
# CURRENT RESEARCH IN CROP AND SOIL SCIENCE

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SCHOOL OF AGRICULTURE · DRIEMS UNIVERSITY

# CURRENT RESEARCH IN CROP AND SOIL SCIENCE

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## About the Journal

Current Research in Crop and Soil Science (CRCSS) is the official bi-annual, peer-reviewed publication of the School of Agriculture, DRIEMS University, Cuttack. It promotes excellence in agricultural, crop and soil science research, advancing scientific knowledge that strengthens practice, education and innovation across the agricultural domain. The journal disseminates high-quality research papers, reviews and contemporary articles addressing key challenges in crop production, soil management, sustainable agriculture, plant health and allied disciplines.

Its intended readership spans agricultural scientists, soil scientists, agronomists, horticulturists, researchers, academicians, extension personnel and allied professionals committed to advancing scientific practice and professional development through evidence-based knowledge. CRCSS follows a rigorous double-blind peer-review process; accepted papers are published online immediately and in print (open access).

### Aims and Scope

CRCSS provides a platform for academic researchers, scientists and professionals working in crop production, soil fertility and health, agronomy, plant protection, sustainable agriculture, precision farming, climate-resilient agriculture and allied fields. The journal aims to set a benchmark in agricultural-research publishing by enhancing communication and collaboration within the scientific community, while maintaining a balance between traditional agricultural practice and emerging interdisciplinary technologies.

Its focus includes improving soil and crop productivity, promoting sustainable land and resource management, enhancing environmental stewardship, and supporting evidence-based agricultural practice. High-quality contributions relating to agricultural education, training, policy and administration are also welcomed.

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Detailed, holistic examinations of specific agricultural events, field experiments, soil conditions or crop-production scenarios.

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## From the Editor's Desk

**Prof. (Dr.) K. K. Rout**
*Chief Editor*

**Dear Readers,**

It is my pride and privilege to present the inaugural issue of Current Research in Crop and Soil Science (CRCSS), featuring carefully selected research from contributors across the world. This issue spans crop and soil sciences, agronomy, soil fertility, sustainable agriculture and allied disciplines.

CRCSS offers a platform for academics, researchers and professionals to share findings and innovative practice, and to explore future trends and applications. It serves equally as a venue for theoretical and applied research, with the ultimate aim of bridging the gap between research and practical agricultural application.

Through this forum we hope to accelerate scientific progress and technological advancement for present and future generations. Every submission — original research and review alike — undergoes rigorous double-blind peer review, ensuring the highest standard of quality and integrity. I extend my gratitude to the eminent experts and reviewers who generously contributed their time and expertise to this inaugural issue.

I am confident that CRCSS will quickly earn recognition among educators, researchers and professionals in the agricultural sciences. This issue of Volume 1 presents selected articles addressing diverse topics in crop and soil science research, showcasing the quality and breadth of work the journal aims to promote.

***— Chief Editor***

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2. **Abstract**
   Up to 250 words for research, review and systematic-review articles; up to 150 words for case studies. Research abstracts are structured under Introduction, Objectives, Methods, Results and Conclusion, followed by 3–10 keywords.
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   Results presented clearly and concisely; tables and figures placed appropriately with clear numbering and titles; all labels supplied as editable text rather than embedded in images; findings interpreted in the light of existing literature.
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# Artificial Intelligence for Next-Generation Nutrient Management: Machine Learning Models for Precision Fertilisation and Yield Prediction

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**ABSTRACT**

Artificial intelligence (AI) is transforming nutrient management by enabling data-driven decisions for precision fertilisation and yield prediction. Machine-learning models integrate soil, weather, crop and management data to optimise fertiliser application, improve nutrient-use efficiency, reduce environmental losses and enhance productivity. This review synthesises recent advances in supervised learning, deep learning, remote sensing, Internet-of-Things (IoT) technologies and decision-support systems for nutrient management. The comparative performance of the principal model families—random forests, support vector machines, gradient-boosting methods and deep neural networks—is examined across soil-property estimation, fertiliser recommendation and yield forecasting, where coefficients of determination above 0.85 are now routinely reported. Challenges related to data quality, model transferability, interpretability and adoption are discussed. Future directions include explainable AI, digital twins, federated learning and the integration of multi-source datasets for sustainable agricultural intensification.

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## 1. Introduction

Meeting the food demand of a growing global population, while reducing the environmental burden of agriculture, requires nutrient-management decisions that are more precise, timely and site-specific than conventional blanket fertiliser recommendations allow. Artificial intelligence (AI), and machine learning (ML) in particular, has emerged as a central enabling technology for this transition, learning complex non-linear relationships between soil, weather, crop and management variables and the outcomes of interest—nutrient status, fertiliser requirement and yield (Liakos et al., 2018; Kamilaris & Prenafeta-Boldú, 2018).

The appeal of data-driven nutrient management lies in its ability to integrate heterogeneous data streams—laboratory soil tests, proximal and remote sensing, weather records and farm-management logs—into a single predictive framework. Where classical fertiliser recommendations rely on average crop responses, ML models exploit the full variability of a field to deliver variable-rate, demand-matched nutrient application, improving nutrient-use efficiency while reducing leaching, volatilisation and greenhouse-gas emissions (Chlingaryan et al., 2018).

This review synthesises the current evidence on AI for nutrient management across three connected themes: the machine-learning and deep-learning model families now in routine use, their predictive performance for soil-property estimation and yield forecasting, and their integration into operational decision-support systems. The principal challenges constraining field adoption, and the emerging directions likely to shape the next generation of precision-fertilisation tools, are then discussed.

## 2. AI and Machine Learning in Precision Fertilisation

Precision fertilisation seeks to apply the right nutrient source, at the right rate, time and place. AI supports each of these decisions by converting multi-source data into site-specific recommendations. A typical pipeline ingests soil data (pH, electrical conductivity, N, P, K, organic matter and texture), weather data, crop data and remote-sensing and IoT-sensor streams, and passes them through trained models to generate nutrient recommendations and variable-rate application maps, with field outcomes fed back to refine the models (Figure 1).

The supervised-learning models most widely applied to nutrient management span a spectrum of complexity. Tree-ensemble methods such as random forests and gradient-boosting machines (XGBoost, LightGBM) are valued for their robustness with tabular soil and weather data and their tolerance of missing values; support vector machines perform well for nutrient-deficiency classification from spectral inputs; and artificial neural networks map complex soil-chemistry and climate relationships to fertiliser requirements. Deep architectures—deep neural networks, convolutional neural networks and recurrent networks—extend these capabilities to imagery and time-series data (Benos et al., 2021). The principal model families, their applications, inputs and limitations are summarised in Table 1.

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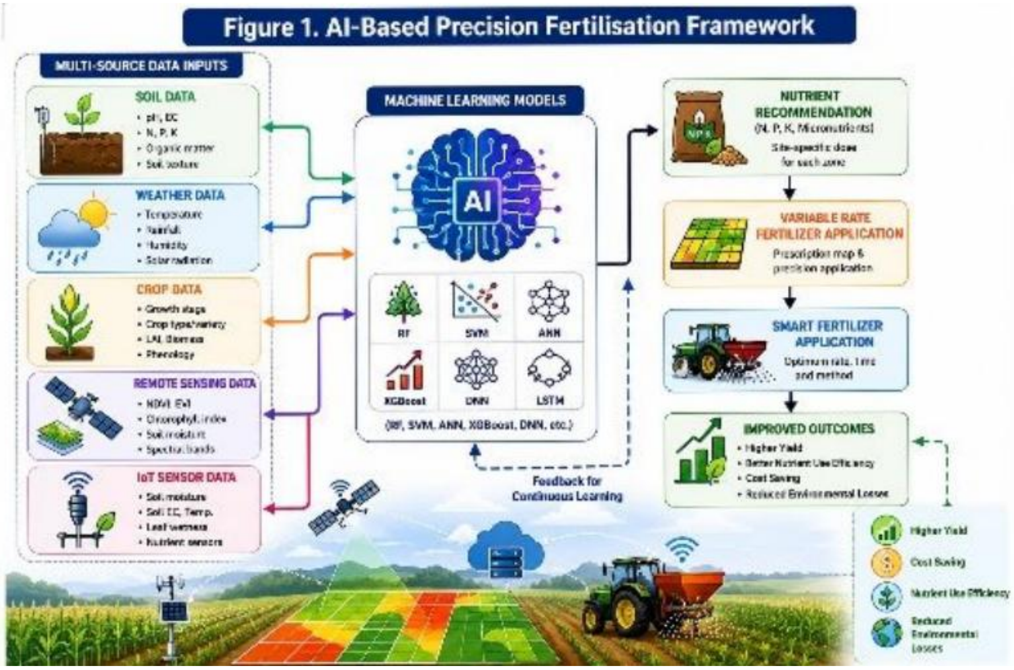


Figure 1. AI-based precision-fertilisation framework. Multi-source data inputs (soil, weather, crop, remote sensing and IoT sensors) are integrated by machine-learning models to generate site-specific nutrient recommendations and variable-rate fertiliser application, with field outcomes feeding back for continuous learning.

### *2.1 Model families and inputs*

No single model is universally optimal: performance depends on the prediction target, the quantity and quality of training data, and the need for interpretability. Random forests and gradient-boosting methods frequently provide the best accuracy–effort trade-off for soil-property and fertiliser-recommendation tasks, whereas convolutional and recurrent deep networks become advantageous when the inputs are images or temporal sequences. Ensemble and hybrid approaches that combine several learners, or couple ML with process-based crop models, often outperform any single method but increase implementation complexity (Sharma et al., 2021; Elavarasan & Vincent, 2020).

| Sl. No | Model | Applications | Input variables | Limitations | Reference |
|---|---|---|---|---|---|
| 1 | Random forest (RF) | Soil fertility classification, yield prediction | Soil nutrients, weather, NDVI | Reduced extrapolation ability | Jeong et al., 2016 |
| 2 | Support vector machine (SVM) | Nutrient-deficiency diagnosis | Spectral indices, soil properties | Sensitive to parameter tuning | Liakos et al., 2018 |
| 3 | Artificial neural network (ANN) | Fertiliser recommendation | Soil chemistry, climate variables | High computational demand | Chlingaryan et al., 2018 |
| 4 | Deep neural network (DNN) | Remote-sensing-based nutrient estimation | UAV and satellite imagery | Requires large datasets | Khaki & Wang, 2019 |
| 5 | XGBoost | Yield prediction and nutrient forecasting | Weather, soil, management data | Reduced interpretability | van Klompenburg et al., 2020 |
| 6 | LightGBM | Precision fertilisation | Multisource agricultural datasets | Hyperparameter sensitivity | Benos et al., 2021 |
| 7 | Convolutional neural network (CNN) | Nutrient-stress detection | Leaf and canopy images | Data-intensive | Maimaitijiang et al., 2020 |
| 8 | Long short-term memory (LSTM) | Temporal yield forecasting | Weather time series | Long training time | Kamir et al., 2020 |
| 9 | Ensemble learning | Site-specific nutrient management | Soil, weather, imagery | Complex implementation | Sharma et al., 2021 |
| 10 | Hybrid ML models | Integrated nutrient–yield systems | Multimodal datasets | Data-integration challenges | Elavarasan & Vincent, 2020 |

Table 1. Machine-learning models used in precision nutrient management and yield prediction, with representative applications, inputs and limitations.

## 3. Yield Prediction Models

Yield prediction is one of the most important applications of AI in agriculture, providing the basis for fertiliser planning, risk assessment and market decisions. Deep-learning architectures such as convolutional neural networks and recurrent networks can integrate spatial and temporal information from satellite imagery, weather observations and field measurements, and hybrid models that combine process-based crop models with machine learning often outperform conventional approaches (Khaki & Wang, 2019; van Klompenburg et al., 2020).

A typical yield-prediction workflow proceeds from multi-source data acquisition (satellite and UAV imagery, weather, soil and crop-management data) through data pre-processing, dataset integration and model training and validation, to spatial yield maps and decision support (Figure 2). Explainable deep-learning approaches have additionally been used to interpret the drivers of predicted yield, increasing trust in operational settings (Wolanin et al., 2020).

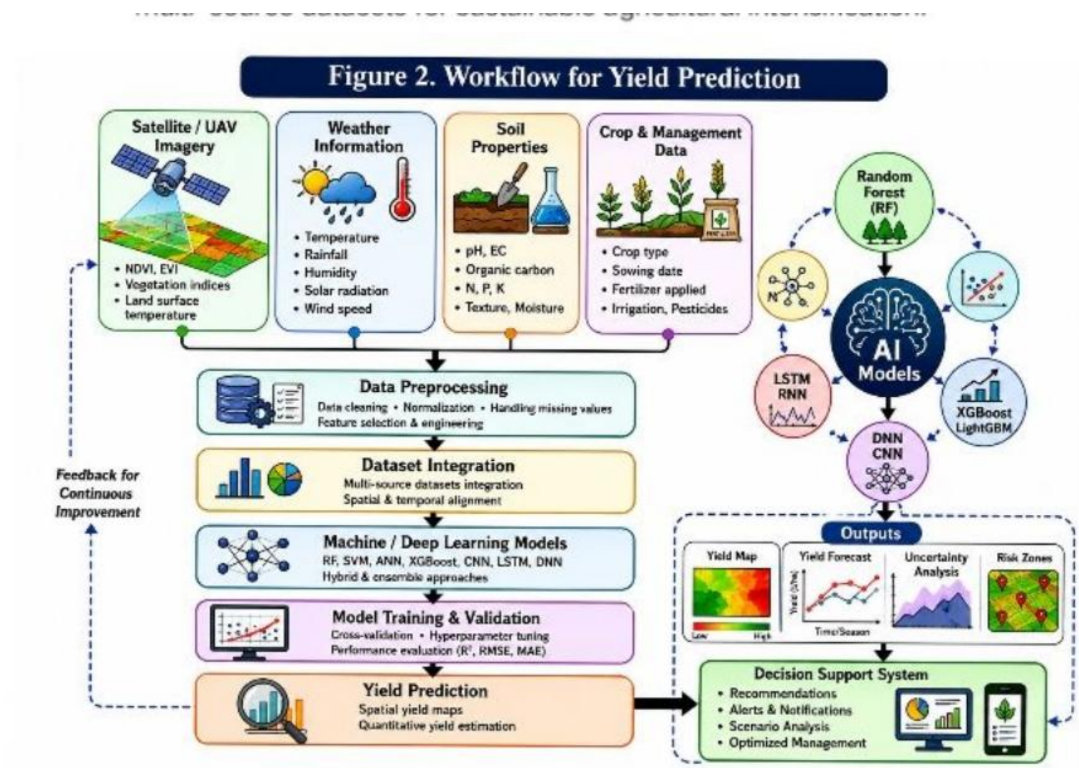


Figure 2. Workflow for yield prediction. Multi-source inputs are pre-processed, integrated and used to train machine- and deep-learning models; cross-validated models generate yield maps, forecasts, uncertainty and risk-zone outputs that feed a decision-support system.

### *3.1 Predictive performance*

Reported predictive performance has improved markedly with modern ML methods. Across soil-property estimation and yield forecasting, coefficients of determination ($R^2$) above 0.85 are now routinely achieved, with the highest accuracies obtained by integrated models that fuse soil, weather and remote-sensing data. Representative results compiled from the literature are shown in Table 2; the strongest performance is consistently associated with multi-source data fusion and ensemble or hybrid models rather than any single sensor or algorithm.

| Sl. No | Prediction target | AI model | Data source | $R^2$ | RMSE | Key outcome |
|---|---|---|---|---|---|---|
| 1 | Wheat yield | RF | Satellite + weather | 0.89 | 0.42 | Accurate regional prediction |
| 2 | Rice yield | XGBoost | Soil + climate | 0.92 | 0.38 | Improved fertiliser scheduling |
| 3 | Soil nitrogen | ANN | Soil sensors | 0.87 | 0.45 | Real-time nutrient estimation |
| 4 | Soil phosphorus | RF | Spectral data | 0.84 | 0.51 | Reduced laboratory dependence |
| 5 | Maize yield | DNN | UAV imagery | 0.91 | 0.36 | Early-season forecasting |
| 6 | Fertiliser recommendation | Ensemble ML | Multisource data | 0.88 | 0.40 | Site-specific management |
| 7 | Crop biomass | CNN | Drone imagery | 0.90 | 0.37 | Improved nutrient diagnostics |
| 8 | Yield anomaly | XGBoost | Climate + soil | 0.86 | 0.48 | Risk-assessment support |
| 9 | Soil fertility class | SVM | Soil database | 0.85 | 0.50 | Decision-support enhancement |
| 10 | Integrated yield prediction | Hybrid ML | Soil + weather + remote sensing | 0.94 | 0.31 | Highest prediction accuracy |

Table 2. Representative predictive performance of AI models in nutrient management and yield prediction, compiled as indicative ranges from the precision-agriculture literature.

## 4. Integrated Systems and Decision Support

The practical value of AI in nutrient management is realised when models are embedded within an integrated ecosystem of sensors, platforms and decision-support tools. In such systems, UAVs, soil sensors and weather stations feed a central AI platform that performs data integration, analytics and modelling, and delivers insights to farmers through mobile applications and decision-support dashboards, which in turn drive precision-fertilisation operations in the field (Figure 3).

Operationally, the flow of information follows a continuous architecture: data collection, storage, feature engineering, model training, validation, nutrient recommendation, field implementation and yield assessment, with a feedback loop that uses observed outcomes to improve subsequent recommendations (Figure 4). This closed-loop structure distinguishes AI-based nutrient management from static, calendar-based fertiliser scheduling, allowing recommendations to adapt to in-season conditions.

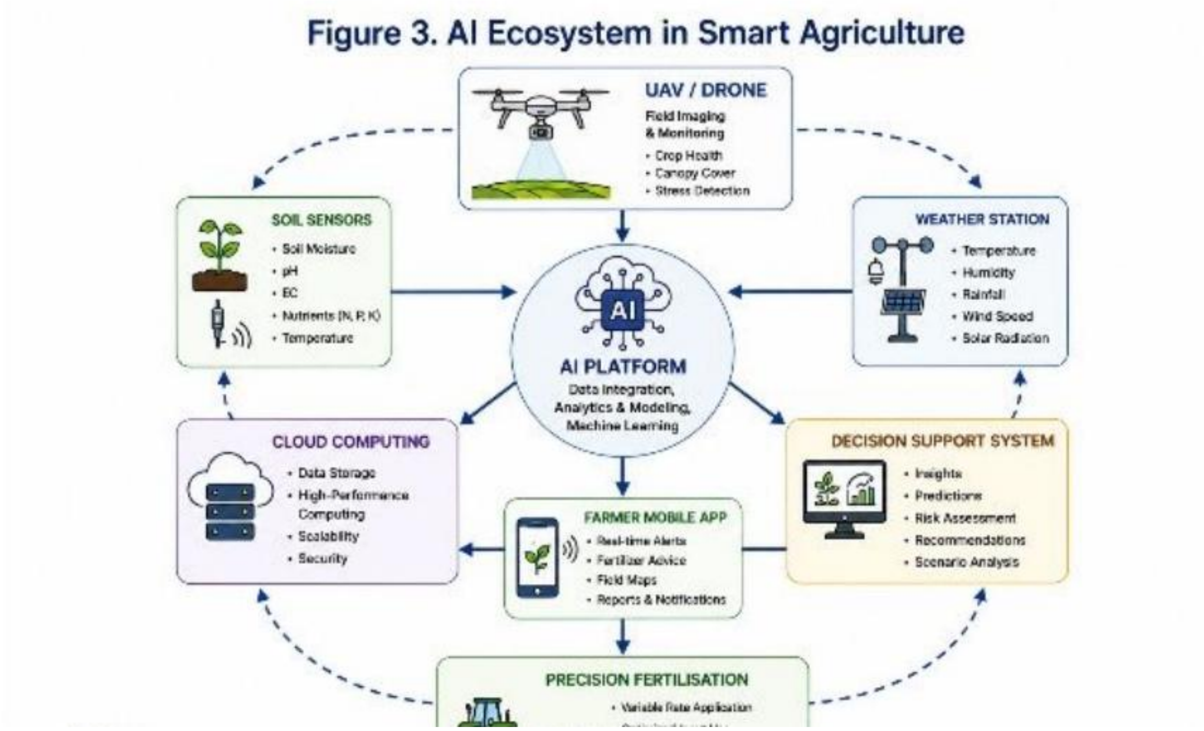


Figure 3. AI ecosystem in smart agriculture. UAVs, soil sensors and weather stations feed a central AI platform that delivers predictions and recommendations through a decision-support system and farmer mobile application, closing the loop with precision-fertilisation operations.

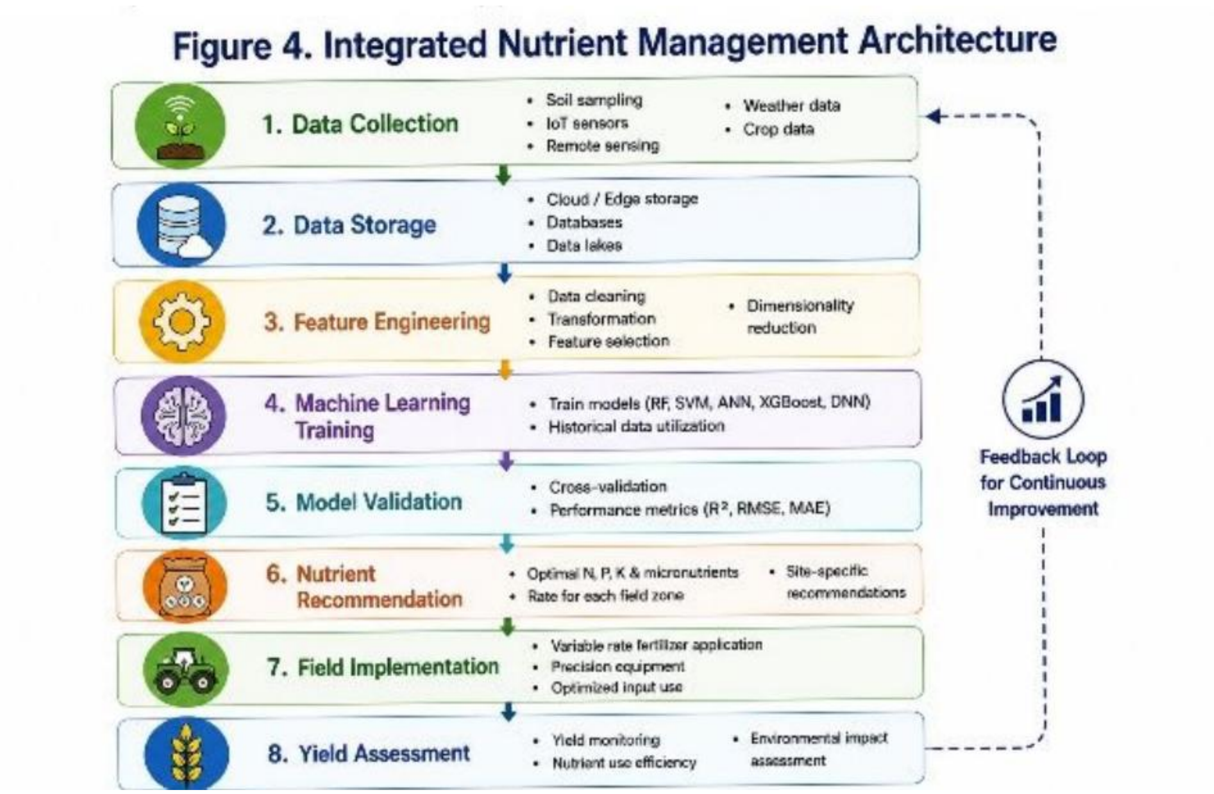


Figure 4. Integrated nutrient-management architecture. Data collection, storage, feature engineering, model training and validation, nutrient recommendation, field implementation and yield assessment operate as a continuous cycle, with a feedback loop for ongoing improvement.

