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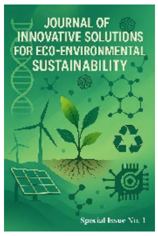

Review Article

Next-Generation Nutrient Management Strategies for Rice: Enhancing Productivity and Soil Quality for Sustainable Development

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ABSTRACT

Rice is a staple food for more than half of the global population, underscoring the importance of sustainably intensifying rice production systems to ensure food security. Conventional nutrient management practices often lead to inefficient nutrient use, environmental contamination, and soil degradation. This review synthesizes recent developments in next-generation nutrient management strategies designed to improve both rice productivity and soil quality. Specifically, it examines site-specific nutrient management, controlled-release fertilizers, integrated nutrient management, digital agriculture tools, microbial biofertilizers, and conservation agriculture practices. These approaches are evaluated for their potential to increase nitrogen use efficiency, minimize environmental impacts, enhance soil health, and sustain or boost yield potential. The review also addresses implementation challenges in various rice ecosystems and proposes a framework for context-specific adoption. Ultimately, it identifies future research priorities, emphasising the need for a comprehensive evaluation of these technologies across multiple growing seasons and diverse agroecological zones.

1. Introduction

Rice (*Oryza sativa* L.) is the primary food source for more than 3.5 billion people worldwide and provides approximately 20% of the global dietary energy [1,2]. With the global population projected to reach 9.7 billion by 2050, rice production is expected to increase by an estimated 42% to meet the growing demand [3,4]. However, this production increase must occur within significant constraints: diminishing arable land, increasing water scarcity, labour shortages, and mounting pressure to reduce the environmental impacts of agriculture [5].

Conventional rice cultivation typically relies on high inputs of synthetic fertilizers, especially nitrogen (N), phosphorus (P), and potassium (K), to achieve maximum yields. Global fertilizer consumption in rice cultivation has increased substantially over recent decades, with nitrogen application rates in many Asian countries exceeding 200 kg N ha^{-1} per season [6]. However, this intensive fertilizer use has resulted in diminishing returns in terms of yield increases while contributing to significant environmental problems, including greenhouse gas emissions, water eutrophication, soil acidification, and reduced microbial diversity [7,8]. The average nitrogen use efficiency (NUE) in global rice systems remains alarmingly low, with estimates ranging from 30-40% [9,10]. This inefficiency represents both an economic loss for farmers and a significant environmental burden. Phosphorus use efficiency is similarly problematic, with most applied P becoming fixed in soils and unavailable for plant uptake [11]. Meanwhile, long-term intensive rice cultivation has led to deteriorated soil quality in many regions, characterized by decreased soil organic carbon, reduced biological activity, compaction, and micronutrient deficiencies [12,13].

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Sustainable intensification has emerged as a framework for addressing these challenges, aiming to increase agricultural production while reducing environmental impacts and enhancing resource use efficiency [14,15]. Within this context, next-generation nutrient management strategies represent a paradigm shift from conventional blanket fertilizer recommendations toward knowledge-intensive, precision-based approaches that optimize nutrient supply according to crop demand, soil conditions, and environmental constraints [16,17]. The objectives of this review are to: (1) synthesize recent advances in next-generation nutrient management strategies for rice cultivation, (2) evaluate their effectiveness in enhancing both productivity and soil quality, (3) identify implementation challenges across diverse rice ecosystems, and (4) propose future research directions to address knowledge gaps. This review examines six promising approaches: site-specific nutrient management, controlled-release fertilizers, integrated nutrient management, digital agriculture applications, microbial biofertilizers, and conservation agriculture practices. These strategies represent a continuum from incremental improvements to transformative changes in rice nutrient management.

2. Current Challenges in Rice Nutrient Management

2.1. Low Nutrient Use Efficiency

Despite decades of research and extension efforts, nitrogen use efficiency in rice cultivation remains suboptimal. Global estimates suggest that rice crops utilize only 30-40% of applied nitrogen [9], with the remainder being lost through various pathways, including ammonia volatilization, denitrification, leaching, and runoff [18]. In flooded rice systems, nitrogen losses are particularly pronounced due to rapid nitrification-denitrification cycles and ammonia volatilization, which can account for up to 50% of applied N under certain conditions [19]. Similar challenges exist for phosphorus management. Though rice requires substantial P for optimal growth and yield formation, only 15-30% of applied P fertilizers are typically utilized by the crop in the season of application [11]. The remainder becomes rapidly fixed in soil minerals or organic compounds, leading to P accumulation in soils yet, paradoxically, the continued need for P fertilization to meet crop demands [20]. Potassium use efficiency varies widely in rice systems, ranging from 40% to 60%, depending on soil type, management practices, and environmental conditions [21]. In many intensive rice systems, particularly in Asia, soil K mining has occurred due to imbalanced fertilization focusing predominantly on N and P [22]. Micronutrient deficiencies have emerged as additional challenges in many rice-growing regions. Zinc deficiency affects approximately 50% of rice soils globally, while deficiencies in iron, manganese, copper, and boron are also increasingly reported [23,24]. These deficiencies not only limit productivity but also affect grain nutritional quality.

