Scholars Journal of Agriculture and Veterinary Sciences

OPEN ACCESS

Abbreviated Key Title: Sch J Agric Vet Sci
ISSN 2348–8883 (Print) | ISSN 2348–1854 (Online)
Journal homepage: https://saspublishers.com

Enhancing Soil Nutrient Efficiency for Sustainable Agriculture

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DOI: https://doi.org/10.36347/sjavs.2025.v12i07.001 | **Received:** 12.05.2025 | **Accepted:** 15.07.2025 | **Published:** 18.07.2025

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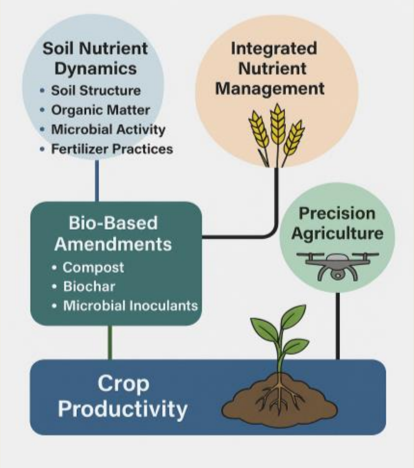
Abstract **Review Article**



The growing demand for agricultural productivity, coupled with the urgent need for environmental conservation, underscores the importance of enhancing soil nutrient efficiency as a cornerstone of sustainable agriculture. This review explores current advancements, strategies, and innovations aimed at improving nutrient use efficiency (NUE) to promote crop productivity while minimizing ecological impacts. Key factors affecting soil nutrient dynamics—including soil structure, organic matter content, microbial activity, and fertilizer practices—are discussed in detail. The role of integrated nutrient management (INM), precision agriculture technologies, and bio-based amendments such as compost, biochar, and microbial inoculants is critically examined. Special attention is given to site-specific nutrient management approaches and the development of slow- and controlled-release fertilizers that align with plant uptake patterns, thereby reducing nutrient losses through leaching and volatilization. The review also highlights recent biotechnological interventions, including the use of plant-growth-promoting rhizobacteria (PGPR) and genetically improved crop varieties with enhanced nutrient uptake and utilization capacities. Furthermore, the article addresses challenges such as soil degradation, climate variability, and socio-economic barriers that influence the implementation of nutrient-efficient practices. By synthesizing recent research and practical insights, this review advocates for holistic and adaptive nutrient management strategies that support long-term agricultural sustainability, improve resource use efficiency, and ensure food security in the face of global environmental and population pressures.

Keywords: Soil nutrient efficiency, Sustainable agriculture, Soil fertility management, Nutrient use efficiency, Soil health.

Citation: Iqra Zahoor, Farzana, Mubashar Hussain Ch, Muqaddas Shafeeq, Abu Bakar Afzal, Syed Muhammad Salman Haider, Esha Arshad, Maria Zafar, Sharjeel Ahmad. Enhancing Soil Nutrient Efficiency for Sustainable Agriculture. Sch J Agric Vet Sci, 2025 Jul 12(7): 232-241.

INTRODUCTION

The 21st century presents an unprecedented challenge to global agriculture, how to sustainably meet the food requirements of a growing population while preserving environmental integrity. With the world population projected to surpass 9 billion by 2050, global food demand is expected to rise significantly, necessitating a 60–70% increase in food production (Aryal *et al.,* 2022). This demand surge exerts tremendous pressure on agricultural systems to deliver higher yields from diminishing arable land, under increasingly variable climatic conditions. In this context, the importance of sustainable intensification—producing more with fewer inputs—has become a central focus in agricultural research and policy (Shrestha *et al.,* 2021). At the heart of this challenge lies the crucial issue of nutrient use, which directly impacts crop productivity, resource efficiency, and ecological sustainability (Dixit *et al.,* 2024). Nutrient inputs, particularly nitrogen (N), phosphorus (P), and potassium (K), are vital for plant growth and have historically played a key role in boosting agricultural productivity (Yahaya *et al.,* 2023). However, the inefficient use of these nutrients has led to a host of environmental problems, including soil degradation, water eutrophication, greenhouse gas emissions, and loss of biodiversity (Tyagi *et al.,* 2022). It is estimated that more than 50% of applied nitrogen and phosphorus fertilizers are not utilized by crops, instead leaching into ecosystems and causing long-term damage (Penuelas *et al.,* 2023). Such inefficiencies not only compromise environmental health but also represent a substantial economic loss for farmers. As awareness of these issues grows, the focus has increasingly shifted toward enhancing Nutrient Use Efficiency (NUE)—a measure of how effectively plants absorb and utilize nutrients applied to the soil (Congreves *et al.,* 2021).

