drainage (Roy *et al.*, 2025; Vijay *et al.*, 2021). On untreated soils (like sandy tropical soils and weathered Ferralsols) in water-scarce soils, 50 to 80 percent of rainfall can be lost through percolation. Biochar amendments can address this issue, enhancing the water-holding capacity by 15-30, as demonstrated in field tests and meta-analyses. They also save 20 40 per cent of irrigation requirements and do not lose crop productivity during the droughts (Rahim *et al.*, 2023; Vijay *et al.*, 2021). The outcomes of pyrolysis engineering are these physicochemical advantages that decrease bulk density and enhance plant-available water. This helps in more robust and resilient root systems. Biochar can also boost yields in rainfed systems (1325) and usually outcompetes traditional amendments like compost due to its long-lasting, multi-seasonal retention of water (Kannan *et al.*, 2024; Roy *et al.*, 2025).

Table 4. Soil Fertility Indices Post-Biochar Application

Soil Parameter	Before Biochar	After Biochar	Improvement (%)
Cation Exchange (CEC)	12.5 cmol/kg	18.2 cmol/kg	45.6%
Water Retention	15%	22%	46.7%
Organic Matter	1.2%	2.5%	108.3%
Available P	15 mg/kg	22 mg/kg	46.7%
Exchangeable K	120 mg/kg	185 mg/kg	54.2%
Microbial Biomass	210 mg/kg	350 mg/kg	66.7%
Aggregate Stability	35%	55%	57.1%
Bulk Density	1.45 g/cm^3	1.25 g/cm^3	-13.8%

7. Yield Optimization:

Biochar provides reliable nutrient retention, water retention, and microbial activity across a wide range of climatic zones, such as the nutrient-poor tropical Ferralsols and acidic temperate soils, due to its development of synergistic physicochemical impacts on nutrient retention, water retention, and microbial activity, which are confirmed by large-scale field trials and meta-analyses(Vij Amendments in the tropical and weathered soils with constrained baseline yields due to leaching and toxicity increase resiliently by 1325% during droughts, with up to 20% improvements in acidic and nutrient-deficient environments via enhanced CEC(50150 Although net positive results have been confirmed in meta-analyses, despite variability caused by feedstock, soil type, and climate, which are acknowledged in conflicting reports, net positive results bring a reduction in fertilizer requirements by 2030-30% and scalable adoption in regenerative agriculture(Werner *et al.*, 2022,Das & Pandey, 2025; Vijay *et al.*, 2021).

8. Carbon Sequestration:

This technology is a highly powerful negative emissions technology, which can sequester 0.7 to 1.8 gigatons of atmospheric CO_2^- each year by converting labile biomass into highly stable recalcitrant aromatic carbon (Hoque *et al.*, 2025). Biochar is also able to prevent the release of strong greenhouse gases such as methane and nitrous oxide by diverting organic waste off of pathways that cause rapid aerobic/anaerobic decomposition, resulting in emission reductions of 19.8%-28.2 in different agricultural systems (Murtaza *et al.*, 2023; Niazi *et al.*, 2023).

Table 5. Global Crop Yield Response to Biochar

Crop Type	Control Yield (t/ha)	Biochar Yield (t/ha)	Variance (%)
Maize	6.5	7.8	+20%
Rice	4.2	5.1	+21%
Wheat	3.8	4.3	+13%
Soybean	2.9	3.4	+17%
Potato	22.0	28.5	+29%
Tomato	45.0	58.0	+28%
Cotton	1.8	2.1	+16%
Barley	3.2	3.7	+15%

This permanence guarantees that the carbon which has been locked in the soil matrix is centennial or millennial-insensitive, and thus is a true mechanism of drawing carbon out of the atmosphere (Werner *et al.*, 2022). What is more, by incorporating biochar production systems into energy infrastructures, further climate advantages can be achieved as combustible co-products, i.e. syngas and bio-oil, can be capturing and thus allow replacing fossil fuels (Arrouays *et al.*, 2017).