2.2. Environmental Impacts

The environmental consequences of inefficient nutrient management in rice systems are substantial and wide-ranging. Rice cultivation contributes significantly to agricultural greenhouse gas emissions, accounting for approximately 10% of global agricultural methane emissions and substantial nitrous oxide emissions, mainly from alternate wetting and drying systems [25]. Nitrous oxide (N_2O) has a global warming potential approximately 300 times that of CO_2, making even small emissions significant in terms of climate impact [26]. Water quality impacts are equally concerning. Nitrogen and phosphorus losses from rice fields contribute to the eutrophication of surface waters, harmful algal blooms, and hypoxic "dead zones" in coastal areas [27]. In major rice-growing regions such as the Yangtze River basin in China, the Mekong Delta, and the Mississippi River basin, agricultural nutrient runoff has been identified as a primary driver of water quality degradation [28,29]. Soil acidification represents another significant environmental impact of intensive nitrogen fertilization. Long-term studies have documented pH declines in rice soils receiving high ammonium-based fertilizer applications, with consequent effects on nutrient availability and soil biological function [7]. This acidification can enhance the mobility of heavy metals in soils, potentially increasing their uptake by rice plants and raising concerns about food safety [30].

2.3. Soil Quality Deterioration

Intensive rice cultivation has led to widespread deterioration in soil quality in many production regions. Declining soil health is evident in soil organic carbon depletion, as conventional puddling and intensive tillage accelerate organic matter decomposition, reducing soil carbon sequestration and storage [31,32,33]. Repeated puddling in conventional rice systems destroys soil aggregates, increases bulk density, and forms hardpans that restrict root growth and water movement [34]. High-input systems often exhibit reduced soil biodiversity, including lower populations of beneficial organisms such as earthworms, mycorrhizal fungi, and nitrogen-fixing bacteria [12]. A focus on macronutrients has led to micronutrient depletion in many rice soils, and imbalanced nitrogen-to-phosphorus ratios have produced antagonistic effects on nutrient uptake [22]. In irrigated rice systems, especially in arid and semi-arid regions, improper water management and fertilization have contributed to soil salinization and sodification [35]. Collectively, these soil quality challenges create a negative feedback loop: declining soil health requires increased fertilizer inputs to maintain yields, which further intensifies environmental impacts and economic pressures on farmers.

2.4. Climate Change Impacts

Climate change significantly complicates the management of rice nutrients. Rising temperatures accelerate soil organic matter decomposition, which can increase nitrogen mineralization rates and nitrogen losses [36,37]. Extreme weather events, such as floods and droughts, disrupt nutrient cycling, leading to increased nutrient losses during heavy rainfall and reduced nutrient availability during droughts [38]. Elevated atmospheric CO_2 concentrations generally increase rice biomass and yield potential, thereby raising nutrient demand [39]. However, elevated CO_2 has also been shown to reduce grain protein content and mineral concentrations, which presents concerns regarding nutritional quality [40]. Addressing these interconnected challenges requires the development of nutrient management strategies that enhance productivity, protect environmental and soil quality, and improve resilience to climate variability.

3. Site-Specific Nutrient Management

3.1. Principles and Approaches

Site-specific nutrient management (SSNM) marks a significant shift from uniform fertilizer recommendations to nutrient applications tailored to field-specific conditions and crop requirements. The main principle of SSNM is to synchronize nutrient supply with the specific demands of the rice crop, considering indigenous nutrient sources from soil, water, and organic inputs [16]. Developed by the International Rice Research Institute (IRRI) in partnership with national agricultural research systems in Asia, SSNM involves several key steps. These include estimating attainable yield targets based on climate, variety, and management practices; determining indigenous nutrient supplies through soil testing, omission plots, or crop nutrient status assessments; and calculating crop nutrient requirements using yield targets and nutrient removal rates. SSNM also emphasizes optimizing the timing of nutrient applications to coincide with critical growth stages and adjusting management based on in-season crop monitoring. Several frameworks have emerged from these principles. Nutrient Expert (NE) is a decision support system that generates field-specific fertilizer recommendations without extensive soil testing [41]. The Rice Crop Manager (RCM) is a web-based tool that provides recommendations for nutrient, water, and weed management based on farmer-reported field conditions, previous management practices, and yield expectations [42]. Leaf Color Charts (LCC) offer a simple, cost-effective method for in-season monitoring of rice leaf nitrogen status to guide topdressing decisions [43]. Real-time Nitrogen Management (RTNM) utilises chlorophyll meters, digital imaging, or remote sensing to assess crop nitrogen status, enabling precise, need-based applications [44].