Improving NUE is critical for making agriculture both more productive and more sustainable. Enhanced nutrient efficiency can lead to higher yields with lower input costs, minimize environmental pollution, and contribute to climate resilience (Govindasamy *et al.,* 2023). It also aligns closely with the principles of climate-smart agriculture and the United Nations Sustainable Development Goals (SDGs), particularly those relating to zero hunger, clean water, responsible consumption and production, and climate action. NUE is not a singular strategy but a multi-dimensional concept that encompasses agronomic practices, soil health, plant genetics, fertilizer technologies, and precision farming techniques (Siku *et al.,* 2022). As such, it serves as a nexus where science, policy, and practice converge to address both current and future agricultural challenges. Despite the clear benefits, achieving high nutrient use efficiency remains complex. Factors such as soil type, crop species, climatic conditions, and management practices all influence nutrient uptake and utilization (Waqas *et al.,* 2020). Moreover, the interaction of biological, chemical, and physical processes in soil-plant systems makes it difficult to implement one-size-fits-all solutions (Jakhro *et al.,* 2025). Nevertheless, recent advances in genomics, microbiology, digital agriculture, and nutrient delivery systems offer promising pathways for enhancing NUE across diverse agroecosystems. From slow-release fertilizers and bio-stimulants to sensor-based nutrient monitoring and data-driven decision-making tools, innovative approaches are being developed and refined to close the gap between nutrient supply and plant demand (Kunwar *et al.,* 2025).

This review aims to provide a comprehensive overview of the current state of nutrient use efficiency in sustainable agriculture. It will examine the driving forces behind the push for improved NUE, including global food demand and environmental imperatives, and explore the scientific, technological, and management strategies being employed to enhance nutrient efficiency. By synthesizing recent research and identifying knowledge gaps, the review will contribute to a deeper understanding of how nutrient efficiency can serve as a cornerstone for future agricultural sustainability.

2. Soil Nutrient Dynamics: Key Influencing Factors

2.1 Soil Structure and Organic Matter

Soil structure and organic matter are foundational determinants of nutrient dynamics, influencing both the storage and mobility of essential plant nutrients (Friedel *et al.,* 2021). Aggregates protect organic matter from rapid decomposition, thereby stabilizing nutrient pools and fostering slow-release mechanisms that synchronize with plant uptake. Organic matter, particularly humus, acts as a reservoir for macronutrients like nitrogen, phosphorus, and potassium, as well as micronutrients, by forming complexes that prevent leaching (Sekaran *et al.,* 2022). It also contributes to cation exchange capacity (CEC), which governs the soil's ability to retain positively charged nutrient ions. Furthermore, decomposition of organic residues—such as plant litter, root exudates, and composted materials—releases nutrients through mineralization, a process mediated by soil organisms (Hoffland *et al.,* 2020). Thus, the interplay between soil structure and organic matter is pivotal in maintaining long-term soil fertility and nutrient balance. Soil compaction, erosion, and depletion of organic content, often resulting from intensive land use, can disrupt this delicate equilibrium, leading to reduced nutrient availability and impaired ecosystem functioning (Bashir *et al.,* 2021).