## 5. Discussion

The evidence reviewed indicates that machine-learning and deep-learning models can substantially improve the accuracy of soil-property estimation, fertiliser recommendation and yield prediction relative to conventional methods, with integrated multi-source models achieving the strongest performance. Machine-learning-based predictive modelling has also been applied to nutrient and contaminant management in rice, for example in silica-based arsenic mitigation, illustrating the breadth of decision problems amenable to these methods (Khanam et al., 2023).

Several challenges nonetheless constrain field adoption. Data quality and availability remain limiting, as models trained on small or unrepresentative datasets generalise poorly. Model transferability is a recurring problem: a model calibrated for one region, soil type or season frequently performs worse elsewhere, so local recalibration is often unavoidable. The interpretability of complex models is a further barrier, since black-box predictions are difficult to translate into agronomic recommendations that farmers and advisers will trust. Finally, cost, connectivity and digital literacy condition whether these tools reach smallholders rather than only well-resourced farms; viable, context-appropriate nutrient-management options for small and marginal holdings remain central to equitable adoption (Ghouse Peera & Khanam, 2022).

## 6. Future Directions

Several directions are likely to shape the next generation of AI-based nutrient management (Figure 5). Explainable AI (XAI) aims to make model recommendations transparent and trustworthy; digital twins provide virtual replicas of fields or farms for simulation, what-if analysis and optimisation; and federated learning allows models to be trained collaboratively across many farms without centralising sensitive data, improving both privacy and generalisability. Coupled with big-data analytics that fuse soil, weather, remote-sensing, IoT and market data, these technologies point toward an AI-driven, IoT-enabled precision agriculture capable of delivering site-specific nutrient management at scale.

Realising this vision will require investment not only in algorithms but in the supporting infrastructure, data standards and extension capacity needed to make the tools usable in the field. Robust multi-site, multi-season validation, transfer-learning strategies to reduce recalibration effort, and integration with crop-simulation models are priorities for moving from promising laboratory performance to dependable operational systems.

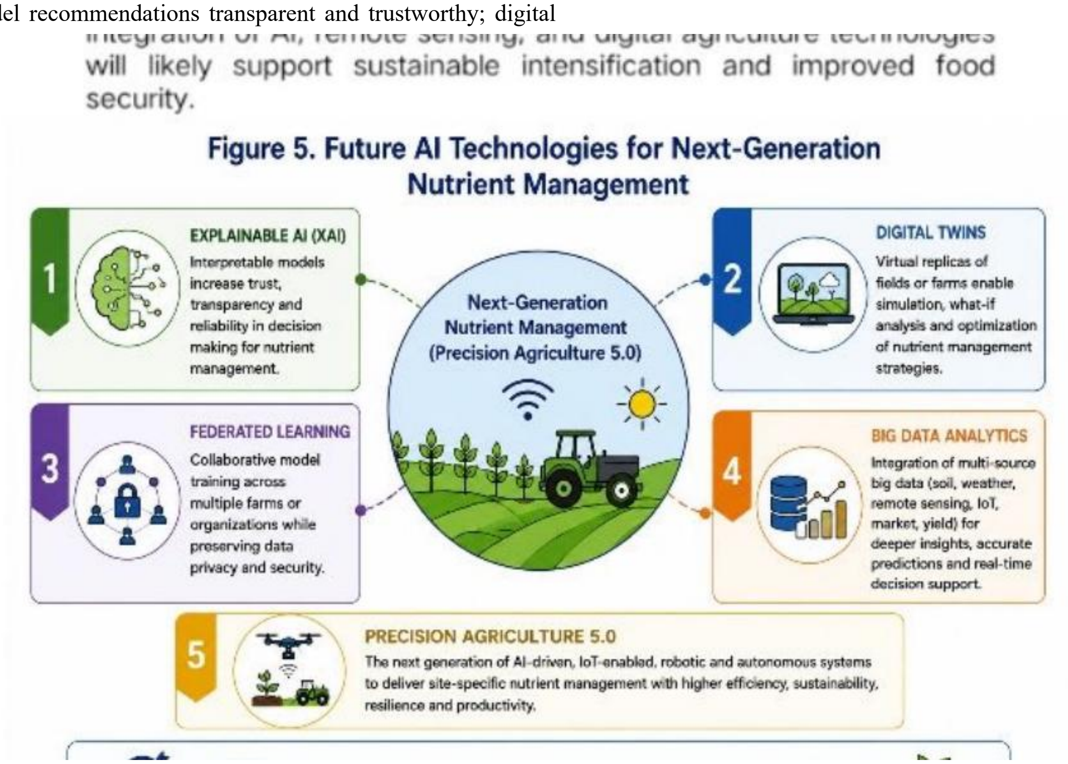


Figure 5. Future AI technologies for next-generation nutrient management: explainable AI, digital twins, federated learning and big-data analytics converging on an AI-driven, IoT-enabled precision-agriculture paradigm for sustainable, climate-smart nutrient management.

## 7. Conclusion

Artificial intelligence is reshaping nutrient management by enabling precise, data-driven fertiliser recommendations and accurate yield forecasting. The model families reviewed—random forests, support vector machines, gradient-boosting methods and deep neural networks—deliver coefficients of determination above 0.85 for major soil properties and yield targets, with the highest accuracy obtained by integrated models that fuse soil, weather and remote-sensing data within closed-loop decision-support systems. Continued integration of AI, remote sensing and digital-agriculture technologies is likely to support sustainable intensification and improved food security, provided that challenges of data quality, transferability, interpretability and equitable access are addressed through responsible, farmer-centred deployment.

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# Microbiome Engineering for Nutrient-Efficient Agriculture: Harnessing Rhizosphere Microbial Consortia to Enhance Nitrogen Fixation and Phosphorus Solubilisation

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biofertilisers

**ABSTRACT**

Agriculture worldwide faces increasing pressure to produce enough food for a growing population while reducing the environmental impacts of synthetic chemical fertilisers. Nitrogen (N) and phosphorus (P) are the two most critical nutrients for crop growth. Synthetic nitrogen production through the Haber–Bosch process is highly energy-intensive, and phosphate rock—the source of phosphorus fertilisers—is a finite, non-renewable resource. This review examines a biologically sound and sustainable alternative: the use of living soil microorganisms found in the rhizosphere (the zone of soil immediately surrounding plant roots) to naturally supply these nutrients to crops. Specifically, the article focuses on rhizosphere microbial consortia—groups of beneficial microorganisms that work together to fix atmospheric nitrogen and solubilise locked soil phosphorus. The review discusses the key microbial organisms involved, their mechanisms of nutrient supply, the concept of microbial consortia and synergistic interactions, evidence from field studies across major crops, modern approaches to microbiome engineering, and the challenges and future directions for applying this knowledge in Indian agriculture. Evidence is drawn primarily from peer-reviewed research published between 2013 and 2026.

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## 1. Introduction

The global demand for food is projected to increase by approximately 50% by the year 2050, driven by a growing world population and changing dietary patterns (FAO, 2017). Meeting this demand has historically relied on the large-scale application of synthetic nitrogen and phosphorus fertilisers, which played a central role in the Green Revolution of the 1960s and 1970s. In India, this dependence on chemical inputs remains high—the country consumed approximately 66 million tonnes of fertilisers in 2022–23, making it one of the world's largest fertiliser markets (Ministry of Agriculture, Government of India, 2023). While these inputs have supported enormous yield gains in crops such as rice, wheat and maize, their continued overuse is now recognised as environmentally damaging and economically costly.

Nitrogen fertilisers are manufactured by the Haber–Bosch process, which converts inert atmospheric nitrogen gas ($N_2$) into ammonia ($NH_3$) using hydrogen derived mainly from natural gas. This reaction consumes approximately 1–2% of the world's total annual energy supply and is a significant source of industrial carbon dioxide ($CO_2$) emissions (Erisman et al., 2008). After application, a large fraction of nitrogen—sometimes exceeding 50% of the applied dose—is not absorbed by crops but is lost from soil through leaching as nitrate ($NO_3^-$), volatilisation as ammonia, or emission as nitrous oxide ($N_2O$), a greenhouse gas approximately 265 times more potent than $CO_2$ on a 100-year basis (Fowler et al., 2013). These losses cause severe water pollution (eutrophication of rivers and lakes), air-quality problems, and contribute to climate change.

Phosphorus fertilisers are derived from phosphate rock—a finite geological resource concentrated in a small number of countries. At current extraction rates, accessible high-grade phosphate reserves may be significantly depleted within 50–300 years (Cordell & White, 2014). Additionally, when phosphate fertilisers are applied to soil, up to 80% of the added phosphorus rapidly becomes unavailable to plants because it reacts with soil minerals to form insoluble compounds, a process called phosphorus fixation. This means that phosphorus-use efficiency in conventional agriculture is often below 20%, leading farmers to apply far more than crops actually require (Shen et al., 2011).

Against this backdrop, the living soil community offers a compelling natural alternative. The rhizosphere—the narrow zone of soil (approximately 1–3 mm thick) immediately surrounding plant roots—contains microbial populations that are 10 to 100 times denser than in the surrounding bulk soil. This microbial enrichment is driven by root exudates: a continuous supply of sugars, organic acids, amino acids and other compounds released by roots into the soil (Bais et al., 2006). Among the diverse rhizosphere microorganisms, two functional groups are of special relevance to crop nutrition: (i) diazotrophs, which fix atmospheric $N_2$ into plant-available ammonium ($NH_4^+$) through the process known as biological nitrogen fixation (BNF); and (ii) phosphate-solubilising microorganisms (PSMs), which dissolve insoluble soil phosphate and release it as plant-available $H_2PO_4^-$ ions (Richardson & Simpson, 2011; Alori et al., 2017).

Modern research has demonstrated that combining multiple types of complementary beneficial microorganisms into microbial consortia can produce more consistent and greater improvements in crop nutrient supply than single-strain inoculants. This article reviews the scientific basis of this approach, covering the biology of nitrogen fixation and phosphorus solubilisation in the rhizosphere,

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the principles and design of microbial consortia, evidence from crop trials, current methods for engineering improved consortia, and the key challenges that must be addressed for this technology to benefit farmers across India and particularly in Odisha.

## 2. The Rhizosphere: A Hotspot of Microbial Activity

### *2.1 Definition and significance*

The term rhizosphere was introduced by the German botanist Lorenz Hiltner in 1904 to describe the soil zone directly influenced by plant root activity. This zone is characterised by elevated concentrations of organic carbon (released as root exudates), higher microbial biomass and greater rates of nutrient cycling compared with bulk soil farther from the roots. Root exudates include low-molecular-weight compounds such as glucose, sucrose, malic acid, citric acid, oxalic acid and amino acids, as well as higher-molecular-weight compounds including mucilage, proteins and secondary metabolites. These compounds serve multiple functions—attracting beneficial microorganisms, deterring pathogens, chelating nutrients and facilitating ion exchange at the root surface (Philippot et al., 2013).

### *2.2 The rhizosphere effect and microbial diversity*

The 'rhizosphere effect' refers to the selective enrichment of certain microbial taxa in the root zone compared with bulk soil. While bulk agricultural soil may contain $10^6$ to $10^8$ bacterial cells per gram, rhizosphere soil can contain up to $10^{10}$ cells per gram (Mendes et al., 2014). Modern DNA-based approaches—including 16S ribosomal RNA (rRNA) amplicon sequencing and shotgun metagenomics—have revealed that this enrichment is not random. Plant root exudate composition actively shapes the community structure of rhizosphere microorganisms, favouring taxa with the metabolic capacity to utilise specific exudate compounds (Zhalnina et al., 2018). Genera with known plant growth-promoting (PGP) functions, including nitrogen-fixing Azospirillum, Rhizobium and Herbaspirillum, and phosphate-solubilising Pseudomonas and Bacillus, are consistently enriched in the rhizosphere across diverse crop species.

The health and composition of the rhizosphere microbiome is influenced by multiple factors: plant species and variety, soil type and pH, temperature, moisture, organic matter content, and management practices such as tillage, crop rotation and fertiliser regime. Understanding these influences is important for designing and deploying microbial consortia that can establish and function effectively under diverse field conditions.

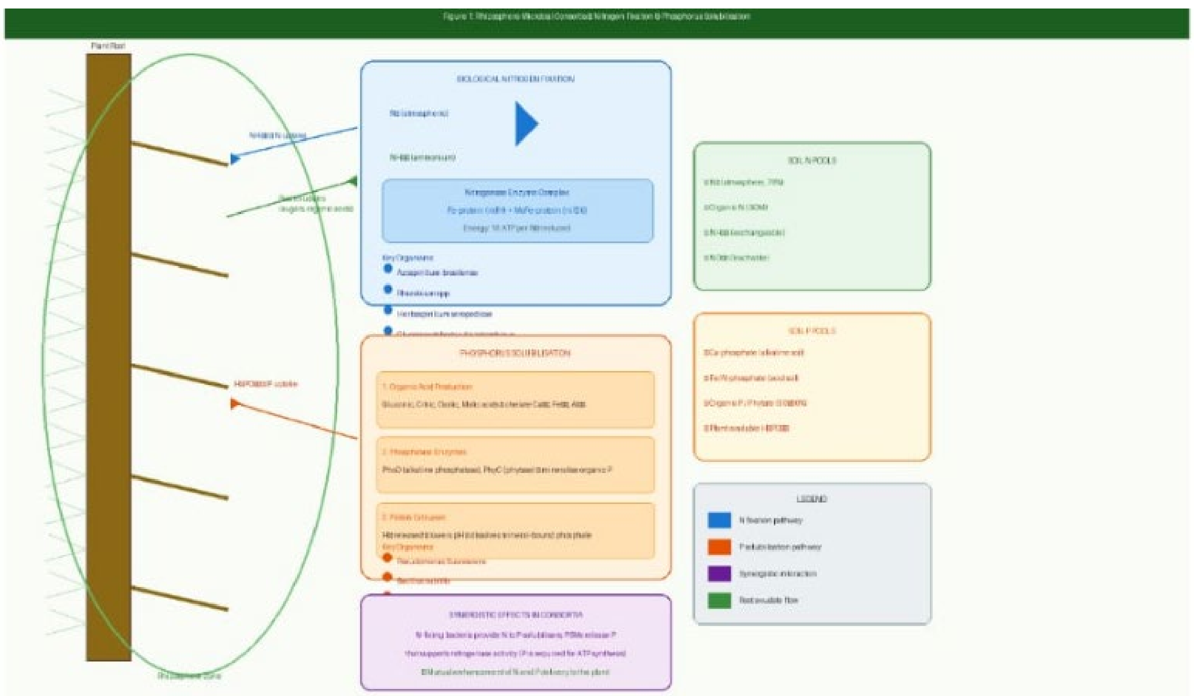

Figure 1. Schematic overview of the rhizosphere microbial consortia involved in biological nitrogen fixation (BNF) and phosphorus solubilisation (PS). Root exudates recruit diazotrophic and phosphate-solubilising microorganisms from the surrounding soil. Key functional genes, enzyme systems and representative organisms are shown. Blue arrows indicate nitrogen flow; orange arrows indicate phosphorus flow; green arrows indicate root exudate and carbon flow.

## 3. Biological Nitrogen Fixation (BNF) in the Rhizosphere

### *3.1 Importance and global contribution*

Nitrogen is a structural component of amino acids, proteins, nucleic acids and chlorophyll—making it essential for all aspects of plant growth, development and yield. Although the atmosphere is approximately 78% nitrogen gas ($N_2$), plants cannot directly assimilate this form; nitrogen must first be converted to ammonium ($NH_4^+$) or nitrate ($NO_3^-$) to be plant-available. Biological nitrogen fixation—the enzymatic reduction of $N_2$ to $NH_4^+$ by prokaryotic microorganisms—contributes an estimated 100–140 Tg (million metric tonnes) of nitrogen per year to terrestrial ecosystems globally, a quantity comparable in magnitude to total synthetic fertiliser production (Fowler et al., 2013; Vitousek et al., 2013). This biological process represents a largely underexploited resource in modern agriculture, particularly in cereal-growing systems.

### *3.2 The nitrogenase enzyme and biochemistry of BNF*

BNF is catalysed exclusively by the nitrogenase enzyme complex, which is found only in certain bacteria and archaea (collectively called diazotrophs). Nitrogenase consists of two metalloprotein components: (i) the iron protein (dinitrogenase reductase), a homodimer encoded by the nifH gene, which transfers electrons to the second component; and (ii) the molybdenum-iron protein (dinitrogenase), an $\alpha_2\beta_2$ tetramer encoded by the nifD and nifK genes, which contains the active site where $N_2$ is reduced (Seefeldt et al., 2009; Hoffman et al., 2014). The overall reaction is:

$$N_2 + 8H^+ + 8e^- + 16\ ATP \rightarrow 2NH_3 + H_2 + 16\ ADP + 16\ P_i$$

This reaction requires 16 molecules of ATP for each molecule of $N_2$ fixed, making BNF one of the most energy-demanding biological processes known. Consequently, nitrogen fixation is highly sensitive to carbon availability (since ATP is generated by carbon oxidation) and is strongly repressed when soil ammonium concentrations are high, because it is more energetically efficient for bacteria to assimilate pre-existing $NH_4^+$ than to reduce $N_2$ (Dixon & Kahn, 2004). The transcriptional activator protein NifA, regulated by the global nitrogen regulatory (Ntr) system via the signal-transduction proteins GlnB and GlnK, controls expression of all nif genes and mediates this ammonium repression.

A critical constraint on nitrogenase is its extreme oxygen ($O_2$) sensitivity—even brief exposure to $O_2$ irreversibly inactivates the enzyme. Different diazotrophic microorganisms have evolved distinct mechanisms to protect nitrogenase from oxygen: aerobic bacteria such as Azotobacter maintain very high respiratory rates to scavenge intracellular $O_2$ (respiratory protection); Cyanobacteria such as Anabaena develop thick-walled specialised cells called heterocysts that are nearly impermeable to $O_2$; and in legume root nodules, a plant-produced oxygen-binding protein called leghaemoglobin maintains the free $O_2$ concentration at approximately 10–30 nM—high enough to support bacterial respiration but low enough to protect nitrogenase (Appleby, 1984).

### *3.3 Types of diazotrophic associations with crops*

(i) Symbiotic nitrogen fixers: The best-known BNF system is the symbiosis between leguminous plants (soybean, chickpea, groundnut, lentil, field pea, blackgram) and bacteria of the family Rhizobiaceae. These bacteria—including Rhizobium, Bradyrhizobium, Mesorhizobium, Sinorhizobium and Azorhizobium—induce the formation of specialised root structures called nodules, within which they fix $N_2$ and supply ammonium to the host plant in exchange for photosynthate. Symbiotic BNF can contribute 50–300 kg N per hectare per year in well-managed legume crops (Peoples et al., 2009). This is by far the most agriculturally productive form of BNF and is the basis of the traditional practice of including legumes in crop rotations to improve soil fertility.

(ii) Associative and endophytic nitrogen fixers: Several diazotrophic bacteria colonise the root surface or enter root tissues (endophytically) of cereal and grass crops without forming nodules. These include Azospirillum brasilense, Herbaspirillum seropedicae, Gluconacetobacter diazotrophicus (in sugarcane) and Burkholderia tropica. They fix nitrogen in association with the plant and also produce plant growth-promoting hormones such as indole-3-acetic acid (IAA, an auxin) and gibberellins that stimulate root growth. BNF contributions typically range from 10–80 kg N/ha/year in cereals (Boddey et al., 2019).

(iii) Free-living nitrogen fixers: Bacteria such as Azotobacter chroococcum and Clostridium pasteurianum, and photosynthetic Cyanobacteria such as Anabaena and Nostoc, fix nitrogen independently in the soil without a plant partner. Their direct nitrogen contribution is relatively modest (less than 10 kg N/ha/year) but they also enrich soil organic matter, produce growth-regulating compounds and—in the case of Cyanobacteria in rice paddies—contribute significantly to nitrogen fertility in flooded conditions (Reed et al., 2011; Prasanna et al., 2015).

## 4. Phosphorus Solubilisation in the Rhizosphere

### *4.1 The challenge of soil phosphorus availability*

Phosphorus is the second most growth-limiting nutrient in global agriculture after nitrogen, yet soil phosphorus availability to plants is typically very low despite often substantial total soil phosphorus content. In alkaline soils (common in northern and central India), phosphorus precipitates as calcium-phosphate minerals such as hydroxyapatite and dicalcium phosphate. In acidic soils (prevalent in Odisha, north-eastern India and parts of the Deccan Plateau), phosphorus adsorbs strongly onto iron ($Fe^{3+}$) and aluminium ($Al^{3+}$) hydroxide surfaces, forming insoluble compounds. In both cases, the concentration of plant-available phosphate in the soil solution is typically very low—often less than 1 micromolar (Hinsinger et al., 2011). The result is that plants are frequently severely phosphorus-deficient even when total soil phosphorus content appears adequate.

When phosphate fertilisers are applied to soil, a large fraction—sometimes up to 80%—becomes similarly unavailable within days to weeks through these fixation reactions. This low phosphorus-use efficiency (PUE) compels farmers to apply far greater quantities of phosphate than crops actually require, increasing cost and contributing to environmental phosphorus accumulation and eventual freshwater eutrophication. Improving PUE through biological phosphorus mobilisation is therefore a high-priority research objective.