3.2. Impact on Productivity and Resource Use Efficiency

Extensive research in Asia's primary rice-growing regions has established the effectiveness of site-specific nutrient management (SSNM) in enhancing both yield and nutrient use efficiency. Meta-analyses indicate that SSNM implementation results in average yield increases of 0.3 to 0.8 t ha^{-1}, or approximately 5 to 15 percent, compared to conventional farmer practices. These yield gains are often accompanied by reductions in fertilizer use [45,46,47]. Regarding nutrient use efficiency, SSNM consistently improves nitrogen agronomic efficiency by 30 to 50 percent and recovery efficiency by 5 to 15 percentage points [48]. Furthermore, a review by Xie et al. [49] analyzing 403 site-years of data from China reported a 5 percent increase in rice yields and a 32 percent reduction in nitrogen fertilizer use relative to farmers' practices. The Nutrient Expert decision support tool has also demonstrated potential to improve nutrient management efficiency. Studies conducted in several Asian countries found that Nutrient Expert recommendations increased rice yields by an average of 0.5 t ha^{-1}, improved net returns by \$110 ha^{-1}, and enhanced nitrogen use efficiency by 5 to 15 kg grain per kg nitrogen applied [50,51].

3.3. Soil Quality Impacts

Although the productivity and efficiency benefits of site-specific nutrient management (SSNM) are well established, its long-term effects on soil quality have received less thorough investigation. Current evidence indicates that SSNM generally produces positive or neutral outcomes for soil health indicators. Increases in soil organic carbon are possible through optimized nutrient supply and greater biomass production, which can enhance carbon inputs from roots and residues. However, this increase is typically modest in conventional tillage systems unless organic matter management is also implemented [52]. Research from the Philippines and India has demonstrated that SSNM improves soil biological properties, including microbial biomass carbon and nitrogen, and enhances soil enzyme activities compared to conventional practices [53,54]. Long-term application of SSNM, defined as more than five years, has been linked to improved soil chemical properties, including stable soil pH, reduced accumulation of excess nutrients, and improved micronutrient status relative to conventional fertilization [22]. By aligning nutrient inputs with crop removal, SSNM promotes balanced nutrient budgets and may reduce both nutrient depletion and excess accumulation [55]. Nevertheless, SSNM alone may not resolve structural soil degradation associated with conventional rice cultivation practices such as puddling. Comprehensive improvement of soil health may require integration with conservation tillage or other soil management strategies.

4. Controlled-Release Fertilizers and Enhanced Efficiency Fertilizers

4.1. Types and Mechanisms

Controlled-release fertilizers (CRFs) and enhanced efficiency fertilizers (EEFs) are technological strategies designed to improve nutrient use efficiency by regulating the rate, pattern, or timing of nutrient release to align with crop uptake. This approach is especially important in rice systems, where conventional fertilizers are prone to significant losses in aquatic environments.

Major categories include:

- *Polymer-coated fertilizers*: Nutrients encapsulated within polymer coatings that control release rates based on moisture, temperature, and coating thickness. Examples include polymer-coated urea products that provide gradual N release over 2-6 months [56].
- *Sulfur-coated fertilizers*: Typically, urea coated with sulfur and wax sealants, providing intermediate-duration controlled release with the added benefit of supplying sulfur [57].
- *Nitrification inhibitors*: Compounds that delay the bacterial oxidation of ammonium to nitrite, thereby reducing nitrogen losses through denitrification and leaching. Common examples include dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DMPP), and nitrapyrin [58].
- *Urease inhibitors*: Compounds that inhibit the urease enzyme, thereby slowing the hydrolysis of urea and reducing ammonia volatilization. N-(n-butyl) thiophosphoric triamide (NBPT) is the most widely used example [59].
- *Double inhibitors*: Products combining both nitrification and urease inhibitors to comprehensively reduce nitrogen loss pathways [60].
- *Zeolites and other mineral additives*: Natural or synthetic aluminosilicate minerals with high cation exchange capacity

that can absorb ammonium ions and slowly release them [61,62].

Release mechanisms include physical diffusion control using polymer coatings, biochemical inhibition through enzyme inhibitors, and ion exchange processes involving zeolites. The ideal release pattern should closely match the nitrogen uptake curve of the rice crop, which typically exhibits peak demand during the vegetative stage and grain-filling period [63].