2.2 Microbial Activity in Nutrient Cycling

Soil microbial communities are central agents in nutrient cycling, driving the transformation and mobilization of nutrients through biological processes such as nitrogen fixation, nitrification, denitrification, and phosphorus solubilization (Mahala *et al.,* 2020). Bacteria, fungi, actinomycetes, and archaea decompose organic residues, releasing nutrients in plant-available forms. Nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter) convert atmospheric nitrogen into ammonia, while nitrifying microbes oxidize ammonium to nitrate, a form accessible to plants. Similarly, mycorrhizal fungi extend the root's nutrient foraging zone and enhance phosphorus uptake by secreting enzymes that liberate bound phosphate ions (Sharma *et al.,* 2023). Microbial consortia also influence the turnover of sulfur, iron, and other micronutrients, often mediated through redox reactions and pH shifts in the rhizosphere. The composition and activity of soil microbiota are influenced by multiple factors, including temperature, moisture, pH, organic inputs, and land management practices (Philippot *et al.,* 2024). A diverse and active microbial community not only improves nutrient cycling efficiency but also enhances soil resilience against perturbations (Philippot *et al.,* 2021). Disruptions to microbial balance—due to pollution, overuse of agrochemicals, or monoculture systems—can lead to nutrient imbalances, accumulation of toxic compounds, and reduced nutrient use efficiency, highlighting the need for practices that support microbial health in agricultural soils.

2.3 Impacts of Conventional Fertilizer Practices

Conventional fertilizer practices, particularly the over-application of synthetic nitrogen and phosphorus, have profound effects on soil nutrient dynamics and broader ecological processes (Nakachew *et al.,* 2024). While these inputs initially boost crop yields by supplying readily available nutrients, their long-term use often leads to unintended consequences such as nutrient leaching, soil acidification, and microbial disruption. Excess nitrogen, in the form of nitrates, can leach into groundwater or volatilize as nitrous oxide, a potent greenhouse gas, thereby reducing nutrient use efficiency and contributing to environmental pollution (Fagodiya *et al.,* 2020). Phosphorus, though less mobile, can accumulate in soil and runoff into water bodies, causing eutrophication and biodiversity loss in aquatic ecosystems. Moreover, high concentrations of inorganic fertilizers can inhibit beneficial microbial populations involved in nutrient cycling, such as nitrogen-fixing and phosphorus-solubilizing organisms, thereby reducing the natural regenerative capacity of soils (Prasad *et al.,* 2021). The overreliance on chemical inputs often leads to nutrient imbalances, where secondary and micronutrients become limiting factors. In contrast, integrated nutrient management combining organic amendments with judicious use of inorganic fertilizers has shown promise in restoring soil health, enhancing nutrient synchronization, and reducing environmental footprints. Thus, re-evaluating conventional fertilizer strategies is crucial for achieving sustainable nutrient management and long-term agricultural productivity (Haque, S. E. (2021).

3. Innovative Approaches to Enhance Nutrient Use Efficiency

3.1 Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) is a comprehensive strategy that synergistically combines the use of organic manures, crop residues, biofertilizers, and mineral fertilizers to optimize nutrient availability and uptake while maintaining soil health (Kushwah *et al.,* 2024). This approach addresses the shortcomings of relying solely on chemical fertilizers, such as nutrient imbalances, reduced microbial diversity, and long-term soil degradation. INM enhances nutrient use efficiency by synchronizing nutrient supply with crop demand, improving nutrient retention in the root zone, and fostering beneficial microbial interactions that facilitate nutrient cycling (Bargaz *et al.,* 2018). Furthermore, it reduces environmental pollution caused by nutrient runoff and leaching. By integrating locally available organic materials with inorganic sources, INM also contributes to sustainable resource use and resilience against climate-induced stresses (Dutta *et al.,* 2024). Long-term studies have demonstrated that INM improves crop productivity and profitability, particularly in resource-limited farming systems, by ensuring a balanced and sustained nutrient supply. Therefore, INM is increasingly recognized as a key component in sustainable agricultural intensification and climate-smart agriculture initiatives (Wu *et al.,* 2015).