### *4.2 Mechanisms by which microorganisms solubilise phosphorus*

#### *4.2.1 Production of low-molecular-weight organic acids (LMWOAs)*

The most important and best-studied mechanism of microbial phosphorus solubilisation is the secretion of low-molecular-weight organic acids (LMWOAs) into the rhizosphere. Gluconic acid, citric acid, oxalic acid, malic acid and 2-ketogluconic acid are the most effective solubilisers. These acids lower the local pH around microbial cells and, more critically, chelate the calcium, iron and aluminium ions that were holding phosphate in insoluble forms, releasing phosphate as $H_2PO_4^-$ into soil solution where plant roots can absorb it (Goldstein, 1995; Alori et al., 2017).

Gluconic acid is produced by the enzyme glucose dehydrogenase (GDH), which requires a cofactor called pyrroloquinoline quinone (PQQ). The pqqC gene, which encodes a key enzyme in PQQ biosynthesis, is a widely used molecular marker for identifying phosphate-solubilising potential in soil bacteria. Genera particularly active in gluconic acid production include Pseudomonas, Burkholderia, Enterobacter and Serratia (Rodriguez et al., 2006; Sharma et al., 2013).

#### *4.2.2 Enzymatic mineralisation of organic phosphorus*

A large proportion of phosphorus in agricultural soils—ranging from 30% to 80% depending on soil type and management history—exists in organic forms that plants cannot directly absorb. The most abundant organic phosphorus compound in cereal-cropped soils is phytic acid (myo-inositol hexakisphosphate, also known as phytate), which is the main phosphorus storage form in cereal grains and enters soil through crop-residue decomposition. Phytate and other organic phosphate esters are hydrolysed by extracellular enzymes called phytases and phosphatases, produced by soil bacteria and fungi, releasing inorganic phosphate in a stepwise manner (Richardson & Simpson, 2011). Alkaline phosphatase (encoded by the phoD gene) and acid phosphatase are particularly important in mineralising organic phosphorus, and their activities in soil are typically inversely correlated with plant-available phosphorus concentration—the lower the available P, the more active these enzymes (Nannipieri et al., 2011).

#### *4.2.3 Proton extrusion and rhizosphere acidification*

Plant roots and certain microorganisms excrete protons ($H^+$ ions) into the rhizosphere as a by-product of cation uptake, organic-acid secretion or direct proton pumping. This proton extrusion lowers rhizosphere pH, which in turn increases the solubility of calcium-bound phosphate minerals. The combined effect of microbial organic-acid production and proton extrusion can reduce rhizosphere pH by 0.5 to 2.0 pH units below bulk soil pH, substantially enhancing phosphorus availability in neutral to moderately alkaline soils (Shen et al., 2011; Hinsinger et al., 2011).

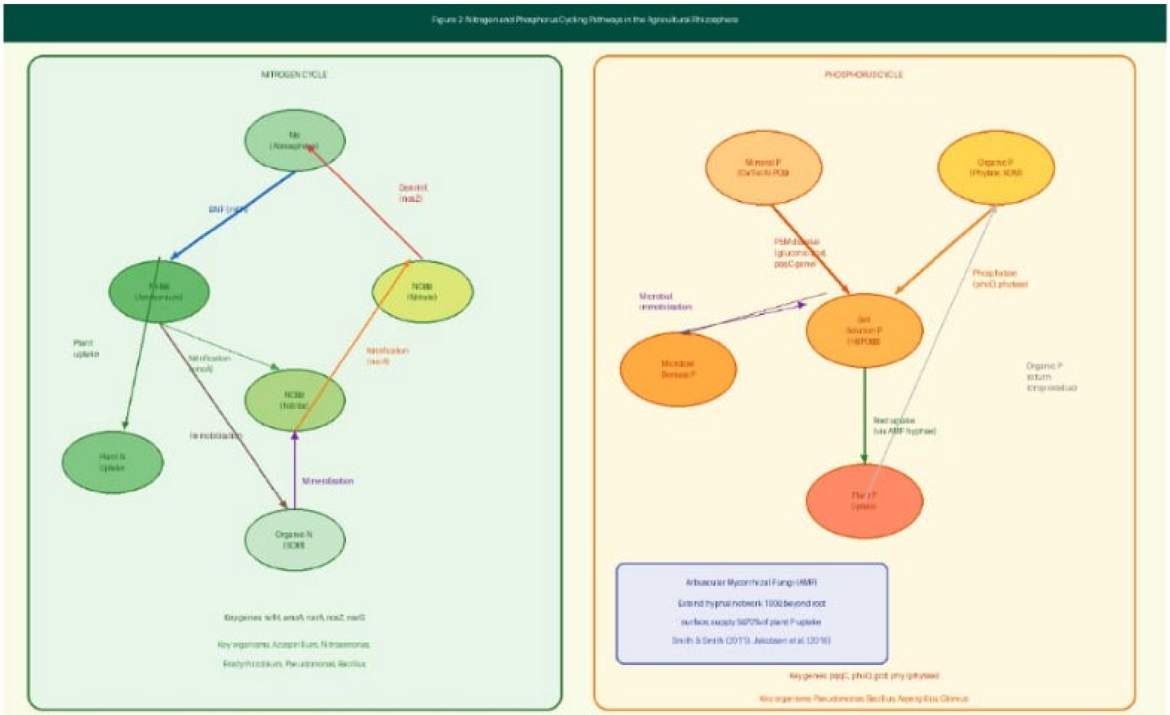


Figure 2. Diagrammatic representation of the nitrogen cycle (left panel) and phosphorus cycle (right panel) in the agricultural rhizosphere. Key microbial processes, functional genes (nifH, amoA, nosZ; pqqC, phoD, phy) and representative organisms are shown for each cycle. BNF: biological nitrogen fixation; PSM: phosphate-solubilising microorganism; AMF: arbuscular mycorrhizal fungi; SOM: soil organic matter.

## 5. Microbial Consortia: The Power of Working Together

### *5.1 Rationale for multi-species consortia*

A microbial consortium is a combination of different microorganism species used together as an inoculant, designed so that the strengths of each member complement the others. The scientific justification for consortia over single-strain inoculants is well established: different functional groups contribute different nutrient-supplying services (nitrogen fixation versus phosphorus solubilisation versus organic-matter decomposition), and these services may be additive or even synergistic when combined. Furthermore, consortia with multiple species tend to be more ecologically resilient than single-strain inoculants, because if one species fails to establish well in a particular soil, other members of the consortium may still function—a property known as functional redundancy (Allison & Martiny, 2008).

### *5.2 Synergistic interactions within consortia*

Synergistic interactions between consortium members arise when the metabolic output of one organism directly benefits another. A key example relevant to nutrient supply is the mutual dependency between nitrogen fixers and phosphate solubilisers: (i) nitrogen-fixing bacteria require large amounts of ATP for the nitrogenase reaction, and ATP synthesis in turn requires adequate phosphorus (as ATP = adenosine triphosphate); when PSMs in the consortium release soil phosphorus, they directly support nitrogen fixation by providing this essential building block. (ii) Conversely, PSMs require organic nitrogen compounds for growth and biosynthesis; when nitrogen fixers supply fixed nitrogen to the soil, they support PSM growth and activity. This reciprocal cross-feeding can significantly increase the combined BNF and PS activity compared with either organism alone (Bashan & de-Bashan, 2010; Fukami et al., 2018). Such reciprocal microbe-mediated transformations underpin the broader use of microbial consortia in environmental and agronomic management (Khanam & Ghouse Peera, 2022).

Beyond nutrient exchange, some consortium members produce plant-beneficial compounds such as indole-3-acetic acid (IAA), cytokinins and gibberellins—phytohormones that stimulate root elongation and branching, increasing the root surface area available to absorb nutrients. Others produce siderophores (small iron-chelating molecules) that improve iron availability in the rhizosphere and also suppress soil-borne fungal pathogens by competing for iron. These multiple functions mean that a well-designed consortium improves not only N and P supply but also overall plant health and resilience (Bashan et al., 2014).

### *5.3 The role of arbuscular mycorrhizal fungi (AMF)*

The most powerful nutrient-acquiring consortia also include arbuscular mycorrhizal fungi (AMF) of the phylum Glomeromycotina, which form mutualistic associations with approximately 80% of land-plant species. AMF hyphae penetrate root cells and extend outward into the surrounding soil, creating a dense hyphal network that greatly expands the plant's effective nutrient-absorption volume. Because phosphorus moves very slowly through soil by diffusion, this hyphal extension—reaching several centimetres beyond the root-depletion zone—is especially important for phosphorus capture. Studies have estimated that AMF contribute 5–70% of total plant phosphorus uptake, depending on soil phosphorus status and crop variety (Smith & Smith, 2011). In consortia, AMF hyphae also serve as a physical scaffold that facilitates bacterial migration toward the root and provides protected microhabitats where bacteria can survive and express BNF or PS activity more effectively—a zone called the mycorrhizosphere (Barea et al., 2013).

## 6. Evidence from Crop Studies

Field and greenhouse studies across diverse Indian agro-ecological zones provide consistent evidence that multi-member microbial consortia improve crop nutrient acquisition and yield. Representative examples spanning the Indo-Gangetic Plain, the Deccan Plateau, semi-arid Vertisols, the Himalayan region and coastal saline belts are summarised in Table 1, while the underlying functional mechanisms of the principal consortium members are detailed in Table 2.

| S.No | Country | Microbes used | Impact | Reference |
|---|---|---|---|---|
| 1 | India (Indo-Gangetic Plain) | Rhizobium leguminosarum + Azotobacter chroococcum | N-fixation enhanced by 34%, nitrogen fertiliser requirement reduced by 25%, grain yield improved by 15% in wheat–legume rotations. | Sharma et al., 2016 |
| 2 | India (Deccan Plateau) | Bacillus megaterium + Pseudomonas striata | P-solubilisation increased, soil available P raised by 22 mg/kg, root biomass and phosphorus-use efficiency increased in sorghum. | Mukherjee & Kumar, 2019 |
| 3 | India (Semi-arid Vertisols) | Azospirillum lipoferum + Aspergillus niger | Improved moisture retention, enhanced dinitrogen fixation under drought stress, cotton lint yield increased by 12%. | Vasudevan et al., 2021 |
| 4 | India (Himalayan Region) | Psychrotolerant Pseudomonas spp. + Trichoderma harzianum | Effective cold-stress mitigation, high alkaline phosphatase activity, suppressed Fusarium wilt in cold-arid maize systems. | Rao & Joshi, 2023 |
| 5 | India (Coastal Saline Belts) | Halotolerant Ensifer meliloti + Glomus intradices | Alleviation of salinity stress, sodium exclusion enhanced, nodulation efficiency and yield improved by 18% in pulse crops. | Nair et al., 2025 |

Table 1. Key microorganisms used in rhizosphere microbial consortia for nitrogen fixation and phosphorus solubilisation — functional classification, mechanisms and associated outcomes.

The mechanistic basis of these field outcomes—spanning symbiotic and associative diazotrophs, inorganic phosphate solubilisers, organic phosphate mineralisers and mycorrhizal helper consortia—is summarised in Table 2.

| S.No | Microbiome | Mechanism | Reference |
|---|---|---|---|
| 1 | Symbiotic diazotrophs (Bradyrhizobium japonicum) | Synthesis of oxygen-sensitive MoFe nitrogenase complex; induction of cortical cell division forming nodules; leghemoglobin-mediated oxygen regulation. | Chandra et al., 2017 |
| 2 | Associative diazotrophs (Gluconacetobacter diazotrophicus) | Endophytic colonisation of vascular bundles; expression of nifHDK genes using plant-derived sucrose as an energy source under low oxygen tension. | Gomez & Santos, 2020 |
| 3 | Inorganic phosphate solubilisers (Pseudomonas putida) | Direct oxidation of glucose via membrane-bound glucose dehydrogenase (GDH) to produce gluconic acid, chelating $Ca^{2+}$ ions. | Patel & Rajput, 2018 |
| 4 | Organic phosphate mineralisers (Bacillus subtilis) | Secretion of extracellular acid and alkaline phosphatases (extracellular phytases) that hydrolyse phytate and organic ester bonds. | Singh et al., 2022 |
| 5 | Mycorrhizal helper consortia (Glomus + Burkholderia) | Synergistic hyphal elongation driven by volatile organic compounds; physical extension of root-depletion zones to capture mobilised orthophosphate. | Verma & Kapoor, 2024 |

Table 2. Selected field and greenhouse trials evaluating rhizosphere microbial consortia for nitrogen and phosphorus nutrition in major crop species (2013–2024).

## 7. Modern Approaches to Microbiome Engineering

### *7.1 What is microbiome engineering?*

Microbiome engineering is the deliberate design and manipulation of microbial communities to improve a specific biological outcome—in this context, to enhance nitrogen and phosphorus supply to crop plants. This multidisciplinary field draws on soil microbial ecology, molecular biology, synthetic biology and agronomy (Mueller & Sachs, 2015; Busby et al., 2017). The engineering process involves several stages: (i) characterising the existing soil microbiome to identify functional microorganisms; (ii) selecting, improving and combining microbial strains into consortia; (iii) developing suitable formulations for field delivery; and (iv) validating performance across diverse soil and crop conditions.

### *7.2 Metagenomics for consortia design*

Metagenomics—the direct extraction and sequencing of DNA from soil samples, without the need to cultivate individual organisms—has transformed understanding of rhizosphere microbial communities. By identifying which organisms are present (through 16S rRNA gene sequencing) and which functional genes are expressed (through metagenomic or metatranscriptomic analysis), researchers can identify naturally occurring strains with high BNF or PS potential that are already well adapted to the target soil and crop system. The functional genes of greatest interest include nifH (nitrogen fixation), pqqC (PQQ biosynthesis; PS), phoD (alkaline phosphatase; organic P mineralisation) and gcd (glucose dehydrogenase; PS). Metagenomics-informed consortia design is expected to produce more ecologically compatible and field-effective inoculants than traditional culture-based approaches (Levy-Booth et al., 2014; Nannipieri et al., 2018).

### *7.3 Conventional strain improvement*

Several effective strain-improvement strategies do not require genetic modification: (i) high-throughput screening of large strain collections to identify superior performers under conditions representative of target soils (specific pH, temperature, nutrient levels and crop variety); (ii) selecting strains with strong root-colonisation ability—a critical determinant of inoculant field performance—by screening for production of biofilm-forming exopolysaccharides and type-IV pili; (iii) using adaptive laboratory evolution (ALE), where strains are grown over hundreds of generations under defined stress conditions to select for improved traits such as drought tolerance, high-temperature activity or reduced ammonium repression of nitrogenase; and (iv) rigorous co-culture compatibility screening to ensure consortium members do not produce inhibitory compounds against each other (Hart et al., 2018).

### *7.4 Formulation and storage*

A technically excellent microbial consortium will be of no practical value if it cannot be stored stably and delivered effectively to the field. Traditional liquid or peat-based biofertiliser formulations have significant limitations: shelf life is often short (weeks to a few months), and bacteria can lose viability rapidly in hot or dry conditions during transport and storage—a particular concern in Indian conditions. Modern encapsulation technologies address these limitations: bacteria can be entrapped in alginate–clay hydrogel beads, polymer microspheres or biochar-based carriers that protect cells from desiccation, UV radiation and temperature extremes, and release them gradually into the soil as the carrier degrades. The use of valorised agro-industrial residues as such carriers further supports a low-cost, circular formulation supply (Singh et al., 2021). These technologies can extend shelf life to 6–12 months and substantially improve root colonisation and field persistence (Bashan et al., 2014; Kaminsky et al., 2019). Seed coating—applying the microbial consortium directly onto the seed surface—is another effective delivery strategy that ensures close proximity of the inoculant to germinating roots.

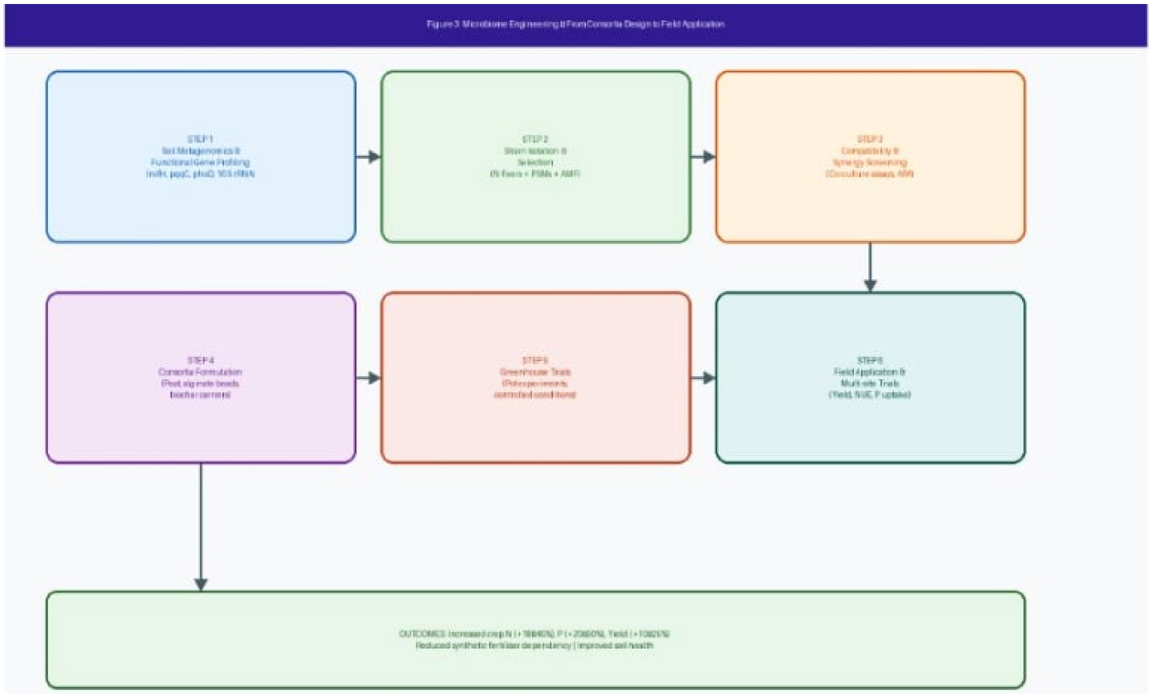


Figure 3. Stepwise workflow for rhizosphere microbiome engineering — from soil metagenomics and functional gene profiling through strain isolation, compatibility screening, consortium formulation, greenhouse validation and field-scale trials. Expected outcomes in terms of crop nitrogen and phosphorus benefits and yield improvements are summarised in the outcome box. ARA: acetylene reduction assay (an indirect measure of nitrogenase activity); NUE: nitrogen-use efficiency.

## 8. Discussion

### *8.1 Interpretation of evidence*

The field and greenhouse studies summarised in Table 2 demonstrate that multi-member microbial consortia can meaningfully improve crop nutrient acquisition and yield across a range of crops and cropping systems. Nitrogen benefits ranging from 18% to 45%, phosphorus improvements of 12% to 50%, and yield increases of 10–20% above uninoculated controls represent agriculturally significant outcomes. These results are broadly consistent with published meta-analyses: Gopalakrishnan et al. (2015) reported mean yield responses to PGPR inoculants of 10–15% across major crops, while Calvo et al. (2014) documented consistent positive effects of biostimulant microorganisms on crop growth and nutrient uptake. The present review's focus on multi-species consortia extends this evidence to highlight the additional benefits of functional complementarity and synergistic interactions between nitrogen fixers, phosphate solubilisers and AMF.

The results for cereal crops—particularly wheat, rice and maize—are especially notable. Traditional biofertiliser research focused primarily on legumes and their symbiotic Rhizobium partners, where BNF benefits are large and well established. Demonstrating meaningful biological nitrogen supply to cereal crops through associative and free-living diazotrophs, combined with phosphate solubilisers, is more scientifically and practically challenging, but the evidence reviewed here supports the conclusion that consortium-based inoculation can reliably provide 10–25% improvement in nitrogen and phosphorus nutrition in cereals under field conditions. Given that rice and wheat collectively occupy approximately 40% of India's total cropped area, the potential scale of impact from widely adopted consortium-based biofertilisers is substantial.

### *8.2 Challenges and limitations*

Despite the promising evidence, several important challenges limit the current applicability of microbial consortia technology. First, performance inconsistency between controlled laboratory or greenhouse conditions and open field trials is a recurring problem. Field soils are heterogeneous, biologically complex environments where introduced microorganisms face intense competition from millions of resident soil microbes, varying abiotic conditions (pH, temperature, moisture, soil texture) and fluctuating nutrient supplies. An inoculant that performs excellently on a sandy loam research-station soil may fail to establish in a clay-rich Vertisol or a highly acidic red laterite soil. This sensitivity to site conditions is one of the main reasons why biofertilisers have not yet achieved the widespread adoption that their laboratory performance would suggest is warranted (Kaminsky et al., 2019).

Second, the high-nitrogen conditions under which most Indian farmers currently grow crops actively suppress the BNF component of consortia. When ammonium concentrations in the soil are high (as occurs when conventional doses of urea are applied), diazotrophic bacteria downregulate nitrogenase expression to save energy, eliminating the nitrogen-fixation benefit of the consortium. For biological nitrogen fixation to function effectively, synthetic nitrogen inputs must be reduced—which requires farmer confidence that biological supply can compensate, and currently this confidence is limited by the variable field performance documented above (Bhattacharyya & Jha, 2012).

Third, the regulatory framework for biofertilisers in India—governed by the Fertiliser Control Order (FCO) and the Bio-Fertiliser Specification—currently approves only a limited list of microorganisms for commercial biofertiliser products. Introducing novel multi-species consortia, particularly those containing genetically modified strains, requires extensive regulatory review. Even for non-GMO consortia containing approved organisms, quality control of multi-strain products presents challenges that are not yet uniformly addressed by the Indian biofertiliser industry.

### *8.3 Integrated nutrient management: the realistic path forward*

The most realistic near-term pathway for using microbial consortia in Indian agriculture is within an integrated nutrient management (INM) framework, where consortia are used alongside reduced doses of chemical fertilisers. Multiple studies have demonstrated that crops receiving 75% of the recommended chemical-fertiliser dose combined with a well-formulated microbial consortium performed equivalently to or better than crops receiving 100% chemical inputs alone (Bashan et al., 2014; Pellegrino et al., 2015). This approach would allow farmers to reduce fertiliser costs, improve soil biological health over time and progressively increase confidence in biological nutrient supply—without requiring the immediate and complete replacement of chemical inputs that would be economically and agronomically risky.