4.2. Performance in Rice Systems

Research on controlled-release fertilizers (CRFs) and enhanced-efficiency fertilizers (EEFs) in rice systems has demonstrated positive impacts on both yield and environmental outcomes. However, performance varies depending on the product type, environmental conditions, and management practices. Linquist et al. [64] conducted a meta-analysis of 59 studies and reported average yield increases of 5.7% for EEFs compared to conventional fertilizers, with nitrification inhibitors providing the greatest yield benefits. Qiao et al. [65] analyzed 93 field studies in China and found that polymer-coated urea increased rice yields by 11.4% on average and reduced nitrogen application rates by 20.1%. Improvements in nitrogen use efficiency (NUE) are generally more pronounced than yield gains. Azeem et al. [66] documented 10-30% increases in NUE for various controlled-release products in rice. These efficiency improvements contribute to environmental benefits, such as reduced nitrous oxide emissions, ammonia volatilization, and nitrogen leaching. For example, Akiyama et al. [58] found that nitrification inhibitors reduced nitrous oxide emissions by 30% in rice systems, while urease inhibitors reduced ammonia volatilization by 40-60% [67]. An additional advantage of these technologies is the potential to reduce fertilizer application frequency. Many polymer-coated products allow for a single basal application to replace the conventional split application method, thereby reducing labor requirements and application costs [63]. This single-application strategy is particularly promising in mechanized rice systems and regions with labor constraints.

4.3. Soil Quality Effects

The effects of controlled-release fertilizers (CRFs) and enhanced-efficiency fertilizers (EEFs) on soil quality parameters extend beyond improving nutrient use efficiency. Inhibitors that reduce nitrification rates can slow soil acidification associated with ammonium-based fertilizers. Long-term studies in China have shown higher soil pH in plots treated with inhibitor-containing fertilizers compared to conventional urea [68]. The influence of inhibitors on soil microbial communities is still under investigation. Although initial concerns suggested possible negative effects on beneficial microorganisms, recent research demonstrates that these impacts are generally transient and specific to certain microbial groups, rather than being broadly harmful [69]. Some studies have observed increased microbial functional diversity under controlled-release fertilization [70]. Enhanced nutrient use efficiency often results in greater biomass production and potentially higher carbon inputs to soil. For example, Li et al. [71] found that long-term application of polymer-coated urea in a rice-wheat rotation increased soil organic carbon by 7.5% compared to conventional fertilization. Several studies have also reported increased activities of key soil enzymes involved in carbon, nitrogen, and phosphorus cycling under controlled-release fertilization, indicating improved biochemical functioning [70,72].

4.4 Economic and Practical Considerations

Although controlled-release fertilizers (CRFs) and enhanced-efficiency fertilizers (EEFs) offer notable agronomic and environmental advantages, their adoption in rice production systems remains constrained, primarily due to higher costs relative to conventional fertilizers. These products are typically priced at two to four times the cost of standard fertilizers, which poses a substantial barrier for smallholder farmers [57]. Furthermore, despite meta-analyses indicating generally positive returns, the performance of CRFs and EEFs varies considerably across different environments and seasons, contributing to perceptions of investment risk [73]. Inadequate quality control and regulatory oversight in some developing markets further undermine product consistency and erode farmer confidence [74]. Additionally, limited knowledge among farmers and extension agents regarding the optimal use and benefits of these technologies restricts their effective implementation [60]. Access is further limited by insufficient local market availability and inadequate storage infrastructure, particularly in remote regions [75]. Recent innovations aimed at overcoming these barriers include the development of more affordable coating technologies, targeted application in high-value rice varieties, government subsidy programs for environmentally beneficial inputs, and the promotion of locally produced alternatives [76].

5. Integrated Nutrient Management

5.1. Concept and Components

Integrated Nutrient Management (INM) is a comprehensive strategy that integrates organic, inorganic, and biological nutrient sources to sustain soil fertility and plant nutrition while reducing environmental impacts [77]. The core principle of INM asserts that a single nutrient source cannot deliver the optimal benefits required for productivity, sustainability, and soil health. In rice systems, INM involves several key components. Mineral fertilizers supply concentrated and readily available nutrients that can be managed to meet specific crop requirements. Crop residues, such as rice straw and stubble, are returned to fields directly or after composting to recycle nutrients and increase organic matter. Green manures, including leguminous crops such as Sesbania, Crotalaria, or Azolla, are cultivated before or alongside rice to fix nitrogen and provide organic inputs. Animal manures and composts provide processed organic materials that gradually release nutrients and enhance the physical and biological properties of the soil. Biofertilizers introduce microbial inoculants, such as nitrogen-fixing bacteria, phosphorus-solubilizing microorganisms, and arbuscular mycorrhizal fungi. Where safe and appropriate, industrial and urban wastes, including biochar, municipal composts, or processed biosolids, may also be incorporated. The INM approach prioritizes the substitution of organic for inorganic inputs and their strategic combination to maximize synergistic effects. For instance, integrating mineral fertilizers with organic inputs can enhance nutrient use efficiency by promoting temporary immobilization and synchronized nutrient release, reducing phosphorus fixation, and stimulating microbial activity [78,54].