3.2 Precision Agriculture Technologies

Precision agriculture technologies represent a paradigm shift in nutrient management by leveraging advanced tools such as GPS, remote sensing, GIS, variable rate technology (VRT), and Internet of Things (IoT)-enabled sensors to deliver nutrients in precise amounts, at optimal times, and to specific field locations. This site-aware strategy minimizes nutrient losses, enhances nutrient uptake, and supports environmentally sound farming practices (Nayak *et al.,* 2024). By capturing spatial and temporal variability in soil and crop conditions, precision agriculture allows farmers to apply inputs more efficiently and economically, leading to reduced input costs and improved yields. Real-time monitoring systems help track crop health and soil nutrient status, facilitating data-driven decisions and adaptive management. Moreover, drone-based imagery and satellite data are increasingly used to map nutrient deficiencies and optimize fertilization regimes at sub-field resolution. These technologies are especially beneficial in large-scale commercial farming but are becoming more accessible to smallholders through shared service models and mobile platforms (Paul *et al.,* 2022). Precision agriculture, when integrated with digital decision-support systems, is a powerful tool to maximize nutrient use efficiency while minimizing the ecological footprint of agricultural production.

3.3 Site-Specific Nutrient Management (SSNM)

Site-Specific Nutrient Management (SSNM) is an innovative, knowledge-based approach that tailors nutrient applications to the unique characteristics of each field or even sub-field, taking into account variations in soil fertility, crop type, and environmental conditions. Unlike blanket fertilizer recommendations, SSNM involves detailed field assessments, including soil testing, yield goal estimation, and nutrient budgeting, to optimize nutrient inputs and improve crop nutrient uptake (MIMOUNE *et al.,* 2024). This approach significantly enhances nutrient use efficiency by synchronizing fertilizer application with crop demand throughout the growing season. SSNM not only improves yield and nutrient recovery but also minimizes environmental risks such as nitrogen leaching and phosphorus runoff. Decision-support tools and mobile applications have been developed to facilitate SSNM implementation, particularly in smallholder systems across Asia and Africa. Moreover, SSNM is highly adaptable, allowing for continuous refinement based on field performance and changing agroecological conditions. By promoting judicious nutrient use, SSNM supports sustainable agricultural practices and contributes to food security and environmental conservation (Sida *et al.,* 2023).

3.4 Slow- and Controlled-Release Fertilizers

Slow- and controlled-release fertilizers (SRFs and CRFs) represent a technologically advanced strategy to enhance nutrient use efficiency by regulating the release of nutrients in synchronization with crop uptake patterns. These fertilizers are engineered with coatings or matrix materials that delay nutrient solubility, thereby reducing the frequency and quantity of applications needed (Li *et al.,* 2024). The gradual nutrient release minimizes leaching, volatilization, and runoff losses common inefficiencies associated with conventional fertilizers while maintaining a consistent nutrient supply to plants. SRFs and CRFs are particularly effective in improving nitrogen use efficiency, which is critical given nitrogen's mobility in the soil-plant system and its environmental implications (Asadu *et al.,* 2024). In addition to increasing agronomic efficiency, these fertilizers reduce labor costs and environmental burdens, such as greenhouse gas emissions and water contamination. Innovations in biodegradable coatings and polymer technologies are expanding the applicability and environmental compatibility of SRFs and CRFs. Their integration into mainstream farming practices, supported by policy incentives and farmer training, holds significant promise for sustainable intensification and climate-resilient agriculture (Moradi *et al.,* 2024).

4. Bio-Based Soil Amendments

4.1 Compost and Vermicompost

Compost and vermicompost are organic soil amendments derived from the decomposition and transformation of agricultural residues, food waste, and other biodegradable materials through microbial or vermi-biological activity. These amendments are recognized for their ability to enhance soil fertility and nutrient availability in a sustainable and environmentally friendly manner (Raza *et al.,* 2022). Composting involves the aerobic degradation of organic matter, resulting in a stable humus-like material rich in macro- and micronutrients, organic carbon, and beneficial microorganisms. Vermicomposting, facilitated by epigeic earthworms such as Eisenia fetida, further improves the quality of the compost by fragmenting, aerating, and biologically transforming the organic material. These processes not only concentrate essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), but also enhance microbial biomass and enzymatic activity in soil (Hajam *et al.,* 2023). The slow and steady release of nutrients from compost and vermicompost reduces the risk of leaching losses and nutrient imbalances, thereby improving nutrient use efficiency. Additionally, these bio-amendments contribute to improving soil physical properties such as aggregation, porosity, and water-holding capacity, all of which are critical for sustaining plant growth and mitigating the adverse impacts of climate variability (Farooq *et al.,* 2024). Their role in sequestering carbon and enhancing microbial diversity makes them indispensable components of integrated nutrient management strategies aimed at long-term soil health and sustainable agricultural productivity.