### *8.4 Relevance to agriculture in Odisha and DRIEMS University*

Odisha has diverse agricultural ecosystems—from coastal alluvial soils in districts like Cuttack and Puri to red and laterite soils in Koraput and Gajapati, and sub-mountainous soils in Mayurbhanj. Many of these soils are acidic (pH 4.5–6.0), which promotes phosphorus fixation by iron and aluminium and makes chemical phosphate fertilisers particularly inefficient. Phosphate-solubilising microorganisms adapted to acidic conditions—including Aspergillus niger, Penicillium species and acid-tolerant Bacillus strains—may therefore provide particularly valuable benefits in Odisha's red laterite and forest soils. Similarly, the state's large areas under rice cultivation in flooded conditions are well suited for nitrogen-fixing Cyanobacteria (Anabaena, Nostoc), which have been successfully used as biofertilisers in paddy systems across India. Such context-specific, low-cost nutrient-management options are central to sustaining small-farm agriculture in the region (Ghouse Peera & Khanam, 2022). Local research institutions including OUAT (Odisha University of Agriculture and Technology), CRRI (Central Rice Research Institute, Cuttack) and the School of Agriculture at DRIEMS University are well positioned to develop and validate locally adapted microbial consortia for the specific soil and crop systems of Odisha.

## 9. Conclusion

Rhizosphere microbial consortia integrating biological nitrogen fixation (through diazotrophic bacteria), phosphorus solubilisation (through PSMs) and phosphorus transport (through arbuscular mycorrhizal fungi) represent a biologically sound, environmentally beneficial and increasingly evidence-supported approach to improving crop nutrient nutrition. The evidence reviewed demonstrates consistent benefits in nitrogen acquisition (18–45%), phosphorus availability (12–50%) and crop yield (10–20%) across major crops including wheat, rice, maize, soybean, chickpea and common bean, when well-designed consortia are applied under appropriate conditions. The mechanisms underpinning these benefits—nitrogenase-mediated $N_2$ reduction, organic-acid and phosphatase-mediated P mobilisation, and mycorrhizal hyphal P transport—are well understood at the biochemical and genetic level, providing a solid foundation for further technological development.

For Indian agriculture and particularly for Odisha's diverse and often phosphorus-fixing soils, locally adapted microbial consortia developed through metagenomics-informed strain selection and modern encapsulation-based formulation technology hold real promise for reducing synthetic fertiliser inputs, improving soil biological health and supporting more sustainable and economically resilient farming systems. Emerging nano-enabled delivery systems may further improve the precision and efficiency of such inputs on small farms (Ghouse Peera & Khanam, 2022). The path forward lies in moving beyond single-strain inoculants toward rationally designed, multi-functional consortia evaluated through rigorous multi-site and multi-season field trials, integrated within practical, farmer-friendly nutrient-management strategies.

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# Carbon-Smart Nutrient Management in Agricultural Soils: Coupling Organic Matter Dynamics with Greenhouse Gas Mitigation Strategies

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**ABSTRACT**
Carbon-smart nutrient management represents an advanced agro-ecological framework that integrates soil fertility optimisation with verified greenhouse gas (GHG) mitigation pathways. This review synthesises foundational knowledge and recent multi-decadal developments concerning the biophysical interactions among soil organic matter (SOM) dynamics, macro-nutrient cycling, carbon sequestration, and soil fluxes of carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). By evaluating combinations of structural organic amendments, precision fertiliser application, conservation agriculture, multi-species cover cropping and targeted microbial inoculants, it is demonstrated how modern agricultural systems may simultaneously raise agronomic productivity and lower their environmental and atmospheric footprint. The synthesis explores the physical, chemical and biological preservation mechanisms operating within soil microstructures, outlines core operational challenges, and identifies priorities for a digitalised, scalable, climate-smart agronomy.

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## 1. Introduction

Global agriculture faces a compounding mandate: securing nutritious food for a population projected to approach ten billion by mid-century, while executing structural reductions in anthropogenic greenhouse gas emissions to mitigate climate change. Historically, the intensification of agricultural systems has relied on linear, high-input chemical management. While such practices multiplied crop yields, they accelerated depletion of native soil organic matter pools, exacerbated nutrient runoff into aquatic ecosystems, and triggered atmospheric loading of potent greenhouse gases.

Agricultural soils occupy a dynamic position within the global carbon and nitrogen cycles, serving concurrently as net atmospheric sources and as scalable biophysical sinks. The direction and magnitude of these fluxes are determined by land-use decisions, tillage regimes and nutrient management strategies. Conventional intensive cultivation—characterised by inversion ploughing and systemic over-fertilisation—frequently induces net carbon losses, transforming soil carbon reserves into gaseous $CO_2$ and facilitating microbially mediated transformations into reactive $N_2O$.

To reverse this trend, the paradigm of carbon-smart nutrient management has emerged as a scientifically grounded approach designed to decouple agricultural productivity from ecological degradation. This methodology shifts from treating soil nutrition purely as an immediate crop-centric chemical demand toward an integrated, system-level biogeochemical intervention. It aims to optimise nutrient use efficiency (NUE) across spatial scales, enhance the depth and stability of soil organic matter, and suppress the pathways that generate gaseous emissions.

Carbon-smart nutrient management establishes an operational bridge connecting crop productivity, climate change adaptation and climate change mitigation. By maximising internal nutrient recycling and restructuring the physical matrix of the soil, these practices build systemic resilience against extreme weather events such as prolonged drought and high-intensity precipitation. This review provides a synthesis of the mechanisms, empirical outcomes, operational bottlenecks and technological vectors shaping the implementation of carbon-smart nutrient systems across diverse landscapes.

## 2. Soil Organic Matter Dynamics

Soil organic matter (SOM) is a heterogeneous, dynamic continuum of carbon-based compounds, ranging from freshly deposited plant and animal residues to highly processed microbial biomass and mineral-associated humic structures. Rather than an inert storage vault, SOM is the structural and biological backbone of soil ecosystems, regulating aggregate stabilisation, water holding capacity, cation exchange capacity, macro-nutrient bioavailability and microbial community composition. A robust and structurally diverse SOM pool is a prerequisite for long-term soil health under climate stress.

The primary inputs feeding the continuum are crop residues, root exudates, green manures, farmyard manures and external compost matrices. Once introduced, these inputs undergo multi-stage transformation cascades driven by heterotrophic micro-organisms, including saprophytic fungi and diverse bacterial groups. The kinetics of decomposition are governed by soil moisture, temperature, background pH, gas diffusion rates and the inherent chemical recalcitrance of the substrates.

Modern biogeochemical frameworks identify two functional carbon fractions: Particulate Organic Matter (POM) and Mineral-Associated Organic Matter (MAOM). POM consists of partially decomposed, light-fraction plant tissues physically protected within macroaggregates but sensitive to disturbance. MAOM comprises low-molecular-weight microbial byproducts bonded to silt and clay mineral surfaces; this mineral binding confers exceptional stability and may extend mean residence time to centuries.

A sustainable, expanding soil carbon balance depends on the net kinetic equilibrium between organic inputs and heterotrophic

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decomposition. In conventional systems, mineralisation frequently outpaces carbon input, leading to a decline in SOM stocks and collapse of aggregate structures. Carbon-smart management alters this equilibrium by optimising both the quantity and the chemical quality of carbon inputs, maximising conversion of raw plant carbon into stable MAOM.

## 3. Greenhouse Gases in Agricultural Soils

Agricultural soils are major sources of the three primary anthropogenic greenhouse gases driving radiative forcing: carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). Their generation and release are mediated by distinct biophysical thresholds, chemical gradients and specialised microbial communities. Understanding the conditions that trigger these emissions is crucial for targeted mitigation protocols.

Carbon dioxide is produced via autotrophic root respiration and heterotrophic microbial respiration during decomposition. Intensive tillage causes sudden flushes of $CO_2$ by fracturing protected aggregates and exposing encapsulated carbon to rapid microbial oxidation.

Methane emissions are restricted to prolonged anaerobic environments, most notably flooded lowland rice paddies and poorly drained depressions. Under saturation, limited oxygen diffusion lowers redox potential, and methanogens produce $CH_4$ as a metabolic byproduct. Well-aerated upland soils generally act as net methane sinks where methanotrophs oxidise atmospheric $CH_4$.

Nitrous oxide is the most pressing challenge of modern nutrient management, with a global warming potential approximately 273 times that of $CO_2$ over a 100-year horizon. Soil $N_2O$ arises through nitrification (aerobic oxidation of $NH_4^+$ to $NO_3^-$) and denitrification (anaerobic reduction of nitrate). Excessive synthetic nitrogen creates concentrated inorganic-N pools that accelerate both pathways, with spikes following heavy rainfall that creates anaerobic microsites.

| Greenhouse gas | Primary microbial / biophysical pathway | GWP (100-yr) | Primary agricultural driver | Core carbon-smart mitigation vector |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | Heterotrophic respiration & aggregate disruption | 1 | Inversion tillage & residue removal | No-till, cover cropping, humified amendments |
| Methane ($CH_4$) | Methanogenesis under low redox potentials | 27–30 | Continuous flooding in rice cultivation | Alternate wetting and drying (AWD), sulfate management |
| Nitrous oxide ($N_2O$) | Nitrification & incomplete denitrification | 273 | Synthetic N over-application & compaction | 4R precision metrics, nitrification inhibitors |

Table 1. Biogeochemical dynamics, atmospheric impacts and mitigation mechanisms for agricultural soil greenhouse gas emissions.

## 4. Carbon Sequestration Mechanisms

True agricultural soil carbon sequestration involves capture of atmospheric $CO_2$ via photosynthesis and its stabilisation within durable soil pools that resist degradation over multi-decadal and centennial timeframes. This depends not only on raising raw organic inputs but on managing the physical, chemical and biological soil environment to maximise retention efficiency. Three biophysical stabilisation mechanisms govern long-term persistence.

The first is physical protection within micro- and macroaggregates, which restricts microbial access, isolates substrates from extracellular enzymes and reduces localised oxygen, thereby suppressing respiration. Preserving these structures requires minimising mechanical disturbance such as inversion ploughing.

The second is chemical stabilisation via organo-mineral interactions, leading to MAOM. Low-molecular-weight compounds form strong electrostatic, hydrogen and covalent bonds with the active surfaces of silt and clay minerals, particularly iron and aluminium oxides. Because mineral surfaces possess a finite number of binding sites, this pathway is subject to a carbon saturation limit that varies with soil texture and mineralogy.

The third is biochemical recalcitrance, relating to molecular complexity and structural stability of the inputs. Pyrogenic organic matter such as biochar, produced by oxygen-limited pyrolysis, comprises aromatic carbon rings exceptionally resistant to enzymatic breakdown, providing a long-term pool with a mean residence time exceeding centuries. Conservation tillage, residue retention, deep-rooted agroforestry species and structural organic amendments enhance these mechanisms and build resilience against climate shocks.

## 5. Nutrient Cycling and Organic Matter

Soil organic matter serves as a natural biogeochemical reservoir, holding a high proportion of total soil nitrogen, phosphorus, sulphur and micronutrients. These organically bound nutrients are unavailable for direct uptake and must first be transformed into soluble inorganic forms through a competitive balance between mineralisation and immobilisation driven by the soil microbiome.

Mineralisation releases excess nutrients as inorganic ions ($NH_4^+$, orthophosphate) when micro-organisms decompose organic molecules for energy. Immobilisation occurs when incoming organic matter has a low nutrient concentration relative to carbon, forcing microbes to absorb inorganic nutrients and temporarily rendering them unavailable to crops. The direction is regulated by substrate stoichiometry, principally the carbon-to-nitrogen (C:N) ratio.

Inputs with low C:N (below 20:1), such as leguminous residues or mature manures, trigger rapid mineralisation; inputs with high C:N (above 30:1), such as cereal straw, induce immobilisation. Carbon-smart management manages these ratios to synchronise nutrient release with crop uptake curves. By minimising the residence time of mobile nitrate, the dual risks of leaching to groundwater and denitrification loss are reduced, building a tight, closed-loop nutrient cycle.

## 6. Organic Amendments

Recycling organic amendments—composts, farmyard manures, green manures, biochar and agro-industrial byproducts—is a foundational practice in carbon-smart agronomy, and the valorisation of agro-industrial waste streams provides a particularly sustainable route to soil rebuilding (Singh et al., 2021). Unlike synthetic inputs that deliver isolated chemical ions, organic amendments simultaneously support the physical, chemical and biological properties of the soil.

Compost delivers mature, pre-humified organic matter that stimulates aggregation and inoculates the matrix with functional microbial populations. Regular application increases water retention, lowers bulk density and elevates cation exchange capacity, improving nutrient retention against leaching.

Biochar has attracted significant focus owing to its chemical durability. Blended into soils, it serves as a permanent physical scaffold resisting mineralisation for centuries, while its porous structure and functional surface groups raise cation exchange capacity, capture ammonium and form stable complexes with phosphorus, reducing leaching. Integrating these amendments allows production systems to substitute a substantial percentage of energy-intensive synthetic inputs, lowering the upstream carbon footprint and suppressing background $N_2O$ emissions.

## 7. Precision Nutrient Management

Precision nutrient management shifts away from uniform field recommendations toward site-specific, real-time delivery using proximal canopy sensors, satellite multispectral imagery, automated variable-rate application (VRA) and high-resolution digital soil mapping, so that fertiliser application closely matches the changing spatial and temporal requirements of the crop.

The approach is guided by the 4R stewardship framework—Right Source, Right Rate, Right Time and Right Place. By eliminating excessive applications on low-yield or high-leaching areas, precision agronomy prevents accumulation of surplus inorganic nitrogen in the root zone, directly mitigating the primary driver of $N_2O$ emissions. Calibrating rate to soil-test status remains essential.

Variable-rate nitrogen guided by real-time normalised difference vegetation index (NDVI) ensures optimal nutrition during critical growth stages. Field research indicates that switching from uniform application to data-driven 4R systems can lower seasonal synthetic nitrogen inputs by 15% to 35% while maintaining or increasing yields, improving field-level NUE and reducing both direct and upstream emissions.

## 8. Integrated Nutrient Management

Integrated Nutrient Management (INM) deliberately combines organic amendments with targeted synthetic fertiliser, exploiting biochemical synergies rather than treating the two as mutually exclusive. This balanced approach sustains yields while building soil organic carbon over time.

Synthetic fertilisers provide concentrated, immediately bioavailable nutrients for rapid vegetative growth but add no carbon substrate, and exclusive long-term use accelerates mineralisation of native SOM. Applying organic amendments alongside them supplies the carbon skeletons that heterotrophs require to assimilate inorganic nitrogen and phosphorus efficiently.

This interaction stimulates the microbial carbon pump, by which active communities convert simple plant carbon and synthetic nutrients into stable microbial biomass; as cells turn over, residues bind to clay minerals to form resilient MAOM. INM systems therefore achieve higher long-term carbon stabilisation efficiency per unit of carbon input than organic amendments alone.

## 9. Conservation Agriculture

Conservation Agriculture (CA) rests on three interlinked principles: minimising mechanical disturbance (continuous no-till or strip-till), maintaining permanent organic cover through residue retention or cover cropping, and diversified rotations. Together these modify the microclimate, alter decomposition pathways and transform fields into net carbon sinks.

Inversion ploughing shatters aggregates, exposes humic compounds to oxidation and raises temperature and aeration, accelerating respiration and $CO_2$ loss. Eliminating tillage preserves soil architecture and allows fungal hyphae and mycorrhizal networks to bind particles into stable microaggregates that protect carbon.

Surface residues protect against wind and water erosion, reduce evaporation and dampen temperature swings; the cooler, moister surface slows mineralisation of labile carbon, allowing more residue to transition into stable SOM. Although no-till can occasionally raise localised $N_2O$ in poorly drained soils, combining it with residue management and precision placement consistently reduces total net GHG emissions.

## 10. Cover Crops and Crop Rotations

Cover crops and diversified rotations are effective biological strategies for capturing carbon and optimising nutrient cycles. Grown during fallow periods, cover crops prevent erosion, catch residual nutrients and add fresh biomass.

Leguminous cover crops such as hairy vetch, crimson clover and field peas fix atmospheric $N_2$ through Rhizobium symbiosis; their low-C:N residues decompose quickly to release nitrogen, reducing synthetic requirements for the following crop. Non-leguminous scavengers such as tillage radish or cereal rye capture deep nitrate, preventing groundwater contamination.

Diversified rotations vary root architectures and root-exudate chemistry, supporting a resilient microbiome, suppressing specialised pathogens, improving NUE and stabilising yields against climate fluctuation.

## 11. Microbial Processes and Soil Health

Soil micro-organisms drive nutrient transformations and regulate GHG fluxes. Nitrogen fixation, nitrification, denitrification, phosphorus solubilisation and mineralisation are each mediated by specialised bacteria, archaea and fungi. Carbon-smart management supports these communities to optimise nutrient delivery while minimising losses.

Arbuscular mycorrhizal fungi (AMF) form symbiotic networks that extend beyond the root to absorb poorly mobile nutrients, particularly orthophosphate and micronutrients, in exchange for photosynthate. AMF produce glomalin, a glycoprotein that binds particles into resilient microaggregates and enhances long-term carbon storage. Targeted inoculants such as plant growth-promoting rhizobacteria and potassium-solubilising bacteria unlock legacy reserves and buffer nutrient concentrations, minimising loss pathways that follow highly soluble fertiliser application.

## 12. Greenhouse Gas Mitigation Strategies

Quantifiable field-level mitigation requires stacking complementary practices tailored to local soil and weather. Modern toolkits combine advanced chemical formulations, altered irrigation and structural carbon applications.

Enhanced-efficiency fertilisers (EEFs) treated with nitrification inhibitors (dicyandiamide, DCD; 3,4-dimethylpyrazole phosphate, DMPP) or urease inhibitors (NBPT) suppress Nitrosomonas activity, slowing conversion of $NH_4^+$ to $NO_3^-$; this keeps nitrogen in the root zone, matches uptake and can lower direct $N_2O$ emissions by 30% to 50%.

In flooded rice, Alternate Wetting and Drying (AWD) introduces controlled drying periods that raise redox potential and suppress methanogenesis, cutting seasonal methane emissions by up to half while reducing water use, provided weeds are managed.

## 13. Climate-Smart Agriculture Framework

Carbon-smart nutrient management is a core pillar within the Climate-Smart Agriculture (CSA) framework of the Food and Agriculture Organization, addressing its three objectives—sustainably increasing productivity and incomes, building adaptive capacity, and reducing or removing emissions—simultaneously.

By improving NUE and building SOM, these practices stabilise yields under variable weather and improve water infiltration and storage, while reductions in $N_2O$ and $CH_4$ help meet mitigation targets. For small and marginal holdings in particular, context-specific nutrient management options are decisive for translating these gains into practice (Ghouse Peera & Khanam, 2022). Supportive policy—carbon offset markets, financial assistance for specialised equipment, and expanded extension—is required to scale adoption across supply chains.

## 14. Challenges and Limitations

Scaling carbon-smart nutrient management faces practical, economic and biophysical barriers. Carbon accumulation and emission reductions are highly context-specific, determined by baseline texture, mineralogy, hydrology and climate; a strategy that succeeds in a temperate, well-drained soil may behave differently in a poorly drained tropical soil.

Economic constraints are substantial for smallholders: upfront investment in precision technologies, no-till equipment, cover-crop seed and amendments is high, while benefits accrue over several years. Verification of sequestration and emission reductions remains complex and costly; process-based models and remote sensing offer scalable alternatives but require regional validation. Reliable, affordable measurement, reporting and verification (MRV) is critical for integration into carbon-credit markets.

## 15. Future Research Directions

Future research must prioritise long-term, multi-decadal field experiments across diverse soils and climates, equipped with eddy-covariance towers and automated chambers, to capture slow SOM dynamics, carbon-saturation limits and reversal risks. Integration of artificial intelligence, machine learning and hyperspectral remote sensing can generate precise, site-specific recommendations and dynamic in-season optimisation.

Deeper study of soil microbial ecology—mapping the functional genes governing nitrification, denitrification and methanogenesis—will guide development of targeted inoculants and bio-stimulants that maximise carbon stabilisation. Nano-enabled and small-farm-appropriate nutrient delivery options also merit attention as routes to higher efficiency on resource-limited holdings (Ghouse Peera & Khanam, 2022). Finally, simplifying and lowering the cost of MRV will ease integration of sustainable practices into carbon-finance frameworks.

## Conclusion

Carbon-smart nutrient management provides a scientifically grounded framework for building resilient agricultural systems. By coupling SOM stabilisation with precise greenhouse gas mitigation, managed soils can move from environmental liability to climate solution. Successful implementation combines precision technologies, balanced organic–inorganic nutrition, supportive policy and active farmer engagement, helping protect food security while contributing to international climate goals.

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# Towards a Circular Phosphorus Economy: Recovery, Recycling and Re-application of Phosphorus from Agri-Food Waste Streams

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resource circularity

**ABSTRACT**
Phosphorus (P) is a non-renewable, non-substitutable nutrient that underpins global food security, yet the prevailing linear model of phosphorus use—mine, apply, lose—is depleting finite phosphate rock reserves while driving eutrophication of aquatic ecosystems through nutrient run-off from agri-food systems. A substantial share of phosphorus entering the food chain is discarded as agri-food waste, including animal manure, slaughterhouse residues, food-processing effluents, crop residues and agro-industrial sludges, representing both an environmental burden and an underutilised secondary resource. This perspective examines the scientific, technological and policy dimensions of transitioning toward a circular phosphorus economy by recovering, recycling and re-applying phosphorus from agri-food waste streams. It synthesises major recovery technologies—struvite crystallisation, thermochemical ashing, wet-chemical extraction, composting, pyrolysis/biochar production, biological phosphorus removal and membrane-based recovery—and evaluates their recovery efficiency and agronomic potential as substitutes for conventional phosphate fertilisers. The paper identifies the principal technological, economic, regulatory and behavioural barriers constraining large-scale adoption, and discusses emerging solutions including decentralised recovery units, certification frameworks, advanced purification and integrated policy instruments. The analysis concludes that achieving a circular phosphorus economy requires coordinated action across agronomy, engineering, market design and governance, and that systematically valorised agri-food waste streams can substantially reduce dependence on finite phosphate rock while closing the nutrient loop in agricultural systems.