5.2. Performance in Rice Systems

Extensive research in diverse rice ecosystems has demonstrated the effectiveness of integrated nutrient management (INM) in achieving sustainable productivity. For example, a meta-analysis by Huang et al. [79] of 141 studies in Asian rice systems found that combining chemical fertilizers with organic amendments increased yields by 19.8% and improved nitrogen use efficiency by 12.6% compared to chemical fertilizers alone. Long-term experiments further clarify the cumulative benefits of INM. The landmark fertility trials at IRRI, ongoing since 1962, have shown that INM maintains higher and more stable rice yields over decades than either organic or inorganic fertilization alone [52]. In addition, a 25-year experiment in China reported by Bi et al. [80] demonstrated that combined organic-inorganic fertilization produced 8.8-12.5% higher rice yields than equivalent rates of chemical fertilizers alone. The advantages of INM are especially evident under suboptimal or stress conditions. For instance, under drought stress, systems with long-term organic inputs exhibit greater resilience due to improved soil water retention and biological functioning [32]. INM also outperforms other approaches in problem soils, such as acid sulfate soils, saline soils, and areas contaminated with heavy metals [81]. A notable strength of INM is its ability to adapt to local resource availability. In contexts where mineral fertilizers are costly or inaccessible, INM allows farmers to optimize the use of limited inputs by incorporating complementary organic resources [78].

5.3. Soil Quality Enhancement

Integrated nutrient management (INM) offers substantial and well-documented benefits for soil quality. Multiple studies indicate that INM consistently increases soil organic carbon (SOC) compared to mineral fertilization alone. For example, Liu et al. [82] reported that combined organic and inorganic fertilization increased SOC by 19-89% relative to unfertilized controls. INM also improves soil physical properties by enhancing aggregation, reducing bulk density, increasing porosity, and enhancing water-holding capacity. These effects are especially important in puddled rice systems, where soil structure degradation is prevalent [83]. Furthermore, INM supports greater diversity and abundance of soil microbial communities. Zhang et al. [74] observed 15-32% higher microbial biomass carbon and increased enzyme activities under INM compared to conventional NPK fertilization. INM promotes nutrient cycling through mechanisms such as increased biological nitrogen fixation, enhanced mycorrhizal colonization, and a higher abundance of decomposer organisms [76]. Organic inputs also buffer soil pH fluctuations associated with nitrogen fertilization, thereby maintaining conditions favorable for nutrient availability and microbial activity [84,85]. In contaminated soils, organic matter inputs can decrease the bioavailability of heavy metals through complexation and adsorption, potentially reducing their accumulation in rice grains [81]. Collectively, these improvements in soil quality foster positive feedback loops that enhance nutrient use efficiency and system resilience.

6. Digital Agriculture for Nutrient Management

6.1. Emerging Technologies

Digital agriculture is a rapidly advancing field in nutrient management that utilizes information and communication technologies to improve precision, efficiency, and knowledge dissemination in agricultural systems. Several key technologies are transforming rice nutrient management. Remote sensing, including satellite, drone, and proximal sensing, enables non-destructive assessment of crop nutrient status, stress, and biomass at multiple scales. Multispectral and hyperspectral imaging detect changes in leaf chlorophyll content, canopy structure, and other parameters linked to nutrient status [86]. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and indices for nitrogen status assessment are widely used [87]. The Internet of Things (IoT) establishes networks of field sensors that deliver real-time data on soil moisture, temperature, electrical conductivity, and other factors influencing nutrient availability. Advanced systems use nutrient ion-selective electrodes or spectroscopic sensors to directly measure soil nutrient status [88]. Smartphone applications provide accessible decision support platforms, connecting farmers to expert systems and databases. Notable examples include the Rice Crop Manager (RCM) by IRRI, Nutrient Expert for Rice, and commercial applications offering fertilizer calculators and deficiency diagnosis tools [42]. Machine learning and artificial intelligence process complex datasets to identify patterns and generate site-specific recommendations. These methods integrate diverse data sources and account for interactions among soil, weather, management, and crop response [89]. Geographic Information Systems (GIS) support spatial analysis for site-specific fertility mapping, management zone delineation, and variable-rate application prescriptions [90]. Robotics and automation include autonomous vehicles for soil sampling, sensor deployment, and precision fertilizer application [91]. The integration of these technologies forms digital nutrient management ecosystems that enable precise decision-making across spatial and temporal scales, from individual fields to regional planning.