4.2 Biochar Applications

Biochar, a carbon-rich material produced via pyrolysis of biomass under limited oxygen conditions, has gained prominence as a multifunctional soil amendment in sustainable agriculture. Its porous structure, high surface area, and chemical stability make it an effective medium for nutrient retention and microbial colonization. When applied to soil, biochar can significantly improve nutrient use efficiency by adsorbing nutrients like ammonium, nitrate, and phosphate, thereby reducing losses due to leaching and volatilization (Liu *et al.,* 2015). Furthermore, its alkaline nature can ameliorate soil acidity, thereby enhance the availability of essential nutrients and promote favorable conditions for plant growth. The synergistic use of biochar with other organic amendments like compost or manure can further amplify its benefits by improving microbial activity and organic matter mineralization. Biochar also enhances soil cation exchange capacity (CEC), facilitating better nutrient retention and exchange between soil and plant roots. Importantly, biochar contributes to long-term carbon sequestration, aiding in climate change mitigation efforts (Tu *et al.,* 2019). In degraded or nutrient-deficient soils, its application has been shown to improve crop yield, enhance nutrient uptake, and restore soil structure. However, the agronomic effectiveness of biochar depends on various factors including feedstock type, pyrolysis temperature, and application rate, necessitating site-specific evaluation. Overall, the integration of biochar into sustainable agricultural practices offers a promising pathway for enhancing nutrient efficiency while improving soil health and ecological resilience.

4.3 Microbial Inoculants and Plant Growth-Promoting Rhizobacteria (PGPR)

Microbial inoculants, particularly plant growth-promoting rhizobacteria (PGPR), are bio-based agents that play a pivotal role in enhancing soil nutrient efficiency through biological processes. PGPR are a diverse group of beneficial bacteria that colonize plant roots and stimulate growth by various direct and indirect mechanisms (Elnahal *et al.,* 2022). These include nitrogen fixation, phosphate solubilization, siderophore production for iron acquisition, and synthesis of phytohormones such as auxins, gibberellins, and cytokinins. By facilitating these nutrient-cycling processes, PGPR contribute to increased nutrient bioavailability and uptake by crops. Moreover, PGPR can induce systemic resistance against soil-borne pathogens, thereby reducing the need for chemical pesticides and fostering a healthier rhizosphere environment. Inoculation with PGPR not only improves nutrient-use efficiency but also enhances root architecture, water uptake, and stress tolerance under abiotic stresses like salinity and drought. Some microbial inoculants also work synergistically with mycorrhizal fungi and other beneficial soil microbes to form complex, functionally diverse microbial communities that support long-term soil fertility (Wahab *et al.,* 2022). The integration of PGPR into crop management systems has been shown to reduce the dependency on synthetic fertilizers, thereby lowering input costs and minimizing the environmental footprint of agriculture. To fully realize their potential, however, challenges such as strain specificity, formulation stability, and field efficacy under varying agro-ecological conditions must be addressed (Shah *et al.,* 2021). Nevertheless, the use of microbial inoculants represents a promising and eco-friendly approach to enhancing soil nutrient efficiency and advancing sustainable agricultural practices.