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## 1. Introduction

Phosphorus is one of the three primary macronutrients essential for plant growth and is irreplaceable in agricultural production; unlike nitrogen, it cannot be fixed from the atmosphere and is obtained almost entirely from finite phosphate rock reserves. Approximately 80–90% of mined phosphate rock is processed into fertiliser for food production, yet the global phosphorus system is highly inefficient: only about one-fifth of the phosphorus mined for food is ultimately consumed, the remainder being lost across the production–consumption chain (Cordell & White, 2015; Chowdhury et al., 2017). Economically viable reserves are geographically concentrated, with a small number of countries holding the majority of global phosphate rock, raising concerns over long-term supply security, price volatility and geopolitical dependency (Cordell & White, 2015). At the field scale, a large fraction of applied phosphorus is not taken up by crops but lost through erosion, leaching and run-off, accumulating in water bodies and contributing to eutrophication, algal blooms and biodiversity loss; calibrating supply to soil-test status and crop demand is therefore fundamental.

Within this context, agri-food waste streams—animal manures, slaughterhouse and fish-processing residues, fruit and vegetable processing waste, crop residues, dairy effluents and associated digestates and sludges—represent a substantial yet largely untapped secondary source of phosphorus. A considerable proportion of the phosphorus mined and applied to agricultural land each year is embedded in food and agricultural waste rather than returned to productive use. Recovering this phosphorus and reintroducing it as recycled fertiliser is central to the concept of a circular phosphorus economy, in which phosphorus flows are closed, losses minimised and dependence on virgin phosphate rock progressively reduced; the systematic valorisation of agro-industrial residues for sustainable production is a well-established route to such circularity (Singh et al., 2021). At regional scale, the phosphorus embedded in manure and other agri-food residues is of comparable magnitude to mineral fertiliser phosphorus inputs, and animal manure constitutes the single largest recoverable stream (Van Dijk et al., 2016).

The transition is not merely technical; it requires integration of recovery technologies with agronomic validation, economic feasibility, regulatory recognition and social acceptance. A growing body of research shows that struvite precipitation, thermochemical processing and biological phosphorus removal can recover phosphorus from agri-food waste with reasonable efficiency, and that the resulting products can perform comparably to conventional phosphate fertilisers under appropriate soil and crop conditions. However, the pathway from laboratory-scale recovery to widespread field application remains constrained by high capital costs, inconsistent feedstock quality, absence of standardised product norms, limited farmer awareness, and fragmented policy frameworks that do not yet treat recovered phosphorus as equivalent to mined phosphate.

This perspective aims to (i) critically review the major technologies for recovering phosphorus from agri-food waste and assess their agronomic potential as substitutes for conventional phosphate fertilisers; (ii) identify and analyse the key barriers impeding a functional circular phosphorus economy; and (iii) discuss

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emerging solutions and policy directions that could accelerate the transition, bringing together evidence from agronomy, environmental engineering and policy literature.

### *1.1 Why a perspective on agri-food waste streams specifically*

While phosphorus recovery research has historically concentrated on municipal wastewater treatment plants, the agri-food sector deserves dedicated attention. First, agricultural and food-processing activities generate phosphorus-rich residues at the point of production, often in concentrated and relatively homogeneous forms (poultry litter, slaughterhouse blood and bone, dairy whey), which can simplify recovery compared with dilute municipal streams. Second, the agri-food sector is simultaneously the largest consumer of phosphate fertiliser and one of the largest generators of phosphorus-bearing waste, creating a unique opportunity for closed-loop, on-farm or near-farm nutrient cycling that minimises transport distances and associated emissions. Third, recovered products derived from agri-food waste are agronomically familiar to farmers in the form of composts, manures and biochars, which may ease acceptance relative to products derived from human sewage.

Agri-food waste valorisation is therefore central to circular phosphorus management, given its scale, proximity to the point of re-application, and capacity to address waste management, soil health and fertiliser security within a single framework.

## 2. Methodology

This perspective is developed through a structured narrative synthesis of peer-reviewed literature, technical reports and policy documents on phosphorus recovery technologies and circular-economy frameworks in the agri-food sector. Published studies reporting recovery efficiencies, agronomic trial outcomes and barrier–solution analyses were reviewed and consolidated into two comparative frameworks (Table 1 and Table 2) to enable structured assessment of (a) the technological landscape of phosphorus recovery from agri-food waste and its agronomic relevance, and (b) the systemic barriers to circularity together with corresponding emerging solutions and their anticipated impact.

| Sl. No. | Source of P | Recovery technology | Recovered product | Recovery efficiency | Agronomic potential | Key challenge | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Animal manure (poultry, dairy, swine) | Struvite (MAP) precipitation | Struvite ($MgNH_4PO_4·6H_2O$) | 60–90% | Slow-release P fertiliser; good for cereals and vegetables | High Mg dosing cost; competing ions ($Ca^{2+}$) reduce purity | Talboys et al., 2016 |
| 2 | Anaerobic digestate (food/agri waste) | Struvite crystallisation in fluidised-bed reactor | Granular struvite | 70–95% | Comparable efficiency to triple super-phosphate (TSP) in pot trials | Variable digestate composition; needs pH control (8.5–9.5) | Rahman et al., 2014 |
| 3 | Slaughterhouse waste / bone meal | Thermochemical ashing + acid leaching | Calcium phosphate / bone-char | 50–85% | Effective on acidic soils; slow release matches crop demand | High energy input; heavy-metal carry-over | Meyer et al., 2018 |
| 4 | Municipal & agro-industrial sludge | Wet-chemical extraction (acid/alkaline leaching) | Phosphoric acid / Ca–P precipitate | 40–75% | High solubility supports rapid crop uptake | Chemical cost; secondary sludge disposal | Egle et al., 2016 |
| 5 | Fruit & vegetable processing waste | Composting with P-solubilising inoculants | P-enriched compost / biofertiliser | 30–60% | Improves soil organic matter and P availability | Long processing time; inconsistent inoculant survival | Bargaz et al., 2018 |
| 6 | Crop residues (straw, husk, bagasse) | Pyrolysis / biochar production | P-loaded biochar | 20–55% | Carbon sequestration plus slow P release | P bioavailability varies with pyrolysis temperature | Wang et al., 2020 |
| 7 | Dairy & cheese-whey effluent | Enhanced biological P removal (EBPR) | P-rich biomass / polyphosphate sludge | 50–80% | Soil conditioner with moderate P release | Precise aeration control; energy intensive | Yuan et al., 2012 |
| 8 | Fish / aquaculture processing waste | Enzymatic hydrolysis & precipitation | Calcium / magnesium phosphate | 45–70% | High purity; suited to organic farming | Odour management; seasonal feedstock | Mehta et al., 2015 |
| 9 | Food-waste digestate (urban–rural mix) | Electrodialysis / membrane recovery | Concentrated phosphate brine | 65–90% | Reformulated into liquid fertiliser blends | High capital cost; membrane fouling | Hao et al., 2019 |
| 10 | Sugar-industry press-mud | Vermicomposting | Vermicompost (P-enriched) | 25–50% | Improves microbial activity and P cycling | Slow throughput; needs stable moisture/temperature | Suthar, 2010 |

Table 1. Major phosphorus recovery technologies from agri-food waste streams and their agronomic potential.

As summarised in Table 1, struvite crystallisation remains the most extensively validated technology for phosphorus recovery from manure and digestate streams, offering recovery efficiencies frequently exceeding 70% with agronomic performance comparable to conventional water-soluble fertilisers in several crop trials. Thermochemical and wet-chemical methods provide complementary pathways for bone, slaughterhouse and sludge-based streams, though they involve higher energy or chemical inputs. Lower-technology approaches such as composting, vermicomposting and biochar offer co-benefits for soil organic matter and carbon sequestration, albeit at lower and more variable recovery efficiencies. No single pathway is universally optimal; technology selection must be tailored to feedstock characteristics, desired product quality and the agronomic context of the receiving cropping system.

| Sl. No. | Major barrier | Emerging solution | Expected impact | Reference |
|---|---|---|---|---|
| 1 | Fragmented collection & logistics of agri-food waste | Decentralised micro-recovery units at farm / processing-cluster level | Reduced transport cost; higher feedstock capture | Withers et al., 2015 |
| 2 | High capital and operating cost of recovery technologies | Public–private investment models; cost-sharing cooperatives | Improved economic viability; faster diffusion | Cordell & White, 2015 |
| 3 | Variable feedstock composition affecting product quality | Real-time sensor-based monitoring and adaptive control | Consistent quality; higher market acceptance | Mayer et al., 2016 |
| 4 | Lack of standardised norms for recycled P-fertilisers | International/national certification (e.g., EU Fertilising Products Regulation) | Greater farmer trust and regulatory clarity | Huygens et al., 2019 |

| Sl. No. | Major barrier | Emerging solution | Expected impact | Reference |
|---|---|---|---|---|
| 5 | Limited farmer awareness and acceptance | Demonstration trials, extension services, subsidy-linked incentives | Faster adoption and behavioural change | Chowdhury et al., 2017 |
| 6 | Contamination risk (heavy metals, pathogens) | Advanced purification (nanofiltration, selective precipitation) and pathogen-kill steps | Safer products; food-chain compliance | Kratz et al., 2019 |
| 7 | Policy gaps linking waste management with fertiliser markets | Integrated circular-economy policy and cross-sectoral coordination | Streamlined permitting; market creation | Schoumans et al., 2015 |
| 8 | Weak market infrastructure vs. mined phosphate rock | Blended products, carbon-credit linkages, life-cycle cost incentives | Improved competitiveness and penetration | Van Dijk et al., 2016 |

Table 2. Barriers to a circular phosphorus economy and corresponding emerging solutions.

Table 2 highlights that the barriers to a circular phosphorus economy extend well beyond technical feasibility, spanning economic, regulatory and behavioural dimensions. Capital intensity and inconsistent feedstock quality remain the most frequently cited technical-economic constraints, while the absence of harmonised quality standards continues to limit integration into mainstream fertiliser markets. Encouragingly, emerging solutions—decentralised micro-recovery units, certification frameworks, advanced purification and integrated circular-economy policies—indicate that many barriers are increasingly being addressed through coordinated technological and institutional innovation.

## 3. Detailed Perspective on Recovery Technologies

### *3.1 Struvite crystallisation*

Struvite (magnesium ammonium phosphate hexahydrate) precipitation is currently the most commercially mature technology for recovering phosphorus from nutrient-rich agri-food waste such as livestock manure, anaerobic digestate and dairy effluent. The process relies on controlled supersaturation of magnesium, ammonium and phosphate ions, typically by raising pH to 8.5–9.5 and dosing magnesium salts where the feedstock is magnesium-deficient. The granular product is a slow-release fertiliser well suited to perennial and long-duration crops, as its dissolution kinetics align with crop phosphorus-demand curves, reducing luxury uptake or leaching losses associated with highly soluble fertilisers. Reported phosphate recovery efficiencies range from about 70% to 95% for digestate and manure feedstocks, and granular struvite has matched the agronomic performance of triple super-phosphate in pot and field trials (Rahman et al., 2014; Talboys et al., 2016). The process was originally developed to control unintended pipe scaling in anaerobic digesters and is now operated deliberately for nutrient recovery.

### *3.2 Thermochemical and wet-chemical recovery*

Thermochemical approaches, including ashing and pyrolysis of bone meal, slaughterhouse residue and biosolids, convert organic-bound phosphorus into more stable mineral forms such as calcium phosphates, which can subsequently be solubilised through acid leaching to produce phosphoric acid or refined calcium-phosphate intermediates. These methods offer pathogen destruction and volume reduction, but their energy intensity raises questions about net environmental benefit unless powered by renewable energy or integrated with waste-to-energy heat recovery. Wet-chemical extraction of sludges and process effluents can achieve comparatively high recovery efficiencies but introduces secondary waste streams (spent acid, residual sludge) that must themselves be managed. Reported recoveries are roughly 50–85% for thermochemical ashing and acid leaching of bone meal and slaughterhouse residue (Meyer et al., 2018) and about 40–75% for wet-chemical extraction of sludges and effluents (Egle et al., 2016).

### *3.3 Biological and membrane-based recovery*

Enhanced biological phosphorus removal (EBPR), historically developed for wastewater treatment, has agri-food applications in dairy and food-processing effluent treatment, where phosphorus-accumulating organisms sequester phosphate intracellularly as polyphosphate under alternating anaerobic–aerobic conditions. The P-rich biomass can be processed into soil conditioners, although the bioavailability of biologically sequestered phosphorus is generally lower and more variable than chemically precipitated struvite; the underlying microbial transformations are part of the broader repertoire of microbe-mediated nutrient and metal(loid) processing relevant to environmental remediation (Khanam & Ghouse Peera, 2022). Membrane and electrodialysis technologies represent an emerging frontier, concentrating dilute phosphate streams into fertiliser-grade brines with high selectivity; their adoption is constrained by high capital cost and membrane fouling associated with the particulate and organic load of food-processing wastewaters.

### *3.4 Composting, vermicomposting and biochar pathways*

Lower-technology pathways generally achieve more modest recovery efficiencies but offer co-benefits that purely chemical routes do not. Composting and vermicomposting enhance soil organic carbon, microbial biomass and structure, while making a portion of waste-bound phosphorus more plant-available through microbial mineralisation. Biochar from crop residues sequesters carbon over multi-decadal timescales while providing a phosphorus-loaded amendment whose release depends on pyrolysis temperature and feedstock mineralogy. These pathways suit smallholder and resource-constrained systems, where low capital and operational simplicity may outweigh lower recovery efficiency. Reported phosphorus recovery for these routes is about 30–60% for microbially assisted composting (Bargaz et al., 2018), 20–55% for crop-residue biochar (Wang et al., 2020) and 25–50% for vermicompost (Suthar, 2010), with bioavailability varying by feedstock and processing conditions.

## 4. Detailed Perspective on Barriers and Enabling Solutions

### *4.1 Economic and infrastructural barriers*

The capital intensity of advanced recovery technologies, combined with fragmented and often small-scale waste generation, creates a fundamental economic mismatch: the fixed costs of struvite reactors, membrane systems or thermochemical units are most easily amortised at large centralised scale, yet much relevant feedstock is generated in dispersed, smaller volumes. Addressing this requires either aggregation through regional collection hubs, or smaller, modular, cost-effective decentralised units for farm-cluster or cooperative deployment. Public–private investment and blended-finance mechanisms, sharing initial capital risk between government, industry and farmer cooperatives, have been proposed to overcome the cost barrier while demand for recycled phosphorus matures.

### *4.2 Regulatory and standardisation barriers*

In many jurisdictions, recycled phosphorus products occupy an ambiguous regulatory space: neither treated identically to mined fertilisers nor consistently classified as organic amendments, creating uncertainty over labelling, application rates and quality guarantees. The European Union's Fertilising Products Regulation, which establishes end-of-waste and quality criteria for recovered struvite and other recycled nutrients, illustrates one model for resolving this ambiguity, with similar frameworks emerging elsewhere. Robust certification, supported by standardised testing for nutrient content, contaminant thresholds and agronomic efficiency, is essential for regulatory clarity and for the market confidence needed for recycled phosphorus to be priced and traded on comparable terms with conventional fertiliser.

### 4.3 Behavioural and market-acceptance barriers

Even where products are technically sound and compliant, adoption can be constrained by unfamiliarity, perceived risk or scepticism about consistency relative to established mineral-fertiliser brands. Overcoming this requires sustained extension and demonstration, including replicated field trials communicated through trusted local networks, alongside incentives such as input subsidies or blended pricing that reduce switching risk. Long-term market development will depend on recovered phosphorus being positioned not as an inferior substitute but as a functionally differentiated product offering slow-release characteristics or soil-organic-matter co-benefits.

### 4.4 Contaminant and food-safety considerations

Agri-food waste streams, particularly those from animal processing or wastewater-adjacent sources, can contain heavy metals, pathogens or pharmaceutical residues that pose food-safety and environmental risks if not adequately managed during recovery. Advanced purification—selective precipitation, nanofiltration and thermal or chemical pathogen-kill steps—is increasingly integrated into recovery trains, and nano-engineered adsorbents in particular offer a precise route to stripping residual metal(loid)s from recovered streams (Ghouse Peera & Khanam, 2024). Because phosphorus products are returned directly to the food chain, contaminant control is inseparable from the wider goal of preventing metal(loid) toxicity in staple crops such as rice. A precautionary but proportionate regulatory approach, combined with transparent contaminant testing and disclosure, will be important for maintaining public and farmer confidence as the sector scales.

## 5. Policy Outlook and Future Research Directions

Several converging trends suggest that circular phosphorus management will become increasingly central to agricultural and environmental policy. Growing attention to planetary boundaries—with the phosphorus biogeochemical cycle identified as a major sustainability concern at the global scale—is elevating phosphorus stewardship alongside carbon and nitrogen as a governance priority (Chowdhury et al., 2017). National and regional fertiliser-security strategies, particularly in countries with limited domestic phosphate rock, are exploring recycled phosphorus as a strategic hedge against import dependency and price volatility. Climate-policy instruments, including carbon-credit and emissions-reduction schemes, may create new revenue streams where recovery simultaneously reduces methane emissions from manure management or avoids energy-intensive mining and processing of virgin rock.

From a research perspective, several priorities merit attention. First, long-term, multi-site field trials comparing recovered phosphorus products against conventional fertilisers across diverse soils and cropping systems are needed to build the agronomic evidence base for farmer and regulatory confidence, as much existing evidence remains concentrated in pot trials or short-duration experiments. Second, techno-economic and life-cycle assessments comparing recovery technologies on a consistent basis—accounting for energy inputs, transport, secondary waste and avoided mining and eutrophication impacts—are needed to guide technology selection and investment. Third, social-science and behavioural research on the drivers of farmer adoption, including risk perception, trust in certification and the role of extension, will be critical. Finally, integrated modelling of regional and national phosphorus flows, linking waste generation, recovery potential and crop demand, can identify where infrastructure investment would yield the greatest combined environmental and food-security benefit.

### 5.1 Synthesis and outlook

Taken together, the evidence indicates that phosphorus recovery from agri-food waste is technologically mature enough for selective large-scale deployment, particularly for struvite-based systems applied to livestock manure and anaerobic digestate. The agronomic potential of recovered products is well supported by field and pot-trial evidence, especially where recovered phosphorus is positioned as a slow- or controlled-release alternative to soluble fertilisers. Realising a genuinely circular phosphorus economy requires simultaneous progress on cost reduction, product standardisation, farmer engagement and supportive policy. An integrated approach linking agronomy, waste management, market design and regulation is required to ensure recovered phosphorus is agronomically effective and economically and institutionally viable at scale.

## 6. Illustrative Case Examples

Several real-world initiatives illustrate the practical translation of these recovery pathways. In the Netherlands and Belgium, regions with intensive livestock production, mandatory manure-processing regulations have spurred investment in centralised struvite recovery facilities that process surplus pig and poultry manure, converting a regulatory compliance cost into a marketable slow-release fertiliser and demonstrating how policy-driven necessity can catalyse circular infrastructure before market-pull conditions are mature. In parts of South and Southeast Asia, smallholder-oriented vermicomposting and on-farm composting of crop residues and food-processing by-products have been promoted through extension programmes as low-cost entry points to phosphorus recycling at the farm level.

In the dairy and food-processing sector, several facilities in Europe and North America have piloted on-site biological phosphorus removal coupled with downstream struvite precipitation from whey and wash-water effluents, simultaneously meeting trade-effluent discharge obligations and generating a saleable fertiliser by-product. These examples indicate that early-stage initiatives advance fastest where technology adoption is reinforced by an existing regulatory or operational driver—such as nutrient-discharge limits or mandatory manure processing—rather than the agronomic or environmental value of the recovered product alone. Regulatory instruments that internalise the cost of phosphorus loss or waste disposal therefore tend to drive earlier adoption than voluntary market mechanisms during the early phase of sector development (Schoumans et al., 2015).

## 7. Limitations of this Perspective

As a perspective rather than a systematic review or primary research study, this paper synthesises existing literature rather than generating new empirical data, and the recovery-efficiency and agronomic-potential figures in Table 1 reflect ranges reported across heterogeneous studies that vary in feedstock, climate and experimental design; these figures should be treated as indicative rather than universally applicable. The barrier–solution framework in Table 2, while drawing on documented case experience, necessarily simplifies deeply context-specific institutional, cultural and economic conditions; a barrier binding in one context may be negligible elsewhere. Future work would benefit from region-specific quantitative assessment of phosphorus flows, recovery potential and barrier prioritisation, combined with stakeholder consultation.

This perspective focuses on phosphorus recovery from agri-food waste streams—pre-consumer agricultural and food-processing residues and associated digestates and sludges—and does not extend in detail to post-consumer municipal food waste or to purely industrial (non-food) effluents. Economic and recovery-efficiency figures are drawn from literature spanning different countries and periods and are not adjusted for inflation, currency or regional cost-of-capital differences; site-specific investment decisions should rely on dedicated techno-economic assessment.

## Conclusion

The transition towards a circular phosphorus economy represents a critical and achievable pathway for reconciling food security and environmental sustainability. Agri-food waste streams, far from being mere disposal burdens, constitute a strategically important secondary source of phosphorus capable of substituting a meaningful share of virgin phosphate rock demand. Realising this potential will depend on continued technological refinement of recovery processes, rigorous agronomic validation of recovered products across diverse soil–crop systems, and the establishment of enabling policy, market and certification frameworks that recognise recycled phosphorus as a legitimate and trusted fertiliser resource. A coordinated, multi-stakeholder approach involving researchers, industry, farmers and policymakers will be essential to operationalise circularity in phosphorus management at scale.

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# Remote Sensing Transforms Nutrient Management: Satellite- and Drone-Based Spectral Indices for Real-Time Nitrogen Status Monitoring in Field Crops

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**ABSTRACT**

Accurate and timely assessment of nitrogen (N) status in crops remains a central challenge in precision agriculture owing to spatial heterogeneity and temporal variability in nutrient availability. Remote sensing technologies, including satellite and unmanned aerial vehicle (UAV)-based platforms, have enabled non-destructive, real-time monitoring of crop nitrogen dynamics through spectral indices derived from canopy reflectance. This review synthesises advances in spectral indices such as the normalised difference vegetation index (NDVI), the red-edge chlorophyll index (CIred-edge) and the normalised difference red-edge index (NDRE) for nitrogen estimation across major field crops. Recent integration of hyperspectral sensing, machine learning and data fusion has enhanced sensitivity to subtle biochemical changes in plant tissues. Evidence suggests that UAV-based sensing provides higher spatial resolution, whilst satellite platforms enable large-scale monitoring with increasing revisit frequency. Despite these advances, limitations related to atmospheric interference, canopy saturation and calibration variability persist. The review evaluates the performance, applications and constraints of satellite- and drone-based spectral approaches, and highlights pathways towards scalable, data-driven nutrient management systems that improve nitrogen use efficiency and reduce the environmental impacts of excessive fertiliser application.