6.2. Applications and Impact

Digital agriculture applications in rice nutrient management encompass the full management cycle, including planning, implementation, and evaluation. Decision support systems such as Rice Crop Manager (RCM) generate field-specific fertilizer recommendations using farmer inputs, local soil data, and crop models. In the Philippines, RCM recommendations have been shown to increase rice yields by 0.4 t ha^{-1} and net returns by $100 ha^{-1} compared to traditional farmer practices, while also significantly improving nitrogen use efficiency [42]. Real-time nitrogen management tools, including smartphone-based leaf colour analysis, allow farmers to assess crop nitrogen status during the growing season and adjust fertilizer applications dynamically. These methods have improved nitrogen recovery efficiency by 10-15 percentage points over fixed-time applications [92]. Variable rate technology (VRT) employs precision equipment and digital prescription maps to apply fertilizers according to spatial soil fertility patterns. Although VRT is more commonly used in upland cropping systems, its application to rice is also increasing. Experimental trials in China have demonstrated 7-12% fertilizer savings with no yield penalties [93]. Remote sensing systems facilitate early stress detection by identifying nutrient deficiencies before visible symptoms appear, enabling proactive management. For example, multispectral drone imaging has detected nitrogen, phosphorus, and potassium deficiencies in rice 5-10 days earlier than visual observation [87]. At the regional level, satellite-based monitoring and GIS analysis support the planning and development of nutrient management policies. These strategies have been implemented in areas such as the Mekong Delta to identify inefficient nutrient use and guide intervention programs [94]. The benefits of digital approaches extend beyond production efficiency to include environmental outcomes. Precision nutrient management in rice can reduce nitrogen losses by 15-30% and greenhouse gas emissions by 10-20% compared to conventional practices [88].

6.3. Data Integration and Analytics

A primary advantage of digital agriculture is its ability to integrate diverse data streams, yielding insights that surpass the capabilities of individual technologies. Contemporary nutrient management platforms now combine several data types. These include historical data such as yield maps, soil test results, and management records, which establish baselines and support trend analysis. They also incorporate real-time monitoring data from in-season sensor observations, imagery, and farmer inputs, which reflect dynamic conditions influencing nutrient availability and crop response. Environmental data, including weather, hydrological, and edaphic factors, provide essential context for interpreting crop performance and predicting nutrient transformations. Predictive analytics, utilizing crop models, machine learning algorithms, and statistical tools, convert raw data into actionable recommendations. This comprehensive integration supports advanced analyses, including scenario modelling, risk assessment, and adaptive management [95]. Analytical methods have evolved from basic correlation and regression to sophisticated machine learning techniques that can address non-linear and multi-factorial relationships. Deep learning is particularly promising for image-based assessment of nutrient status, while ensemble methods, such as random forests, effectively integrate diverse predictors to forecast yield responses to nutrient management [89].

7. Microbial Biofertilizers and Plant Growth-Promoting Rhizobacteria

7.1. Microbial Resources and Mechanisms

Microbial biofertilizers are an emerging approach in sustainable nutrient management. They utilize beneficial soil microorganisms to improve nutrient availability, uptake, and use efficiency in rice systems. These biological strategies can complement chemical fertilizers and may reduce reliance on them, while also supporting soil health [96,97]. Key microbial resources for rice include nitrogen-fixing microorganisms, such as diazotrophic bacteria that convert atmospheric nitrogen into forms usable by plants. These include free-living bacteria, such as Azotobacter, which are associative nitrogen fixers in the rice rhizosphere; endophytic diazotrophs residing within plant tissues; and cyanobacteria, which are especially important in flooded rice systems [98]. Phosphorus-solubilizing microorganisms (PSMs) increase phosphorus availability by solubilizing inorganic phosphorus and mineralizing organic compounds. Notable genera are *Bacillus*, *Pseudomonas*, *Aspergillus*, and *Penicillium* [99]. Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with rice roots, expanding the effective root surface area and improving uptake of phosphorus and other immobile nutrients. Key genera include *Glomus*, *Gigaspora*, and *Acaulospora* [100]. Plant growth-promoting rhizobacteria (PGPR) support plant growth through various mechanisms, including the production of phytohormones and siderophores, pathogen suppression, and the induction of systemic resistance. Prominent genera for rice are *Pseudomonas*, *Bacillus*, *Azospirillum*, and *Serratia* [101]. Microbial consortia, which combine multiple complementary microorganisms, can address various aspects of plant nutrition and health simultaneously [102]. These microorganisms contribute to nutrient management through various mechanisms, including biological nitrogen fixation, nutrient solubilization, modification of the rhizosphere and root architecture, and enhanced nutrient uptake via the upregulation of plant transporter genes and increased membrane permeability [101].