5. Biotechnological Interventions

5.1 Genetically Improved Crops for Nutrient Uptake

Genetically improved crops represent a cornerstone in the effort to enhance soil nutrient efficiency and ensure sustainable agricultural practices. Traditional crop varieties often exhibit suboptimal nutrient uptake efficiencies, leading to an over-reliance on chemical fertilizers, which can degrade soil health and pollute surrounding ecosystems (Nawaz *et al.,* 2025). Advances in genetic engineering have allowed the development of crop varieties with enhanced root architecture, greater root surface area, and increased expression of transporter proteins that facilitate more efficient uptake of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Maqbool *et al.,* 2022). For instance, transgenic rice and maize expressing high-affinity phosphate transporters or nitrate transporters have demonstrated improved nutrient acquisition from the soil, especially under low-input conditions. In addition, the introduction of genes responsible for symbiotic relationships, such as those involved in mycorrhizal interactions and nitrogen fixation, has further enhanced nutrient accessibility in genetically modified crops. These genetic modifications not only reduce the dependency on synthetic fertilizers but also contribute to maintaining long-term soil fertility and structure, thus aligning agricultural productivity with environmental sustainability (Goyal *et al.,* 2021). The integration of genome editing tools such as CRISPR/Cas9 has further accelerated the precision and efficiency of developing nutrient-efficient cultivars, allowing researchers to target specific genes or regulatory elements associated with nutrient uptake and assimilation. Such innovations promise a transformative shift in modern agriculture, especially in regions where nutrient-poor soils constrain productivity (Hazrati *et al.,* 2025).

5.2 Molecular Approaches to Enhance NUE

Molecular biology has opened new frontiers in understanding and manipulating the complex physiological and biochemical pathways that govern nutrient use efficiency (NUE) in plants. NUE encompasses both nutrient uptake from the soil and the internal utilization of those nutrients for growth and yield. At the molecular level, this involves a suite of genes responsible for nutrient sensing, transport, assimilation, and remobilization (Javed *et al.,* 2022). Advances in transcriptomics, proteomics, and metabolomics have led to the identification of key regulatory genes and transcription factors, such as NIN-like proteins (NLPs) for nitrogen signaling or PHR1 for phosphorus starvation response, which can be targeted to enhance NUE. Functional genomics has enabled the characterization of transporter families like NRTs (nitrate transporters) and PHTs (phosphate transporters), and their overexpression has been shown to significantly improve nutrient uptake and translocation. Furthermore, signal transduction pathways involving phytohormones such as auxins and cytokinins are being manipulated to optimize root growth and enhance nutrient acquisition (Fan *et al.,* 2017). Synthetic biology also offers innovative solutions, including the engineering of synthetic promoters that can modulate gene expression in response to nutrient availability, thus enabling dynamic and efficient nutrient usage. Additionally, RNA interference (RNAi) and gene silencing techniques have been employed to downregulate genes that negatively regulate nutrient assimilation. Such molecular strategies offer the dual benefit of increasing crop yields and reducing environmental externalities by minimizing fertilizer runoff and greenhouse gas emissions, thereby making agriculture more sustainable and resource-efficient (Jagtap *et al.,* 2011).

5.3 Role of Rhizosphere Engineering

Rhizosphere engineering is an emerging and highly promising biotechnological approach aimed at optimizing the complex interactions between plant roots, soil, and microbial communities to enhance soil nutrient efficiency. The rhizosphere the narrow region of soil directly influenced by root secretions and associated microbial activity plays a pivotal role in nutrient cycling and availability (Joshi *et al.,* 2025). Engineering the rhizosphere involves manipulating root exudates to selectively recruit beneficial microbial communities that can facilitate nutrient solubilization, fixation, and mobilization. For instance, root exudates can be genetically modified to enhance the secretion of organic acids or enzymes such as phytases and phosphatases, which liberate bound forms of phosphorus and other micronutrients, making them more bioavailable to plants. Concurrently, the deliberate inoculation of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi into the rhizosphere can improve nutrient uptake through mechanisms such as nitrogen fixation, phosphate solubilization, and production of siderophores that mobilize iron (Timofeeva *et al.,* 2023). Advances in metagenomics and microbiome analysis have deepened our understanding of microbial diversity and function in the rhizosphere, enabling the design of synthetic microbial consortia tailored to specific soil and crop conditions. Furthermore, rhizosphere engineering strategies now include bio-priming of seeds and development of bioformulations that enhance microbial colonization and persistence. These interventions not only improve plant nutrient acquisition and growth but also foster soil health by promoting biodiversity and suppressing pathogens. As such, rhizosphere engineering holds tremendous potential for sustainable intensification of agriculture, particularly in the face of climate change and shrinking arable land (Singh *et al.,* 2023).