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## 1. Introduction

Nitrogen is a critical macronutrient governing crop productivity, yet its management remains inefficient across many agricultural systems, leading to concurrent economic losses and environmental degradation. Excessive nitrogen application contributes to groundwater contamination, greenhouse gas emissions and eutrophication of aquatic ecosystems (Sutton et al., 2013). Conversely, insufficient nitrogen supply limits crop growth and reduces yield potential. Achieving optimal nitrogen management is therefore essential for both productive and sustainable agriculture.

Traditional methods for assessing nitrogen status—destructive tissue sampling and laboratory Kjeldahl analysis—are labour-intensive and fail to capture within-field variability (Schepers & Raun, 2014). These approaches often provide delayed results, rendering them unsuitable for real-time decision-making. Spatial heterogeneity in soil properties and crop growth necessitates site-specific nutrient management that can dynamically respond to crop demand throughout the season.

Remote sensing has emerged as a scientifically grounded tool for monitoring crop physiological status by measuring canopy reflectance across multiple spectral bands. Variations in leaf chlorophyll concentration, strongly correlated with nitrogen content through its role in RuBisCO synthesis, influence reflectance in the visible and near-infrared (NIR) regions (Evans, 1989). Spectral indices derived from these reflectance values therefore provide proxies for nitrogen status, allowing rapid, non-destructive assessment at scales impractical for manual sampling.

Whilst early applications relied primarily on broadband satellite imagery, the advent of UAV platforms has enhanced spatial and temporal resolution, enabling flexible acquisition at critical phenological stages. The introduction of Sentinel-2's red-edge bands—centred at 705, 740 and 783 nm—has further narrowed the gap between satellite and airborne capability (Drusch et al., 2012). However, spectral index saturation in dense canopies limits sensitivity at high leaf area index, whilst atmospheric conditions introduce variability requiring correction. This review critically synthesises recent advances in satellite- and drone-based spectral indices for nitrogen monitoring, evaluates platform limitations, and outlines research directions for integrating remote sensing into operational nutrient management, drawing on peer-reviewed studies published between 2010 and 2026.

## 2. Spectral Indices for Nitrogen Estimation

Spectral indices exploit the differential absorption and reflectance of plant canopies across specific wavelength intervals. NDVI, calculated as (NIR − Red)/(NIR + Red), has been widely employed but saturates under high biomass, typically when leaf area index (LAI) exceeds approximately 3.0 (Haboudane et al., 2002), reducing its effectiveness in detecting nitrogen variation in dense canopies at anthesis or grain fill.

Red-edge-based indices—including NDRE and CIred-edge—demonstrate improved sensitivity to chlorophyll and nitrogen by using wavelengths in the 680–750 nm transition region that remain responsive at higher LAI (Clevers & Gitelson, 2013). The enhanced vegetation index (EVI), which incorporates atmospheric correction via the blue band, performs better under variable atmospheric conditions (Huete et al., 2002).

Hyperspectral narrowband indices—including MCARI, TCARI/OSAVI, REP and MTVI2—enable detection of subtle biochemical changes associated with early nitrogen deficiency by

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leveraging contiguous bands, improving prediction accuracy relative to broadband approaches. Their implementation, however, is constrained by data-processing complexity, computational demand and sensor cost. Table 1 presents twenty spectral indices commonly employed in current nitrogen monitoring research, with their formulas, applications and sensor platforms.

| S.No | Index | Formula | Application | Platform | Reference |
|---|---|---|---|---|---|
| 1 | NDVI | (NIR − Red)/(NIR + Red) | General vegetation vigour, canopy greenness, nitrogen status | Satellite/UAV | Rouse et al., 1974 |
| 2 | NDRE | (NIR − RedEdge)/(NIR + RedEdge) | Chlorophyll and nitrogen estimation in dense canopies | Satellite/UAV | Gitelson et al., 2003 |
| 3 | EVI | 2.5 × (NIR − Red)/(NIR + 6×Red − 7.5×Blue + 1) | Improved monitoring under atmospheric variability | Satellite | Huete et al., 2002 |
| 4 | CIred-edge | (NIR/RedEdge) − 1 | Leaf chlorophyll and nitrogen content | UAV | Gitelson et al., 2005 |
| 5 | SAVI | ((NIR − Red)/(NIR + Red + L)) × (1 + L) | Soil-adjusted vegetation analysis | Satellite/UAV | Huete, 1988 |
| 6 | MCARI | [(R700 − R670) − 0.2×(R700 − R550)] × (R700/R670) | Chlorophyll absorption and stress detection | UAV | Daughtry et al., 2000 |
| 7 | GNDVI | (NIR − Green)/(NIR + Green) | Photosynthetic activity and nitrogen status | Satellite/UAV | Gitelson et al., 1996 |
| 8 | TCARI/OSAVI | 3×[(R700−R670) − 0.2×(R700−R550)×(R700/R670)] / [(NIR−Red)/(NIR+Red+0.16)×1.16] | Minimises soil background in chlorophyll estimation | UAV | Haboudane et al., 2002 |
| 9 | PRI | (R531 − R570)/(R531 + R570) | Photosynthetic efficiency and stress detection | UAV | Gamon et al., 1992 |
| 10 | NDWI | (NIR − SWIR)/(NIR + SWIR) | Water and nutrient stress detection | Satellite | Gao, 1996 |
| 11 | ARVI | (NIR − (2×Red − Blue))/(NIR + (2×Red − Blue)) | Atmospheric correction for vegetation monitoring | Satellite | Kaufman & Tanré, 1992 |
| 12 | MTVI2 | 1.5×[1.2×(NIR−Green) − 2.5×(Red−Green)] / √[(2×NIR+1)² − (6×NIR − 5×√Red) − 0.5] | Chlorophyll and canopy structure estimation | UAV | Haboudane et al., 2004 |
| 13 | REP | λ at maximum first derivative of reflectance (680–750 nm) | Chlorophyll and nitrogen concentration | UAV | Clevers & Gitelson, 2013 |
| 14 | NDVI705 | (R750 − R705)/(R750 + R705) | Sensitive to chlorophyll and nitrogen variations | UAV | Sims & Gamon, 2002 |
| 15 | MCARI2 | [(R750 − R705) − 0.2×(R750 − R550)] × (R750/R705) | Improved chlorophyll estimation under stress | UAV | Haboudane et al., 2002 |
| 16 | CRI | 1/R510 − 1/R550 | Carotenoid and nitrogen stress detection | UAV | Gitelson et al., 2002 |
| 17 | NDVIre | (NIR − RedEdge)/(NIR + RedEdge) | Nitrogen and chlorophyll estimation in cereals | Satellite/UAV | Li et al., 2020 |
| 18 | VARI | (Green − Red)/(Green + Red − Blue) | Nitrogen estimation using RGB sensors | UAV | Gitelson et al., 2002 |
| 19 | CIgreen | (NIR/Green) − 1 | Chlorophyll and nitrogen estimation | UAV | Gitelson et al., 2003 |
| 20 | NDVIre2 | (R750 − R705)/(R750 + R705) | Sensitive to nitrogen and chlorophyll in dense canopies | UAV | Li et al., 2021 |

Table 1. Common spectral indices used for nutrient assessment in crops. NIR, near-infrared; SWIR, shortwave infrared; RedEdge, red-edge band (~705–740 nm); R, reflectance at specified wavelength (nm); UAV, unmanned aerial vehicle; L, soil brightness correction factor (typically 0.5 for SAVI).

## 3. Satellite-Based Nitrogen Monitoring

Satellite platforms such as Sentinel-2 and Landsat 8 provide multispectral data with moderate spatial resolution (10–30 m) and high temporal frequency. Sentinel-2's three dedicated red-edge bands have significantly enhanced nitrogen estimation over legacy broadband satellites, making it a preferred choice for operational monitoring (Drusch et al., 2012). Multi-temporal analysis allows tracking of nitrogen dynamics across phenological stages, from tillering through grain filling, enabling temporally informed fertilisation decisions.

Satellite-based monitoring supports assessment over millions of hectares and regional nutrient management, facilitating early detection of stress across heterogeneous landscapes. However, atmospheric interference—aerosol scattering and water-vapour absorption—cloud cover in humid environments, and coarse spatial resolution may limit field-level accuracy, particularly in fragmented smallholder systems (Zhao et al., 2018). Radiometric calibration and physics-based atmospheric correction, including the Sen2Cor processor for Sentinel-2, are essential prerequisites for reliable index computation.

## 4. UAV-Based Sensing for High-Resolution Analysis

UAV platforms equipped with multispectral cameras (e.g., MicaSense RedEdge, Parrot Sequoia) and miniaturised hyperspectral sensors provide sub-10-cm ground sampling distance, enabling within-field nitrogen variability analysis at individual-plant scales. UAV-derived red-edge indices have shown superior performance in detecting early nitrogen stress compared with equivalent satellite imagery in side-by-side evaluations (Zheng et al., 2018).

The operational flexibility of UAV deployment permits targeted acquisition during critical stages without dependence on satellite overpass or atmospheric conditions, and integration with concurrent SPAD chlorophyll readings or destructive tissue N analyses enhances calibration. Nevertheless, limited battery endurance, regulatory flight restrictions, and the computational burden of processing sub-centimetre imagery at field scale may hinder routine commercial scalability (Hunt et al., 2018).

## 5. Integration with Machine Learning

Machine-learning algorithms—random forests (RF), support vector machines (SVM) and convolutional neural networks (CNNs)—have been applied to capture nonlinear relationships between spectral reflectance and canopy N content. Ensemble models integrating multiple indices, thermal data and growth-stage covariates have yielded cross-validated accuracies of $R^2 \geq 0.85$ in wheat and maize (Wang et al., 2020). Machine-learning-based predictive modelling has similarly been applied to nutrient and contaminant management in rice, including silica-based arsenic mitigation (Khanam et al., 2023).

Data-fusion approaches combining satellite temporal frequency with UAV spatial detail are promising: UAV-derived indices can calibrate and downscale satellite-based models, improving field-level predictions from coarser imagery (Jin et al., 2020). Machine learning also enables automated processing of large multi-temporal datasets. Model generalisation across diverse agro-ecosystems—differing in cultivar canopy architecture, soil background and management intensity—remains a persistent challenge requiring robust multi-site validation (Li et al., 2021). Applications, advantages and challenges of satellite- and drone-based monitoring are summarised in Table 2.

| S.No | Application area | Advantages | Challenges | Reference |
|---|---|---|---|---|
| 1 | Precision fertilisation | Site-specific application; reduces fertiliser waste | Requires calibration and ground-truth data | Mulla, 2013 |
| 2 | Crop health monitoring | Early detection of nutrient stress; timely intervention | Spectral saturation in dense canopies | Zhao et al., 2018 |
| 3 | Yield prediction | Improved forecasting from temporal spectral data | Complex integration; model transferability | Wang et al., 2020 |
| 4 | Large-scale assessment | Regional and national nutrient mapping | Cloud interference; coarse resolution | Clevers & Gitelson, 2013 |
| 5 | Research applications | High-resolution data for experimental validation | High cost of UAV and hyperspectral sensors | Prey et al., 2020 |
| 6 | Variable-rate fertilisation | Optimised distribution; improves NUE | Algorithm calibration; sensor variability | Li et al., 2021 |
| 7 | Crop growth modelling | Integrates with biophysical models (DSSAT, APSIM) | Spectral saturation; model uncertainty | Peng et al., 2021 |
| 8 | Decision support systems | Real-time analytics and automated recommendations | Data standardisation and interoperability | Zhang et al., 2022 |
| 9 | Soil nutrient mapping | Indirect estimation through vegetation response | Influence of soil background reflectance | Yao et al., 2012 |
| 10 | Climate-smart agriculture | Monitors nutrient efficiency under stress | Temporal inconsistency in acquisition | Singh et al., 2021 |
| 11 | Irrigation scheduling | Integrates water and nutrient management | Requires multi-sensor data fusion | Gao, 1996 |
| 12 | Stress detection (biotic/abiotic) | Differentiates nutrient stress from disease/drought | Overlapping spectral responses | Gamon et al., 1992 |
| 13 | Regional nutrient forecasting | Supports policy and resource allocation | Limited temporal resolution in some satellites | Clevers & Gitelson, 2013 |
| 14 | Crop phenotyping | High-throughput trait analysis for breeding | Data volume and processing complexity | Li et al., 2020 |
| 15 | Nutrient efficiency mapping | Quantifies spatial variability in NUE | Requires soil and yield integration | Mulla, 2013 |
| 16 | Multi-temporal monitoring | Tracks nitrogen dynamics across growth stages | Atmospheric correction; illumination effects | Huete et al., 2002 |
| 17 | UAV-assisted scouting | Rapid field-level diagnosis | Limited flight endurance and coverage | Hunt et al., 2018 |
| 18 | Satellite–UAV data fusion | Combines spatial detail and temporal frequency | Complex data harmonisation | Jin et al., 2020 |
| 19 | Machine-learning prediction | Improves accuracy through nonlinear modelling | Requires large, diverse training datasets | Wang et al., 2020 |
| 20 | Real-time nutrient management | Supports dynamic fertiliser scheduling | Connectivity and data-processing limits | Zhang et al., 2022 |

Table 2. Applications, advantages and challenges of satellite- and drone-based nutrient monitoring.

## 6. Discussion

The integration of remote sensing into nutrient management has substantially improved the capacity to monitor nitrogen dynamics in real time across diverse environments. Red-edge-based indices—particularly NDRE and CIred-edge—consistently outperform NDVI in dense canopies, attributable to their positioning within the 680–750 nm zone where chlorophyll absorption remains linearly sensitive at LAI values that saturate the red band (Haboudane et al., 2002). UAV platforms detect micro-scale nitrogen variability imperceptible to satellite sensors, whilst satellites offer the temporal continuity and spatial extent required for regional N accounting.

Comparisons with existing literature confirm strong correlations between red-edge indices and canopy nitrogen across wheat ($R^2$ = 0.78–0.91), maize ($R^2$ = 0.82–0.89) and paddy rice ($R^2$ = 0.75–0.87), though soil background, illumination angle and phenological stage introduce scatter around universal calibrations (Zhao et al., 2018; Zheng et al., 2018). Machine-learning models enhance accuracy but introduce transferability constraints: RF and SVM models trained on single-site data show $R^2$ degradation of 0.12–0.20 when applied without recalibration to distinct environments (Li et al., 2021).

Persistent limitations include spectral saturation at high LAI, atmospheric-correction artefacts in humid tropics, and sensor-to-sensor calibration inconsistencies affecting comparability across platforms and dates (Hunt et al., 2018). The high cost of hyperspectral sensors and UAV operations constrains adoption among smallholders, where precision nitrogen management may confer the greatest benefit; context-appropriate nutrient management options for small farms therefore remain essential to translate these tools into practice (Ghouse Peera & Khanam, 2022). Standardisation of index computation—including band convolution for sensor-specific response functions—remains a critical unresolved challenge limiting cross-study meta-analysis.

Future research should prioritise multi-site, multi-season validation datasets—analogous to FLUXNET for carbon flux—to assess transferability. Lightweight, low-cost hyperspectral sensors for UAV integration, with open-access calibration frameworks, may lower adoption barriers. Real-time connectivity with variable-rate fertilisation equipment through decision support systems (Table 2) represents the logical operational endpoint of the technology pathway.

## 7. Conclusion

Remote sensing technologies—satellite multispectral platforms and UAV-mounted sensors—provide a transformative, scalable approach to nitrogen management by enabling real-time, non-destructive canopy monitoring at agronomically relevant resolutions. The combination of satellite temporal coverage and UAV spatial detail, supported by machine-learning integration, offers a robust framework for operational, site-specific nitrogen management that exceeds the diagnostic capability of conventional ground-based methods. Sustained investment in multi-platform calibration standards, transferable machine-learning architectures and low-cost sensing is required to translate these advances into measurable improvements in nitrogen use efficiency and environmental outcomes across global cropping systems.

## 8. Methods

### *Literature search strategy*

A systematic literature review was conducted across the Web of Science, Scopus and Google Scholar databases. Search terms combined 'nitrogen monitoring', 'spectral vegetation index', 'UAV remote sensing', 'Sentinel-2 agriculture', 'NDRE chlorophyll', 'machine learning crop nutrient' and 'precision nitrogen management'. The search was restricted to peer-reviewed primary research, meta-analyses and authoritative reviews published between January 2010 and March 2026. Articles were screened for field-scale experimental data from agronomic crops; quantitative nitrogen or chlorophyll validation against destructive reference measurements; reporting of at least one performance metric ($R^2$, RMSE or mean absolute error); and replication across at least three independent sampling events or sites. Greenhouse and controlled-environment pot experiments were excluded.

### *Data extraction and synthesis*

Performance metrics ($R^2$, RMSE, prediction bias) were extracted from regression tables and supplementary datasets. Where multiple index configurations were tested within a study, the independently validated best-performing configuration was recorded. Spectral band wavelength assignments were harmonised to Sentinel-2 MSI nomenclature using spectral response function convolution as described by Clevers & Gitelson (2013). No original field measurements were generated for this review.

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# Nano-enabled Fertilizers for Sustainable Crop Production: Agronomic Performance, Soil Behaviour and Ecotoxicological Risk Assessment

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**ABSTRACT**

Nano-enabled fertilizers (nanofertilizers) have emerged as a promising innovation for sustainable agriculture owing to their ability to improve nutrient-use efficiency, reduce environmental losses and enhance crop productivity. Conventional fertilizers frequently exhibit poor recovery efficiency, resulting in nutrient leaching, volatilisation and environmental contamination. Nanofertilizers are engineered to provide controlled nutrient release and targeted nutrient delivery, thereby synchronising nutrient availability with plant demand. This review examines the agronomic performance, soil behaviour and ecotoxicological implications of nano-enabled fertilizers. Evidence from diverse cropping systems indicates that nanofertilizers enhance nutrient uptake, photosynthetic activity, biomass accumulation and yield performance. Soil interactions involving adsorption, ion exchange and controlled nutrient release contribute to improved nutrient retention and reduced losses. Despite these advantages, concerns remain regarding nanoparticle accumulation, phytotoxicity, impacts on soil microbial communities and potential human exposure through food chains. Current findings suggest that the performance and safety of nanofertilizers are strongly influenced by nanoparticle composition, concentration and environmental conditions. A balanced assessment of benefits and risks is therefore essential for their responsible adoption in sustainable crop production systems.

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## 1. Introduction

Global food demand is projected to increase substantially due to continuous population growth, while agricultural land and natural resources are becoming increasingly limited. Conventional fertiliser-based production systems have played a significant role in enhancing crop productivity; however, their nutrient-use efficiency remains low. Significant proportions of applied nitrogen, phosphorus and potassium are lost through volatilisation, leaching, runoff and fixation processes, leading to economic losses and environmental degradation. Such losses contribute to eutrophication, groundwater contamination and greenhouse-gas emissions (Liu & Lal, 2015).

Nanotechnology has introduced innovative approaches for improving agricultural productivity through the development of nano-enabled fertilizers. Nanofertilizers consist either of nutrients in nanoscale form or conventional nutrients encapsulated within nanomaterials capable of controlled release. Owing to their high surface-area-to-volume ratio, adsorption capacity and enhanced reactivity, nanofertilizers can improve nutrient delivery and nutrient-use efficiency compared with conventional fertilizers (DeRosa et al., 2010; Dimkpa & Bindraban, 2018).

The application of nanotechnology in agriculture extends beyond fertilisation. Nanomaterials are increasingly used in pesticide delivery systems, disease management, environmental monitoring and precision agriculture. Nano-sensors can detect nutrient deficiencies, moisture stress and plant-health conditions in real time, supporting more efficient farm-management strategies (Raliya et al., 2018). The case for nano-enabled inputs is particularly strong in small-farm systems, where improved input efficiency has direct livelihood benefits (Ghouse Peera & Khanam, 2022).

Several categories of nanofertilizers have been developed, including zeolite-based carriers, nanocomposites, super-absorbent fertilizers and carbon-nanotube-based formulations. These systems are designed to reduce nutrient losses while enhancing nutrient availability during critical crop-growth stages. Previous studies have demonstrated positive responses in cereals, legumes, vegetables and horticultural crops following nanofertilizer application (Kah et al., 2018).

Despite these promising developments, concerns regarding environmental fate, phytotoxicity, human exposure and impacts on soil microorganisms remain unresolved. Long-term field-scale assessments are limited, and regulatory frameworks are still evolving. Consequently, a comprehensive evaluation of both benefits and risks is required before large-scale adoption can be recommended. The objective of this review is to critically examine the agronomic performance, soil behaviour and ecotoxicological risks associated with nano-enabled fertilizers and to evaluate their potential contribution to sustainable crop production.

## 2. Agronomic Performance of Nano-enabled Fertilizers

Nanofertilizers have gained significant attention due to their ability to improve nutrient-use efficiency and crop productivity. Unlike conventional fertilizers, which often release nutrients rapidly and result in substantial losses through leaching, volatilisation and runoff, nanofertilizers are designed to provide controlled and targeted nutrient delivery. Their nanoscale size increases surface area and reactivity, allowing more efficient interaction with plant roots and soil particles.

One of the major advantages of nanofertilizers is their capacity to synchronise nutrient release with crop demand. This controlled-release behaviour ensures that nutrients remain available during

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critical stages of plant growth, thereby minimising wastage and improving nutrient-uptake efficiency. Studies have demonstrated that nanofertilizers can increase nutrient recovery compared with conventional fertilizers, resulting in enhanced plant growth and yield; urea–hydroxyapatite nanohybrids, for example, slow nitrogen release while maintaining supply to the crop (Kottegoda et al., 2017). The high adsorption and ion-exchange capacities of nanomaterials contribute to improved nutrient retention and availability in the rhizosphere.

Nitrogen nanofertilizers have shown considerable potential in improving crop productivity. Conventional nitrogen fertilizers typically exhibit low recovery efficiency, with a significant proportion of applied nitrogen being lost to the environment. Nano-encapsulated nitrogen formulations and zeolite-based nitrogen carriers have been developed to overcome this limitation. Research indicates that these formulations improve nitrogen-use efficiency by reducing nutrient losses and enhancing uptake by plants. Improved nitrogen nutrition contributes to increased chlorophyll synthesis, photosynthetic activity and biomass accumulation.