7.2. Performance in Rice Systems

Numerous field trials across diverse agroecological zones have evaluated the efficacy of biofertilizers in rice cultivation, producing variable outcomes. Meta-analyses show that diazotrophic inoculants can supply nitrogen benefits equivalent to 20-50 kg N ha^{-1} in rice systems. However, these results depend on environmental conditions, native microbial communities, and management practices [103]. Cyanobacteria and *Azolla* applications in flooded rice can contribute 30-80 kg N ha^{-1} per crop cycle under favourable conditions [104]. Phosphate-solubilizing microorganism (PSM) inoculation has been shown to increase phosphorus uptake by 10-40% in rice, with yield improvements typically between 5-20%, depending on soil phosphorus status and fixation capacity [99]. Zaidi et al. [105] reviewed 30 field trials and found an average increase in rice yield of 15% following PSM application. Arbuscular mycorrhizal fungi (AMF) applications have demonstrated promise in nursery and upland conditions; however, their effectiveness in continuously flooded rice systems is inconsistent due to the presence of anaerobic conditions. In contrast, AMF inoculation in aerobic rice and alternate wetting-drying systems has improved phosphorus uptake efficiency by 15-30% [106,72]. Reviews by Gouda et al. [101] and Vacheron et al. [107] documented rice yield increases of 5-30% following inoculation with plant growth-promoting rhizobacteria (PGPR), with additional benefits including enhanced stress tolerance and disease resistance. Combined biofertilizer formulations generally outperform single-strain inoculants. Reddy [102] reported that multi-strain biofertilizers improved rice yields by 15-25% and enabled chemical fertilizer reductions of 25-50% without yield penalties. Economic analyses indicate that biofertilizers typically offer favorable cost-benefit ratios. For example, Prasanna et al. [104] calculated benefit-cost ratios of 2.5:1 to 5:1 for cyanobacterial applications, and Gouda et al. [101] reported average returns of $3 to $7 for each dollar invested in PGPR technologies.

7.3. Soil Health and Ecosystem Benefits

In addition to supporting plant nutrition, microbial biofertilizers improve soil health and ecosystem functioning. Microbial inoculants enhance carbon sequestration by increasing root biomass, stimulating exudate production, and improving soil aggregation. Long-term studies have demonstrated that systems regularly receiving biofertilizers exhibit 5-15% higher soil organic carbon compared to those using only conventional fertilization [97,108]. Biofertilizer applications also increase soil microbial biomass, diversity, and enzyme activities. For example, Singh et al. [109] observed 20-40% higher dehydrogenase, phosphatase, and β-glucosidase activities after three years of plant growth-promoting rhizobacteria application in rice-wheat systems. Regular biofertilizer inputs enhance soil physical structure, including aggregation, porosity, and water retention, through increased microbial polysaccharide production and other binding agents [102]. Integrating biofertilizers reduces the need for chemical inputs, thereby supporting greater biodiversity conservation within both soil and the broader agroecosystem [110]. Certain biofertilizers also mitigate greenhouse gas emissions from rice paddies by suppressing the growth of methanogenic bacteria or promoting the activity of methanotrophic bacteria. Additionally, nitrogen-fixing inoculants can reduce nitrous oxide emissions by enhancing nitrogen use efficiency [111].

8. Conservation Agriculture-Based Nutrient Management

8.1. Principles and Practices

Conservation agriculture (CA) is a systems-based approach to sustainable crop production that relies on three core principles: minimal soil disturbance, permanent soil cover, and crop diversification through rotation or association [112,113]. When implemented in rice-based systems, these principles require significant changes in nutrient management. Key CA practices for rice include direct seeded rice (DSR), which replaces puddled transplanting with direct seeding into minimally disturbed soil and alters soil redox conditions and nutrient transformation pathways [114]. Reduced or zero tillage minimizes mechanical soil disturbance using specialized seeding equipment, thereby preserving soil structure and organic matter and modifying nutrient cycling [115]. Residue retention involves maintaining crop residues as mulch on the soil surface, providing slow-release nutrients and changing soil environmental conditions [116]. Cover cropping introduces non-rice species during fallow periods to capture nutrients, fix nitrogen in the case of legumes, and add organic matter [117]. Crop rotation systematically alternates rice with other crops to disrupt pest cycles, diversify nutrient demand, and enhance system efficiency [115]. Controlled traffic confines equipment movement to permanent lanes, reducing soil compaction and improving root development and nutrient access [118, 119]. Collectively, these practices create unique agroecological conditions that require tailored nutrient management strategies. The transition from puddled, anaerobic soils to more aerobic environments alters nitrogen transformation, generally reducing denitrification losses but potentially increasing ammonia volatilization, leaching, and immobilization [6]. Additionally, phosphorus and micronutrient availability patterns differ significantly from those in conventional rice systems under CA.