6. Environmental and Socioeconomic Considerations

6.1 Impact on Greenhouse Gas Emissions

Enhancing soil nutrient efficiency plays a pivotal role in mitigating greenhouse gas (GHG) emissions from agricultural systems, which are significant contributors to climate change. Inefficient fertilizer use, especially nitrogen-based fertilizers, leads to increased emissions of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential nearly 300 times that of carbon dioxide (CO_2). Optimized nutrient management—through practices such as precision agriculture, integrated nutrient management (INM), and the application of slow- or controlled-release fertilizers can significantly reduce these emissions by synchronizing nutrient supply with crop demand (Paramesh et al.,2023). Moreover, improving soil health via organic amendments and cover cropping can enhance nutrient cycling and reduce the need for synthetic fertilizers. These approaches not only diminish direct emissions but also contribute to long-term carbon sequestration by increasing soil organic carbon. However, the environmental benefits are influenced by local agroecological conditions, crop types, and farming systems, necessitating site-specific strategies. The environmental co-benefits of improved nutrient efficiency, including reduced water eutrophication and soil degradation, further underscore the importance of integrating GHG considerations into nutrient management frameworks for sustainable agriculture (Jackson *et al.,* 2012).

6.2 Economic Feasibility and Farmer Adoption

The economic viability of strategies aimed at improving soil nutrient efficiency is a critical determinant of their adoption by farmers, especially in resource-constrained settings. Although technologies like precision fertilization, soil testing, and biofertilizers promise long-term gains in productivity and input savings, their initial costs, complexity, and perceived risks can deter smallholder and marginal farmers. Cost-benefit analyses indicate that while some nutrient efficiency interventions yield positive returns over time, the upfront investment and knowledge requirements can be prohibitive without financial and technical support (Chikowo *et al.,* 2014). Furthermore, farmers' willingness to adopt new practices depends on various factors including land tenure security, market access, availability of credit, and access to reliable extension services. Socioeconomic disparities also influence adoption rates; for instance, wealthier or better-educated farmers are more likely to adopt nutrient-efficient practices than their poorer counterparts. Hence, ensuring economic feasibility requires a multifaceted approach subsidizing initial adoption, providing farmer training, and facilitating access to low-cost technologies. Demonstrating the long-term economic advantages, such as yield stability, improved soil fertility, and resilience to climate shocks, is vital for scaling these practices in diverse farming communities JAMES, R. M. (2023).

6.3 Policy and Institutional Support

Policy and institutional frameworks play a foundational role in enabling the widespread implementation of soil nutrient efficiency practices. Governments and development agencies must provide clear and consistent policies that promote sustainable nutrient management while discouraging practices that lead to overuse or misuse of fertilizers. This includes revising fertilizer subsidy schemes to incentivize balanced nutrient use rather than merely promoting high application rates of nitrogen-based products. Institutional support should also include investments in soil health monitoring systems, research and development of locally adapted nutrient management technologies, and robust agricultural extension services. Coordination between agricultural, environmental, and economic planning bodies is essential to align goals related to food security, climate mitigation, and rural development. Additionally, regulatory mechanisms, such as nutrient application guidelines and certification programs for nutrient-efficient practices, can promote accountability and environmental stewardship. International collaboration and knowledge exchange, particularly in the context of climate-smart agriculture, further bolster national efforts. Crucially, participatory governance that involves farmers, researchers, and civil society in policy design and implementation enhances the relevance, equity, and effectiveness of interventions aimed at improving soil nutrient efficiency for sustainable agriculture.