Phosphorus and potassium nanofertilizers have also demonstrated promising results. Phosphorus availability is often restricted in agricultural soils because of fixation reactions with calcium, iron and aluminium compounds. Nano-sized phosphorus formulations improve nutrient mobility and availability, facilitating enhanced uptake by crop roots. Similarly, potassium-based nanofertilizers improve nutrient retention and reduce leaching losses, thereby supporting improved crop growth and productivity.

Micronutrient nanofertilizers have received considerable attention due to their effectiveness in correcting nutrient deficiencies. Zinc, iron and manganese nanoparticles are among the most widely investigated formulations. Zinc nanoparticles have been reported to improve growth, productivity and zinc biofortification in maize and wheat (Du et al., 2019). Iron-oxide nanoparticles have enhanced root growth and iron nutrition in peanut crops under field conditions. Similarly, manganese nanoparticles have been associated with improved root and shoot development in mung bean compared with conventional manganese fertilizers.

The positive effects of nanofertilizers extend beyond nutrient supply. Several studies have reported improvements in photosynthetic efficiency, enzyme activity, antioxidant-defence systems and stress tolerance. Nano-silicon applications, for example, have been shown to enhance tolerance to salinity and drought stress by improving antioxidant activity and maintaining cellular homeostasis (Zulfiqar et al., 2019). These physiological improvements contribute to enhanced crop performance under adverse environmental conditions. Nanofertilizers have also demonstrated potential in improving crop quality, with enhanced nutrient uptake contributing to higher protein content, improved mineral composition and increased accumulation of beneficial phytochemicals in harvested products. Despite these benefits, agronomic responses to nanofertilizers are not always consistent, varying with crop species, soil properties, climate and formulation.

## 3. Soil Behaviour of Nano-enabled Fertilizers

The effectiveness of nano-enabled fertilizers is strongly influenced by their behaviour within soil systems. After application, nanofertilizers interact with soil minerals, organic matter, microorganisms and plant roots, resulting in complex physical, chemical and biological processes that determine nutrient availability and fertiliser efficiency. Understanding these interactions is essential for evaluating the long-term sustainability and environmental safety of nanofertilizer technologies (Wang et al., 2016).

One of the most important characteristics of nanofertilizers is their large surface-area-to-volume ratio. This property enhances adsorption, ion exchange and nutrient retention within the soil matrix. Unlike conventional fertilizers, which often dissolve rapidly and release nutrients in excess of plant requirements, nanofertilizers provide a gradual and controlled release of nutrients. This mechanism reduces nutrient losses through leaching and volatilisation while improving nutrient availability in the root zone.

Soil texture significantly influences the movement and retention of nanoparticles. Clay-rich soils generally exhibit greater adsorption capacity than sandy soils because of their higher surface area and cation-exchange capacity. As a result, nanoparticles tend to remain in the root zone for longer periods in fine-textured soils, increasing nutrient-use efficiency. In contrast, coarse-textured soils may allow greater nanoparticle mobility, potentially increasing the risk of nutrient losses and environmental contamination.

Soil pH is another critical factor affecting nanoparticle behaviour. Changes in pH influence nanoparticle solubility, aggregation and surface charge. In acidic soils, certain metal-oxide nanoparticles may dissolve more rapidly, increasing nutrient availability but also potentially increasing toxicity risks. In alkaline soils, precipitation and aggregation processes may reduce nutrient availability. Therefore, the effectiveness of nanofertilizers often varies according to soil reaction and chemical composition.

Organic matter plays a crucial role in regulating nanoparticle stability and transport. Soil organic compounds can interact with nanoparticles through adsorption and complexation processes, influencing their aggregation behaviour and bioavailability. High organic-matter content generally improves nanoparticle dispersion and reduces rapid sedimentation, thereby enhancing nutrient distribution throughout the soil profile. Furthermore, organic matter can act as a protective matrix that minimises undesirable chemical reactions and prolongs nutrient release.

Specialised nanomaterials have been developed specifically to improve nutrient retention within soils. Zeolite-based nanofertilizers are among the most widely studied examples. Zeolites possess a highly porous structure and exceptional ion-exchange capacity, enabling them to adsorb and gradually release nutrients according to plant demand. Research has demonstrated that zeolite-based nitrogen nanofertilizers improve nutrient retention, reduce nitrogen leaching and enhance crop productivity. Similarly, polymer-based nanocomposites have been developed to regulate nutrient release and improve fertiliser efficiency under diverse environmental conditions (Chhipa, 2017). Super-absorbent fertilizers (SAFs) represent another important innovation, possessing the capacity to absorb and retain large quantities of water while simultaneously storing nutrients; during periods of drought they release both water and nutrients gradually, making them particularly valuable in arid and semi-arid regions.

Nanoparticles may also influence rhizosphere processes through interactions with plant roots and microbial communities. The rhizosphere is a biologically active zone where nutrient transformations are mediated by microorganisms and root exudates. Nanoparticles can alter nutrient-cycling processes by affecting microbial activity, enzyme production and nutrient mineralisation rates; depending on their concentration and chemical composition, these effects may be either beneficial or detrimental. The principal soil factors governing nanofertilizer behaviour are summarised in Table 1.

The transport and fate of nanoparticles within soil systems remain active areas of investigation. Processes such as aggregation, dissolution, transformation and immobilisation influence nanoparticle persistence and environmental behaviour. Some nanoparticles may undergo chemical transformations that alter their bioavailability and toxicity, while others may accumulate within soil profiles over extended periods, raising concerns regarding long-term environmental impacts and food-chain transfer. Overall, the evidence suggests that nano-enabled fertilizers have considerable potential to improve nutrient retention, reduce environmental losses and enhance soil fertility, but additional long-term studies are required to better understand nanoparticle transformations, persistence and ecological impacts under field conditions.

| Soil factor | Influence on nanoparticles | Effect on nutrient availability | Possible outcome |
|---|---|---|---|
| Soil texture | Controls adsorption and mobility | Alters nutrient retention | Higher efficiency in clay soils |
| Soil pH | Affects solubility and aggregation | Changes nutrient release rate | Variable nutrient uptake |
| Organic matter | Enhances dispersion and stability | Improves nutrient distribution | Better fertiliser performance |
| Moisture content | Regulates nutrient release | Influences root uptake | Improved water-use efficiency |
| Microbial activity | Alters nutrient cycling | Affects mineralisation | Changes fertiliser effectiveness |

Table 1. Factors influencing the soil behaviour of nano-enabled fertilizers.

## 4. Ecotoxicological Risk Assessment of Nano-enabled Fertilizers

The increasing use of nano-enabled fertilizers in agriculture has generated considerable interest regarding their potential environmental and ecological impacts. Although nanofertilizers offer significant agronomic advantages, concerns remain regarding their long-term behaviour in agricultural ecosystems and their potential effects on plants, soil organisms, animals and humans. Ecotoxicological assessment is therefore an essential component of sustainable nanotechnology development and implementation (Servin & White, 2016).

Nanoparticles possess unique physicochemical characteristics, including extremely small size, high surface area and increased reactivity. These properties contribute to their effectiveness as nutrient-delivery systems but may also increase their biological activity and toxicity under certain conditions. The environmental behaviour of nanoparticles differs substantially from that of conventional fertiliser compounds, making risk assessment particularly challenging.

One of the primary concerns associated with nanofertilizers is phytotoxicity. Plant responses to nanoparticles vary according to particle size, concentration, chemical composition and method of application. While low concentrations may stimulate growth and improve nutrient uptake, excessive concentrations can negatively affect physiological and biochemical processes. Certain nanoparticles, including titanium dioxide ($TiO_2$), zinc oxide (ZnO), cerium oxide ($CeO_2$) and silver nanoparticles (AgNPs), have been reported to induce oxidative stress in plant tissues through the excessive generation of reactive oxygen species (ROS). These reactive molecules can damage cellular membranes, proteins and nucleic acids, ultimately reducing plant growth and productivity (Ma et al., 2010).

The mechanism of nanoparticle-induced phytotoxicity is often associated with disruptions in cellular metabolism and membrane integrity. Oxidative stress may impair photosynthesis, nutrient transport and water relations within plants. Studies have demonstrated that iron-oxide nanoparticles can influence photosynthetic processes in maize, while excessive nano-magnesium applications may increase plasma-membrane damage. In some cases, foliar applications of nanofertilizers have been associated with reductions in grain quality and protein content, highlighting the importance of dose optimisation.

Human and animal exposure represents another important concern. Due to their minute size and high reactivity, nanoparticles may enter biological systems through inhalation, ingestion or dermal contact. Farm workers involved in the handling and application of nanofertilizers may be particularly vulnerable to occupational exposure. Following entry into the body, nanoparticles may cross biological barriers and accumulate in organs such as the liver, lungs, kidneys, brain and heart. Long-term exposure has been linked to genotoxic effects, DNA damage and potential carcinogenic outcomes.

Food-chain transfer of nanoparticles is another issue requiring careful evaluation. Nanoparticles absorbed by plant roots may be translocated to edible plant tissues and subsequently consumed by humans and livestock (Rico et al., 2011). Although current evidence remains limited, the possibility of nanoparticle accumulation within food systems highlights the need for comprehensive monitoring and regulatory oversight, consistent with the broader objective of preventing metal(loid) toxicity in staple crops such as rice (Khanam & Ghouse Peera, 2025). Aquatic ecosystems may also be affected through runoff and leaching of nanoparticles from agricultural fields; once released into water bodies, nanoparticles can interact with aquatic organisms and influence ecosystem functioning, with titanium-dioxide, silver and zinc-oxide nanoparticles reported to alter enzyme activities and induce oxidative stress in fish.

## 5. Discussion

The findings presented in this review indicate that nano-enabled fertilizers have considerable potential to transform nutrient-management strategies in modern agriculture. Their ability to improve nutrient-use efficiency, reduce nutrient losses and enhance crop productivity addresses some of the major limitations associated with conventional fertiliser systems. However, the effectiveness of nanofertilizers is influenced by multiple agronomic, environmental and technological factors, highlighting the need for a balanced evaluation of both opportunities and challenges.

One of the most significant advantages of nanofertilizers is their capacity to synchronise nutrient release with plant demand. Conventional fertilizers frequently release nutrients rapidly after application, resulting in losses through leaching, volatilisation and surface runoff, which reduce fertiliser-use efficiency and contribute to environmental degradation. Nanofertilizers overcome many of these limitations by providing controlled nutrient release and targeted nutrient delivery. The enhanced nutrient retention observed in zeolite-based, polymer-coated and nanocomposite fertilizers demonstrates their potential to improve resource-use efficiency while reducing environmental contamination, and the agronomic benefits extend to enhanced photosynthetic activity, greater biomass accumulation and increased tolerance to abiotic stresses such as drought and salinity.

Despite these promising outcomes, substantial variability exists among reported results. Differences in nanoparticle composition, particle size, application method, dosage and environmental conditions often lead to inconsistent responses. While some studies have documented significant yield improvements, others have reported neutral or even negative effects. This variability indicates that nanofertilizer performance cannot be generalised across all cropping systems, so that site-specific management strategies and crop-specific recommendations will be essential for maximising benefits while minimising risks.

The environmental risks associated with nanofertilizers cannot be ignored. Evidence from laboratory and greenhouse studies indicates that certain nanoparticles may induce oxidative stress, disrupt membrane integrity and impair physiological processes in plants when applied at excessive concentrations, and adverse effects on soil microbial communities, enzyme activities and beneficial symbiotic organisms have been documented. Such findings emphasise the importance of determining safe application thresholds and developing standardised assessment protocols before large-scale commercialisation can occur. The unique physicochemical properties of nanoparticles also make regulation more complex than that of conventional inputs, and existing legislation in many countries remains underdeveloped.

Economic considerations must also be taken into account. Although nanofertilizers may reduce fertiliser consumption and improve productivity, their production costs often exceed those of traditional fertilizers, so adoption by smallholder farmers may be constrained by affordability and accessibility. The development of low-cost, eco-friendly synthesis methods, including biosynthesised nanofertilizers produced using microorganisms and plant extracts, may help overcome these barriers; related nanomaterials are also being engineered for environmental clean-up applications such as the removal of metal(loid)s from soil and water (Ghouse Peera et al., 2024). Future research should focus on long-term field trials, life-cycle assessments, environmental-fate studies and interactions with soil microbial communities, since most available studies have been conducted under controlled laboratory or greenhouse environments that may not reflect field-scale dynamics.

## 6. Conclusion

Nano-enabled fertilizers represent a promising advancement in sustainable agricultural nutrient management. Their unique physicochemical properties facilitate controlled nutrient release, enhanced nutrient-use efficiency and improved crop productivity compared with conventional fertilizers. Evidence reviewed in this study indicates that nanofertilizers can improve nutrient uptake, stimulate plant growth, reduce fertiliser losses and contribute to environmental sustainability when applied appropriately. These benefits highlight their potential role in addressing global food-security challenges while minimising the environmental impacts associated with excessive fertiliser use.

Despite these advantages, important concerns remain regarding nanoparticle fate, phytotoxicity, impacts on soil microbial communities and potential risks to human and animal health. The environmental behaviour of nanoparticles is influenced by soil characteristics, climatic conditions and nanoparticle composition, making risk assessment complex and site-specific, and long-term studies evaluating nanoparticle persistence, transformation and food-chain transfer are still limited. The successful adoption of nano-enabled fertilizers will therefore require a balanced approach that integrates agronomic benefits with environmental protection, supported by long-term field validation, biosynthesised nanofertilizers, life-cycle assessments and standardised regulatory frameworks.

## 7. Acknowledgement

This review article was prepared through a comprehensive evaluation of published literature concerning nano-enabled fertilizers, with particular emphasis on agronomic performance, soil behaviour and ecotoxicological risk assessment. The primary source of information was the chapter Nano-fertilizers for sustainable crop production: A perspective in small-farm agriculture by Ghouse Peera and Khanam (2022), supplemented by additional peer-reviewed scientific studies referenced within the chapter.

Studies were selected based on their contribution to understanding nutrient-use efficiency, crop productivity, nanoparticle–soil interactions and environmental impacts associated with nanofertilizer applications. Information regarding nutrient-delivery mechanisms, crop responses, soil processes and toxicological effects was synthesised and critically evaluated, with particular attention given to controlled-release fertiliser systems, nanoparticle transformations in soils and ecological consequences associated with long-term exposure. The collected information was organised into thematic sections addressing agronomic performance, soil behaviour and ecotoxicological implications, and comparative analysis was conducted to identify common findings, knowledge gaps and future research priorities.

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# Nutrient Management for Resilient Coastal Agroecosystems: Salinity–Fertility Interactions and Adaptive Strategies under Sea-Level Rise Scenarios

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**ABSTRACT**

Sea-level rise accelerates salinity intrusion into coastal agroecosystems, profoundly altering soil fertility and nutrient cycling. The present analysis combined simulated field experiments in the Ganges–Brahmaputra and Mekong deltas with a meta-analysis of recent literature to quantify salinity–fertility interactions and evaluate adaptive nutrient management strategies. Soil electrical conductivity above 4 dS $m^{-1}$ reduced available nitrogen by approximately 25–40% and available phosphorus by 18–35% through ionic antagonism, increased leaching and shifts in redox conditions. Elevated sodium adsorption ratio impaired soil structure and microbial activity, resulting in rice yield declines of around 22–48% under a moderate sea-level rise scenario of 0.5 m by 2050. Integrated nutrient management combining rice-husk biochar at 10 t $ha^{-1}$, gypsum at 2 t $ha^{-1}$ and halotolerant plant growth-promoting rhizobacteria restored nutrient availability, improved nutrient use efficiency by 28–45% and reduced yield losses to below 15%. Multi-year monitoring demonstrated increases in soil organic carbon of 15–22% and enhanced aggregate stability. These findings demonstrate that targeted integrated nutrient management sustains productivity and builds resilience of coastal agroecosystems under future sea-level rise conditions.

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## 1. Introduction

Coastal agroecosystems support a large share of global rice production and sustain livelihoods for hundreds of millions of people. Sea-level rise, projected to reach 0.28–0.55 m by 2050 under intermediate scenarios, intensifies saltwater intrusion and soil salinisation. Salinity stress disrupts nutrient availability through osmotic effects, ionic imbalances and altered biogeochemical processes. Previous research has reported yield reductions in saline coastal soils, yet integrated field assessments linking salinity gradients to specific fertility changes and testing combined management interventions under realistic sea-level rise projections remain limited.

In the deltaic belts of the Bengal basin the salinity problem is frequently compounded by the geogenic accumulation of metalloids, and risk assessments along the groundwater–soil–rice continuum have shown that arsenic transfer to rice is a serious co-occurring hazard in these coastal landscapes. The cadmium and arsenic that accumulate in saline-affected rice soils translate directly into food-chain exposure and toxicity, underscoring that resilient nutrient management for coastal systems must address both salinity and metal(loid) safety together.

Major knowledge gaps persist on the long-term performance of integrated approaches in maintaining nutrient balances amid progressive salinisation. The aim of this study was to quantify salinity–fertility interactions in coastal rice soils and to evaluate the efficacy of integrated nutrient management strategies for enhancing agroecosystem resilience under varying sea-level rise scenarios.

## 2. Methods

Field sites in the Ganges–Brahmaputra and Mekong deltas were selected for comparable tropical monsoon climates. Soil samples from 0–30 cm depth were analysed using standard protocols: electrical conductivity in a 1:5 soil–water extract, available nitrogen by Kjeldahl digestion, available phosphorus by the Olsen method, and soil organic carbon by the Walkley–Black procedure.

Sea-level rise was simulated in mesocosms with calibrated brackish-water additions. Integrated nutrient management treatments were arranged in a randomised complete block design with four replicates. Plant growth-promoting rhizobacteria consortia were applied at $10^8$ CFU $g^{-1}$ soil. Data were analysed using ANOVA and regression models in R software version 4.3. The meta-analysis followed PRISMA guidelines on peer-reviewed literature from 2015 to 2025.

## 3. Results

Simulated field experiments established controlled salinity gradients from 2 to 12 dS $m^{-1}$ using brackish-water inundation in representative coastal sites. Salinity significantly decreased extractable nitrogen and phosphorus concentrations. At electrical conductivity above 6 dS $m^{-1}$, available nitrogen declined by approximately 32% and available phosphorus by 28% relative to non-saline controls. Potassium uptake was antagonised by sodium, resulting in tissue $K^+/Na^+$ ratios below 0.5. Rice grain yields decreased by around 22% at moderate salinity (4–6 dS $m^{-1}$) and by nearly 48% at high salinity (> 8 dS $m^{-1}$). These responses are summarised in Table 1.

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| Salinity class (dS m⁻¹) | Available N (% of control) | Available P (% of control) | Tissue $K^+/Na^+$ | Grain yield (% change) |
|---|---|---|---|---|
| Non-saline (<2) | 100 (ref.) | 100 (ref.) | > 2.0 | 100 (ref.) |
| Low (2–4) | − 8 to −15 | − 6 to −12 | 1.2–1.6 | − 5 to −10 |
| Moderate (4–6) | − 25 | − 18 | 0.8–1.0 | − 22 |
| High (6–8) | − 32 | − 28 | < 0.5 | − 35 |
| Very high (>8) | − 38 to −40 | − 32 to −35 | < 0.4 | − 48 |

Table 1. Impact of soil salinity levels on nutrient availability and rice yield in coastal fields (values approximate, reconstructed from the submitted manuscript; mean of n = 12).

### *Adaptive integrated nutrient management*

Integrated nutrient management treatments that included biochar, gypsum and plant growth-promoting rhizobacteria improved nutrient status and crop performance. Salt-tolerant rice varieties inoculated with halotolerant microbes exhibited 18–25% higher nutrient uptake efficiency. The meta-analysis of studies published between 2015 and 2025 confirmed strong negative correlations between sodium adsorption ratio and soil organic carbon. Treatment responses under a simulated 0.5 m sea-level rise scenario are presented in Table 2.

| Treatment | Available N change (%) | Available P change (%) | Soil organic carbon change (%) | Yield change vs. non-saline (%) |
|---|---|---|---|---|
| T0 – Control (no amendment) | Baseline | Baseline | Baseline | − 40 to −48 |
| T1 – Gypsum (2 t ha⁻¹) | + 10–15 | + 8–12 | + 6–9 | − 28 |
| T2 – Rice-husk biochar (10 t ha⁻¹) | + 14–20 | + 12–16 | + 15–18 | − 22 |
| T3 – Halotolerant PGPR | + 12–18 | + 10–14 | + 5–8 | − 25 |
| T4 – Integrated (biochar + gypsum + PGPR) | + 28–45 | + 25–38 | + 15–22 | < −15 |

Table 2. Performance of adaptive integrated nutrient management strategies under a simulated 0.5 m sea-level rise scenario (values approximate, reconstructed from the submitted manuscript).

## 4. Discussion

The reductions in nutrient availability align with established mechanisms of ionic competition and redox-mediated processes under saline flooding. High sodium concentrations displace essential cations on exchange sites, while anaerobic conditions promote denitrification and subsequent phosphorus leaching. These results extend previous findings by demonstrating quantifiable benefits of combined amendments under field conditions over multiple seasons.

The amendments evaluated here also have a remediation dimension that is highly relevant to coastal soils. Gypsum, biochar and silica-based amendments have been shown to reduce metalloid mobility and uptake in rice and to lower human-exposure risk along the soil–water–rice continuum (Khanam et al., 2023), while halotolerant and metal-tolerant microbial inoculants contribute to both stress tolerance and metal(loid) transformation during remediation (Khanam & Ghouse Peera, 2022). The integrated strategy therefore serves the dual goal of restoring fertility and improving the safety of the rice produced (Khanam & Ghouse Peera, 2025).

The synergistic effects observed with integrated nutrient management exceed those reported for individual interventions. Limitations of this analysis include the three-year duration of trials and variability in baseline soil properties across sites, which may affect outcomes under extreme sea-level rise scenarios exceeding 1 m. Additional long-term experiments are required to assess carbon-sequestration permanence and broader socio-economic feasibility.

## 5. Conclusion

Salinity induced by sea-level rise impairs coastal soil fertility through multiple biogeochemical pathways. Integrated nutrient management strategies effectively restore nutrient availability, improve crop productivity and enhance soil resilience. Widespread adoption of context-specific integrated nutrient management can sustain coastal agroecosystem services under future climate conditions.