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9. Remediation Potential:

Biochar has great opportunities of cleaning up polluted soils. It is effective in immobilizing heavy metals and organic pollutants because of its hierarchical porosity, high surface area, functional groups that are characterised by oxygen and high ion exchange capacity. Pyrolysis engineering is an additional means of optimizing these properties (Rahim *et al.*, 2023; Roy *et al.*, 2025). Such physicochemical properties facilitate the process of adsorption, complexation and precipitation. Consequently, biochar decreases bioavailability of heavy metals and constrained uptake of heavy metals by plants. It reduces the mobility of organic contaminants (pesticides, polycyclic aromatic hydrocarbons (PAHs), etc.) as well because it is confirmed by field trials and meta-analyses (Kannan *et al.*, 2024; Vijay *et al.*, 2021). In acidic tropical Ferralsols, which are degraded and possibly highly polluted by industries, biochar amendments may alleviate heavy metal toxicity by 30 or 70 percent.

10. Economic Viability:

Biochar will have promising abilities in remediation of soils that are polluted. It is highly effective in immobilizing the heavy metals and organic pollutants, because it has a hierarchical porosity, high surface area, oxygen function groups and has a large ion exchange capacity. These qualities are also optimized with the help of the pyrolysis engineering (Rahim *et al.*, 2023; Roy *et al.*, 2025).

Table 6. Carbon Sequestration Potential by Region

Region	Biomass Potential	Carbon Offset (Mt/yr)	Cost (ton CO_2)
Southeast Asia	High	450	45
Sub-Saharan Africa	Medium	320	35
North America	High	600	65
European Union	Medium	280	80
Latin America	Very High	550	40
China	Very High	700	55
India	High	480	38
Australia	Low	110	70

Such physicochemical properties favor the operations of adsorption, complexation and precipitation. Consequently, biochar decreases the bioavailability of the heavy metals and decreases their absorption by the plants. It also reduces the solubility of organic pollutants like pesticides and polycyclic aromatic hydrocarbons (PAHs) as evidenced in field experiments and meta-analysis (Kannan *et al.*, 2024; Vijay *et al.*, 2021)..

11. Policy and Scalability:

The key to achieving the next level of biochar implementation and turning it into a staple of regenerative agriculture and climate protection is strong policy frameworks and incentives (Das & Pandey, 2025; Rahim *et al.*, 2023). Carbon market entry would enable producers to sell sequestration credits to offset the costs of pyrolysis infrastructure and to provide viable revenue streams based on energy co-products such as syngas and bio-oil produced by decentralized systems that reduce transportation logistics, and subsidies and regulatory approvals would ensure consistent agronomic benefits across a wide range of agroecosystems (Okoro *et al.*, 2024). This can support the UN Sustainable Development Goals through improving soil productivity, decreasing input requirements, and facilitating negative emissions land-neutral at gigaton scales, which makes biochar a climate-sensitive strategy of sustainable land management(Arrouays *et al.*, 2017; Werner *et al.*, 2024).

Table 7. Heavy Metal Remediation in Contaminated Soils

Contaminant	Initial Conc. (mg/kg)	Final Conc. (mg/kg)	Immobilization (%)
Lead (Pb)	500	120	76%
Cadmium (Cd)	15	3	80%
Arsenic (As)	45	18	60%
Mercury (Hg)	10	2.5	75%
Chromium (Cr)	200	85	57.5%
Copper (Cu)	150	40	73.3%
Zinc (Zn)	300	110	63.3%
Nickel (Ni)	80	35	56.2%

12. **Conclusion**:- Effective biochar technology scaling would require an integrated approach to control variable feedstock and performance variability, sound policy incentives (subsidies, regulatory approvals, and integration into carbon markets to get a sequestration credit) and decentralized production model with mobile pyrolysis units and recovery of energy in co-products such as syngas and bio-oil, to overcome existing logistical barriers such as high

transportation costs and economic barriers include production

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