7. Challenges and Future Perspectives

Enhancing soil nutrient efficiency is a critical goal in modern sustainable agriculture, yet it is significantly hindered by the pervasive challenge of soil degradation and the unpredictable impacts of climate variability. Soil degradation—caused by erosion, salinization, nutrient mining, and the excessive use of chemical inputs—has led to the depletion of essential nutrients and the disruption of microbial communities that are vital for nutrient cycling. Simultaneously, climate variability introduces further complexity, as erratic precipitation patterns, extreme weather events, and rising temperatures alter soil moisture dynamics and nutrient availability. These environmental stressors not only reduce crop productivity but also compromise the long-term resilience of agroecosystems. In regions already experiencing nutrient-poor soils, such as parts of sub-Saharan Africa and South Asia, these issues are compounded, making it increasingly difficult to maintain soil health and meet the growing food demand. This situation underscores the urgent need for innovative solutions that integrate ecological principles with site-specific nutrient management.

However, technical solutions alone are insufficient if socio-economic barriers prevent their implementation at scale. Farmers, particularly smallholders, often face significant obstacles to adopting improved nutrient management practices. These barriers include limited access to credit, lack of extension services, inadequate training, and the absence of incentives for adopting sustainable practices. In many cases, traditional knowledge and localized practices are overlooked by top-down development programs, leading to resistance or inefficiency in implementation. Moreover, the upfront costs associated with soil amendments, organic fertilizers, and precision agriculture technologies are frequently prohibitive, especially in resource-limited settings. Socio-economic inequality, insecure land tenure, and market instability further deter investment in long-term soil fertility strategies. Therefore, any approach to improving soil nutrient use efficiency must be inclusive and participatory, taking into account the diverse socio-economic contexts of farming communities and ensuring that farmers are not just recipients of technology, but active stakeholders in co-developing solutions.

To address these multifaceted challenges, there is a growing recognition of the need for adaptive and holistic nutrient management strategies. Such approaches emphasize the integration of organic and inorganic nutrient sources, the use of cover crops, crop rotation, agroforestry, and biofertilizers, as well as the adoption of precision agriculture techniques. These strategies enhance nutrient use efficiency by improving soil structure, increasing biodiversity, and optimizing nutrient delivery to crops. Adaptive management also entails a dynamic understanding of local conditions—adjusting practices in response to soil tests, climate patterns, and pest pressures. Farmer-led innovation, participatory research, and indigenous knowledge systems should be at the forefront of these strategies. Digital tools and remote sensing technologies offer new avenues for real-time monitoring and decision support, although their deployment must be tailored to local capacities and infrastructures. Ultimately, a systems-thinking approach that views the farm not in isolation but as part of a larger socio-ecological landscape is essential to drive meaningful progress in nutrient stewardship.

Looking forward, effective policy and research frameworks will play a pivotal role in advancing soil nutrient efficiency to ensure global food security and environmental sustainability. Policies must shift from input-subsidy models to incentive-based mechanisms that reward conservation and nutrient stewardship. Investment in agricultural research should prioritize soil health, microbial ecology, and climate-smart innovations while fostering cross-sector collaboration among agronomists, ecologists, economists, and policymakers. Strengthening institutional capacities for soil testing, monitoring, and data management is crucial for evidence-based decision-making. Furthermore, international cooperation is needed to align national strategies with global sustainability targets, such as those outlined in the UN Sustainable Development Goals (SDGs). The future of soil nutrient efficiency hinges not only on scientific breakthroughs but also on political will, equitable access to resources, and the empowerment of farmers as agents of change. By bridging knowledge gaps, addressing socio-economic disparities, and fostering inclusive innovation, the agricultural sector can move toward a resilient and nutrient-efficient future.

CONCLUSION

In conclusion, enhancing soil nutrient efficiency stands as a pivotal strategy for achieving sustainable agriculture. By integrating advanced nutrient management practices, adopting innovative technologies, and promoting soil health, it is possible to optimize nutrient use while minimizing environmental impacts. The synergy between scientific research and practical applications can lead to improved crop productivity, soil fertility, and long-term agricultural resilience. Moving forward, continued efforts in precision agriculture, organic amendments, and policy support are essential to foster nutrient-efficient farming systems that meet the growing food demands without compromising ecological balance. Ultimately, a holistic approach to nutrient management will contribute significantly to global food security and environmental sustainability.

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