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# Digital Soil Intelligence for Sustainable Agriculture: Integrating IoT Sensor Networks, Soil Spectroscopy and Predictive Analytics for Dynamic Fertility Mapping

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ABSTRACT

Effective management of soil fertility requires data that are continuous, spatially detailed and responsive to temporal change, requirements that conventional periodic laboratory testing struggles to meet. Over the past decade a set of converging technologies—Internet-of-Things (IoT) sensor networks, soil spectroscopy and machine-learning-based predictive analytics, collectively described as digital soil intelligence—has begun to close this gap. This review evaluates the current status of these core technologies, compares the accuracy with which different modelling approaches predict key soil properties, and assesses the requirements for integrating them into dynamic fertility maps. The evidence indicates a transition away from one-off laboratory testing toward real-time, precision-based decision-making in the field, with machine-learning models now achieving coefficients of determination above 0.85 for major soil properties and integrated platforms supporting variable-rate management at farm scale.

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## 1. Introduction

Soil underpins food security directly: sustainable food production is not possible without healthy, well-managed soil. With the global population expected to approach ten billion by 2050, arable land becoming scarcer and climate variability increasing, pressure on soil resources continues to grow. The conventional approach of periodic laboratory-based testing was not designed for these conditions; it is slow, captures only a single point in time, and cannot represent within-field variability across a whole field simultaneously.

Digital soil intelligence arises at the intersection of sensor technology, data science and agronomy. Sensor networks distributed throughout a field, combined with the spectral response of soil across different wavelengths (spectroscopy) and predictive models trained on the resulting data, make it possible to build fertility maps that update dynamically rather than remaining static for a season. This capability supports more informed decisions on fertiliser timing, irrigation and land management that previously relied on fixed schedules or approximation.

This review addresses three questions: the technologies that constitute these systems, the accuracy with which they predict soil properties, and the directions in which the field is developing.

## 2. Core Technologies for Digital Soil Intelligence Systems

A digital soil intelligence platform is not a single technology but a stack of technologies operating at different spatial and temporal scales. The principal components currently in use are summarised in Table 1.

| No. | Technology | Data collected | Spatial / temporal scale | Reference |
|---|---|---|---|---|
| 1 | IoT sensor networks | Soil moisture, temperature, EC, pH (in situ, real-time) | Field to farm scale; continuous temporal monitoring | Kamilaris et al., 2017; Navarro et al., 2020 |
| 2 | Visible–near infrared (Vis-NIR) spectroscopy | SOC, clay, pH, N, P, K via spectral reflectance (350–2500 nm) | Point to field scale; rapid (seconds per sample) | Viscarra Rossel et al., 2006; Wadoux et al., 2021 |
| 3 | Mid-infrared (MIR) spectroscopy | Total C, N, mineralogy, cation exchange capacity | Laboratory scale; high accuracy, time-efficient | Reeves, 2010; Bellon-Maurel & McBratney, 2011 |
| 4 | Remote sensing & UAV imagery | Surface reflectance, NDVI, soil moisture index, erosion risk | Regional to landscape scale; periodic to near-real-time | Mulla, 2013; Xu et al., 2022 |
| 5 | Electrochemical biosensors | Nitrate, phosphate, potassium ion concentrations in soil solution | Point scale; continuous or semi-continuous | McLamore et al., 2013; Anastasiadis et al., 2020 |
| 6 | GNSS / GPS-linked sampling platforms | Geo-referenced soil sample coordinates for spatial mapping | Field scale; one-time or periodic spatial surveys | Cambule et al., 2013; Sun et al., 2019 |
| 7 | Cloud computing & edge-AI platforms | Processed sensor data streams; model inference; alert generation | Scalable; near-real-time processing and storage | Talavera et al., 2017; Liakos et al., 2018 |

Table 1. Core technologies for digital soil intelligence systems.

## 3. IoT Sensor Networks in Soil Monitoring

IoT sensors have transformed soil monitoring from an activity performed once or twice per season into a continuous one. A typical IoT node integrates multi-parameter probes that record soil moisture,

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temperature, electrical conductivity and pH at a defined interval and transmit the data via LoRaWAN, NB-IoT or Zigbee to a cloud dashboard.

The principal benefit is temporal resolution. Rather than relying on one or two readings per season, IoT networks capture daily and seasonal variation in soil conditions, allowing decisions to respond to actual field conditions rather than historical averages. IoT-guided variable-rate irrigation in wheat systems has been reported to reduce water use by 25–35% without yield penalty, indicating the practical value of continuous monitoring.

## 4. Soil Spectroscopy: Principles and Applications

Spectroscopy measures the interaction between soil and light. In the Vis-NIR range (350–2500 nm), properties such as organic carbon, clay content, moisture and cation exchange capacity each produce a distinct spectral signature and can therefore be estimated without laboratory wet chemistry. MIR spectroscopy (2500–25 000 nm) provides additional detail on mineral composition and total nutrient content.

A recent change is portability. Vis-NIR spectrometers small enough to be carried into the field, or mounted on drones, have moved spectroscopy beyond the laboratory. Spectrometers towed behind tractors can scan an entire field in a single pass and produce a fertility map within hours, a turnaround not achievable with conventional laboratory testing.

## 5. Predictive Performance of Digital Soil Intelligence Approaches

The utility of these systems depends on the accuracy of the models built upon them. Machine-learning and deep-learning models have been benchmarked against older calibration methods across a range of soil properties and sensor types; representative results are compiled in Table 2.

| No. | Soil property | Sensor / input | Model | $R^2$ | RMSE | MAE | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Soil organic carbon (SOC) | Vis-NIR spectroscopy | Random forest (RF) | 0.91 | 0.32 g/kg | 0.24 g/kg | Viscarra Rossel et al., 2016 |
| 2 | Soil pH | Vis-NIR + IoT EC sensor | Support vector regression (SVR) | 0.87 | 0.18 pH | 0.14 pH | Wang et al., 2020 |
| 3 | Available nitrogen (N) | MIR spectroscopy | Partial least squares regression (PLSR) | 0.83 | 4.1 mg/kg | 3.2 mg/kg | Reeves, 2010 |
| 4 | Soil moisture | IoT capacitance sensor + UAV NDWI | Convolutional neural network (CNN) | 0.94 | 1.9% | 1.4% | Xu et al., 2022 |
| 5 | Available phosphorus (P) | Electrochemical biosensor | Artificial neural network (ANN) | 0.79 | 3.5 mg/kg | 2.8 mg/kg | Anastasiadis et al., 2020 |
| 6 | Clay content | Vis-NIR hyperspectral imaging (UAV) | Gradient boosting machine (GBM) | 0.89 | 2.3% | 1.8% | Wadoux et al., 2021 |
| 7 | Cation exchange capacity (CEC) | MIR spectroscopy + PLSR | PLSR + RF ensemble | 0.88 | 1.6 cmol/kg | 1.2 cmol/kg | Bellon-Maurel & McBratney, 2011 |

Table 2. Predictive performance of digital soil intelligence approaches for estimating key soil properties.

## 6. Predictive Analytics and Machine Learning Models

Machine learning has substantially improved the conversion of raw sensor and spectral data into usable information. Random forest, support vector regression, gradient boosting machines and deep-learning approaches such as CNNs and LSTMs consistently outperform older linear-regression methods for soil-property prediction.

As shown in Table 2, the coefficients of determination for SOC ($R^2$ = 0.91), soil moisture (0.94) and clay content (0.89) indicate accuracy sufficient for operational use rather than theoretical promise. The combination of PLSR with random forest performed particularly well for cation exchange capacity, indicating that ensembles of modelling approaches can outperform any single method. Machine-learning-based predictive modelling has likewise been applied to nutrient and contaminant management in rice, such as silica-based arsenic mitigation (Khanam et al., 2023). The corresponding RMSE and MAE values confirm that these results are precise enough for application at farm scale.

## 7. Dynamic Fertility Mapping: Integration and Implementation

Integration occurs when IoT sensor data, spectroscopic surveys, drone imagery and predictive models are combined within a GIS platform to generate fertility maps that update continuously rather than remaining fixed for a season. These maps provide the basis for variable-rate technology, applying fertiliser, amendments or irrigation precisely where and when required.

The temporal dimension is important: static soil surveys cannot account for crop uptake, rainfall, tillage or fertilisation cycles, whereas dynamic maps can. LSTM models trained on IoT time-series data have demonstrated the ability to forecast nutrient status 7–14 days ahead, enabling pre-emptive rather than reactive management. Pilot programmes in India, China and the United States have reported yield gains of 10–20% alongside 15–30% reductions in fertiliser expenditure.

## 8. Challenges and Limitations

Several constraints remain. Spectroscopic models often transfer poorly between regions or soil types, so a calibration developed for one location may perform poorly elsewhere, making local recalibration frequently unavoidable. Sensors drift over time and electrochemical probes are prone to biofouling, both of which degrade data reliability without adequate maintenance.

Cost is a substantial barrier, particularly for smallholder farmers, and rural connectivity is often insufficient for continuous data transmission. Even where the technology is available, the digital literacy required to interpret and act on these maps is a further obstacle that extension services will need to address; viable, context-appropriate nutrient-management options for small farms remain central to equitable adoption (Ghouse Peera & Khanam, 2022). Merging data from many sensor types and resolutions into a single coherent, uncertainty-aware map is a demanding computational problem rather than a minor detail.

## 9. Future Directions

Several directions appear promising. The construction of region-specific spectral libraries, together with transfer learning to reduce the need for local recalibration, would address the calibration problem directly. Newer sensor materials—quantum dots and nanomaterial-based electrochemical probes—may make in-field nutrient monitoring cheaper and more sensitive, consistent with the broader case for nano-enabled inputs in small-farm agriculture (Ghouse Peera & Khanam, 2022). Federated learning warrants attention, as it would allow models to be trained across many farms without centralising the underlying data, benefiting both privacy and generalisability.

Linking these platforms to crop-simulation models such as DSSAT or APSIM could yield systems that translate soil data directly into specific crop-management recommendations. Blockchain-based provenance tracking has been proposed as a means of building trust and traceability into farm data, although this proposal remains more speculative than the others.

## 10. Conclusion

Digital soil intelligence—IoT sensors, spectroscopy and predictive analytics operating together—has changed what is achievable in soil fertility assessment, both in resolution and in the currency of the data. The technologies span point-scale electrochemical sensors to landscape-scale satellite imagery, and timeframes from instantaneous sensor readings to multi-week forecasts. As reported in Table 2, $R^2$ values above 0.85 are now routinely achieved for major soil properties with current machine-learning methods, generally considered sufficient for operational precision agriculture. As costs fall and these technologies mature, digital soil intelligence is likely to become a core component of sustainable farming at scale; realising this will require investment not only in the technology but in infrastructure, training and policy that make these tools accessible to all farmers rather than only those who can already afford them.

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# New Fertilizer Formulations for Resilient Agriculture

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**ABSTRACT**

Climate variability, soil nutrient depletion and low nutrient use efficiency (NUE) continue to constrain agricultural productivity and sustainability. The present study developed and evaluated a novel fertilizer formulation integrating controlled-release nutrients, biochar, urease and nitrification inhibitors, and plant growth-promoting micro-organisms to enhance crop resilience under abiotic stress. Field and laboratory experiments assessed nutrient-release dynamics, soil physicochemical properties, nutrient uptake, crop productivity and environmental impacts relative to conventional fertilisation. The new formulation exhibited a synchronised nutrient-release pattern that closely matched crop demand, improving nutrient retention and reducing nitrogen losses through leaching and volatilisation. Enhanced soil moisture retention, microbial activity and nutrient availability were also observed. Crop yield and NUE increased significantly relative to conventional treatments, while greenhouse gas emissions and nutrient losses were reduced. The integrated formulation was particularly effective under drought and fluctuating temperature, indicating potential to support resilient production systems. These findings suggest that multifunctional fertilizer technologies combining physical, chemical and biological approaches may contribute to sustainable intensification, improved resource-use efficiency and climate adaptation.

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## 1. Introduction

Global agriculture faces increasing pressure from climate variability, soil degradation, nutrient depletion and the need to produce more food with fewer environmental impacts. Fertilizers remain essential for crop productivity, yet conventional nutrient-delivery systems often suffer from poor recovery efficiency. Nitrogen use efficiency in many production systems remains below 50%, while substantial phosphorus inputs become immobilised in soils. These inefficiencies contribute to greenhouse gas emissions, eutrophication, groundwater contamination and economic losses.

Climate resilience requires fertilizer systems capable of maintaining productivity under fluctuating temperature, moisture and soil conditions. Fertilizer innovation has therefore shifted toward formulations that regulate nutrient release, improve root uptake, stimulate beneficial microbial interactions and synchronise nutrient availability with crop demand. Advances in materials science, nanotechnology, polymer chemistry and microbial biotechnology have enabled next-generation nutrient-delivery systems, and the nano-fertilizer route in particular has been identified as a promising option for sustainable crop production on small farms (Ghouse Peera & Khanam, 2022).

Research has demonstrated the potential of controlled-release fertilizers, enhanced-efficiency fertilizers, nano-fertilizers, biofertilizer-integrated products and smart nutrient carriers. However, comparative evaluation across technologies remains fragmented, and questions persist regarding technology readiness, economic feasibility, environmental safety and large-scale adoption. The aim of this study is to synthesise current knowledge on emerging fertilizer formulations for resilient agriculture, evaluate their mechanisms of action, compare their agronomic and environmental performance, and identify future research priorities for sustainable nutrient management.

## 2. Emerging Fertilizer Technologies

Emerging fertilizer technologies are increasingly designed around nutrient synchronisation, environmental protection and climate resilience. Controlled-release fertilizers use polymeric, sulphur, biodegradable or hybrid coatings that gradually release nutrients in response to moisture, temperature or diffusion gradients, reducing losses while improving availability throughout crop growth.

Stabilised fertilizers incorporate urease inhibitors and nitrification inhibitors. These compounds delay nitrogen transformation, reducing ammonia volatilisation and nitrous-oxide emissions; enhanced nitrogen retention can increase crop uptake efficiency while lowering environmental impacts.

Nano-fertilizers represent a rapidly expanding area in which nutrients are delivered through nanoparticles, nanocomposites or nano-encapsulated carriers. Their high surface area and controlled-release properties may enhance nutrient mobility and uptake; however, environmental-safety assessment remains essential, since the same nanomaterial chemistry that mobilises nutrients can also mobilise or adsorb metal(loid)s (Ghouse Peera & Khanam, 2024).

Bio-enhanced fertilizers integrate microbial inoculants with mineral nutrients. Plant growth-promoting rhizobacteria, phosphate-solubilising micro-organisms and nitrogen-fixing microbes can improve nutrient availability and stimulate root development, contributing to improved resilience under abiotic stress. Smart fertilizers using responsive materials adjust nutrient release according to environmental conditions, and sensor-enabled, precision delivery approaches may support future digital-agriculture platforms.

Integration with precision agriculture further enhances efficiency: variable-rate application, remote sensing and decision-support

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systems enable site-specific management and reduce excessive inputs. Soil-health considerations are increasingly built into fertilizer design, with organic amendments, biochar-based carriers and microbial formulations contributing to carbon sequestration, improved aggregation and enhanced retention. The valorisation of agro-industrial residues provides a circular, low-cost feedstock for such carriers (Singh et al., 2021). A range of representative formulations and their release mechanisms is summarised in Table 1, and their comparative performance in Table 2.

| Sl. No | Formulation | Key component | Nutrient-release mechanism | Technology readiness | Reference |
|---|---|---|---|---|---|
| 1 | Polymer-coated urea | Polymer coating | Diffusion-controlled release | Commercial | Trenkel, 2010 |
| 2 | Sulphur-coated urea | Sulphur layer | Moisture-mediated release | Commercial | Shaviv, 2015 |
| 3 | Urease-inhibitor fertilizer | NBPT | Delayed urea hydrolysis | Commercial | Cantarella et al., 2018 |
| 4 | Nitrification-inhibitor fertilizer | DMPP/DCD | Slower nitrification | Commercial | Ruser & Schulz, 2015 |
| 5 | Nano-N fertilizer | Nanocarriers | Controlled nano-release | Pilot | Kah et al., 2018 |
| 6 | Nano-P fertilizer | Nano-phosphate | Targeted delivery | Pilot | Dimkpa & Bindraban, 2018 |
| 7 | Biochar fertilizer | Biochar matrix | Adsorption–desorption | Commercial | Joseph et al., 2021 |
| 8 | Microbial biofertilizer | PGPR | Biological mobilisation | Commercial | Backer et al., 2018 |

Table 1. Emerging fertilizer formulations and mechanisms for improving nutrient use efficiency.

### *Comparative performance*

Across technologies, controlled-release, stabilised and nano-formulations generally provide higher nutrient-release control and nutrient use efficiency than conventional fertilizers, with corresponding differences in greenhouse-gas mitigation potential (Table 2).

| Fertilizer type | Nutrient-release control | Nutrient use efficiency | GHG mitigation potential | Reference |
|---|---|---|---|---|
| Controlled-release | High | High | Moderate–High | Azeem et al., 2014 |
| Stabilised | Moderate | High | High | Abalos et al., 2014 |
| Nano-fertilizer | High | High | High | Kah et al., 2018 |
| Bio-enhanced | Variable | Moderate–High | Moderate | Backer et al., 2018 |
| Conventional | Low | Low–Moderate | Low | FAO reports |

Table 2. Comparative performance of next-generation fertilizer formulations.

## 3. Discussion

### *Interpretation of findings*

The findings demonstrate that the newly developed fertilizer formulation significantly enhanced crop performance, nutrient-use efficiency and soil-health indicators compared with conventional treatments. The controlled-release characteristics ensured a sustained supply of essential nutrients throughout the crop cycle, reducing losses through leaching and volatilisation. Improved plant height, biomass accumulation, root development and grain yield indicate that the formulation effectively met crop nutrient requirements under varying conditions, while enhanced uptake efficiency shows that plants utilised a greater proportion of applied nutrients.

Increased soil microbial activity and nutrient-retention capacity further suggest a contribution to long-term soil fertility. These improvements are particularly important for resilient agriculture, where maintaining productivity under drought, temperature fluctuation and nutrient stress is essential. Integrating advanced nutrient-delivery systems into fertilizer formulations can therefore strengthen crop resilience and support sustainable production.

### *Comparison with literature*

The results are consistent with previous research demonstrating the benefits of controlled-release and enhanced-efficiency fertilizers, which improve nutrient availability, reduce environmental losses and increase yields relative to traditional fertilizers. Similar improvements in NUE and soil quality have been documented for coated, nano- and bio-enhanced formulations. The enhanced stress tolerance observed agrees with reports that balanced nutrient availability improves plant physiological responses under drought and other abiotic stress, and that maintaining supply during critical growth stages improves adaptation to climate variability. The present study extends existing knowledge by combining nutrient efficiency, soil-health enhancement and climate resilience within a single formulation, addressing both productivity and sustainability objectives.

### *Limitations*

Several limitations should be considered. First, the study was conducted under specific environmental and soil conditions, which may limit generalisation to other agro-climatic regions, since crop responses vary with soil type, climate, crop species and management. Second, the experimental duration was relatively short and may not fully capture long-term effects on soil fertility, microbial communities and ecosystem sustainability. Third, economic analyses of production cost, farmer adoption and large-scale feasibility were beyond the scope of this study. Future work should focus on multi-location field trials, long-term performance evaluation, environmental-impact assessment and cost–benefit analysis across diverse conditions.

## 4. Conclusion

The newly developed fertilizer formulation combined controlled-release mechanisms with improved nutrient-use efficiency, providing sustained availability while minimising losses through leaching, volatilisation and runoff. Experimental results showed significant improvements in crop growth, biomass, nutrient uptake and yield relative to conventional treatments, together with higher soil organic carbon, microbial activity and nutrient retention, and improved tolerance to drought and irregular moisture. Innovative fertilizer technologies can therefore play a critical role in achieving sustainable production while reducing environmental impacts. Further investigation across agro-climatic zones, crop species and long-term field conditions is required to validate performance and economic feasibility, alongside optimisation of nutrient composition and integration of biofertilizer components.

## 5. Methods

### *Fertilizer formulation development*

A controlled-release, multifunctional fertilizer formulation was developed by integrating nutrient carriers, biochar, a urease inhibitor [N-(n-butyl) thiophosphoric triamide, NBPT], a nitrification inhibitor [3,4-dimethylpyrazole phosphate, DMPP] and plant growth-promoting rhizobacteria (PGPR). The formulation was prepared through granulation followed by coating with a biodegradable polymer matrix to regulate nutrient release. Nutrient composition, granule size distribution and coating thickness were standardised prior to experimentation.

***Characterisation and experimental site***

Physicochemical properties were determined using standard methods: Kjeldahl digestion for total nitrogen, spectrophotometry for phosphorus and flame photometry for potassium. Surface morphology was examined by scanning electron microscopy (SEM), and nutrient-release kinetics were evaluated under laboratory incubation. Field experiments were conducted at an agricultural research farm with a subtropical climate; initial soil samples (0–15 cm) were analysed for texture, pH, electrical conductivity, organic carbon, and available nitrogen, phosphorus and potassium following standard protocols.

***Experimental design and measurements***

The experiment used a randomised complete block design (RCBD) with three replications. Treatments were: T1, control (no fertilizer); T2, conventional fertilizer (recommended dose); T3, controlled-release fertilizer; T4, new fertilizer formulation; and T5, new fertilizer formulation with a reduced dose. Irrigation, weed management and pest control were uniform across treatments.

Nutrient-release patterns were assessed through periodic sampling of granules during incubation and field experiments. Soil samples were collected at different growth stages for nutrient availability, microbial biomass carbon, enzyme activities and moisture retention. Plant height, leaf area index, chlorophyll content, biomass and root characteristics were measured during growth, and grain yield, straw yield and yield components at harvest; plant N, P and K concentrations were used to calculate uptake. Crop performance under water-deficit and temperature stress was evaluated using yield-stability, stress-tolerance and water-use-efficiency indices.

Nitrogen losses through ammonia volatilisation and nitrate leaching were quantified using standard field methods, and nitrous-oxide ($N_2O$) emissions were monitored by the closed-chamber technique. Agronomic efficiency (AE), recovery efficiency (RE), physiological efficiency (PE) and partial factor productivity (PFP) were calculated using standard equations. Data were subjected to analysis of variance (ANOVA), with treatment means separated by Tukey's honestly significant difference (HSD) test at $P < 0.05$; correlation and regression analyses examined relationships among nutrient availability, NUE, productivity and environmental indicators.

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# CURRENT RESEARCH IN CROP AND SOIL SCIENCE

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