8.2. Impacts on Nutrient Dynamics and Efficiency

Research on nutrient dynamics in conservation agriculture (CA)-based rice systems has identified several key patterns. In non-puddled, aerobic, or semi-aerobic CA rice systems, nitrification rates increase and denitrification rates decrease compared to conventional flooded systems. This shift alters the dominant nitrogen loss pathways from denitrification and ammonia volatilization to nitrate leaching [6]. Multiple studies report that nitrogen losses typically decrease by 10-30% under CA practices, although the extent depends on water management [120]. In mature CA systems, higher soil organic matter and residue cover can temporarily immobilize nitrogen, requiring adjusted fertilization strategies during the transition period. Over time, increased soil organic matter enhances nitrogen mineralization potential and synchronizes nutrient release with crop demand [121]. Reduced soil disturbance and greater biological activity generally improve phosphorus cycling efficiency in CA systems. Mycorrhizal networks, often disrupted by tillage, develop more extensively under CA, thereby improving phosphorus acquisition [115]. However, surface application of phosphorus fertilizers without incorporation can reduce short-term availability due to stratification and surface adsorption [122]. Zinc deficiency, which is common in conventional rice, may be less severe in aerobic CA systems due to altered redox conditions, although this outcome depends on soil pH and organic matter management [123]. CA practices typically result in more heterogeneous nutrient distributions, with stratification concentrating nutrients in surface layers, which affects fertilizer placement and timing [124]. These changes necessitate the development of adapted nutrient management strategies. Meta-analyses demonstrate that CA-based rice systems can maintain yields with 10-30% less nitrogen fertilizer than conventional systems after a transition period of three to five years, provided appropriate management adaptations are implemented [6,125].

8.3. Soil Quality Enhancement

The soil quality benefits of conservation agriculture (CA)-based rice production are well-documented across diverse agroecological zones. Long-term CA implementation consistently increases soil organic carbon (SOC), particularly in surface horizons. A global meta-analysis by Powlson et al. [126] found that zero-tillage with residue retention increased SOC by 5-15% over 10-20 years, with higher gains in tropical systems including rice rotations. CA practices improve soil physical properties by enhancing aggregate stability, increasing infiltration rates, reducing bulk density, increasing porosity, and improving water retention characteristics [127]. These improvements create more favorable conditions for root growth and nutrient uptake. Conservation practices also enhance soil biological activity, including greater soil biodiversity and improved biological functioning. Studies on rice-based CA systems have reported 30-100% increases in earthworm populations, 40-60% higher microbial biomass carbon, and significantly greater enzyme activities compared to conventional management [128,12]. Surface residue cover substantially reduces soil erosion and decreases nutrient losses through runoff and sediment transport. This effect is particularly important in upland or terraced rice systems that are vulnerable to monsoon-driven erosion [115]. Improved infiltration, reduced evaporation, and enhanced soil moisture retention contribute to higher water productivity. This is increasingly important in rice systems facing irrigation constraints [125]. Collectively, these improvements in soil quality create positive feedback loops for nutrient management. Enhanced soil biological, physical, and chemical properties improve nutrient cycling efficiency, reduce external input requirements, and help maintain or increase yields over time.

9. Future Research Directions

9.1. Knowledge Gaps and Research Priorities

Although rice nutrient management has advanced considerably, several critical knowledge gaps persist and require targeted research. Most existing studies assess technologies over short periods, typically one to three seasons. However, improvements in soil health and system optimization may only become evident over longer durations. Therefore, long-term time-series research across diverse agroecological zones is necessary to evaluate sustainability and system trajectories. The interactions among nutrient management practices, water regimes, soil properties, and climate conditions are not yet fully understood. Systematic studies using factorial designs across environmental gradients would improve predictive accuracy and the specificity of recommendations. While the efficacy of biofertilizers is established, further investigation into the interactions between introduced and native microbiomes, their persistence, and functional roles would inform the design and application of better inoculants. Quantitative analysis of how nutrient management strategies influence resilience to climate extremes is essential for adaptation planning, yet remains underexplored. The links between nutrient management and biotic stresses are also insufficiently characterized, though they are vital for integrated crop management. Research that connects field-level nutrient management to broader food system outcomes, such as nutritional quality, food safety, market acceptance, and value chain dynamics, should be prioritized. Economic analyses that incorporate risk, multi-year returns, ecosystem service valuation, and varying decision time horizons would more accurately reflect farmers' decision-making processes. Additionally, socio-technical research is needed to develop effective scaling strategies for implementing beneficial practices at the landscape level. Addressing these gaps will require several methodological approaches: establishing and maintaining long-term research sites in major rice agroecologies to assess system-level outcomes; forming participatory research networks where farmers implement and evaluate practices in diverse contexts; employing high-throughput, non-destructive monitoring of crop nutrient status, root architecture, and physiological responses to clarify management effects; integrating crop, soil, hydrology, and climate models to predict outcomes at multiple scales; applying genomic, metagenomic, transcriptomic, and metabolomic techniques to elucidate soil-plant-microbe interactions; utilizing machine learning and artificial intelligence to analyze complex datasets and optimize recommendations; and ensuring interdisciplinary collaboration across soil science, agronomy, ecology, economics, engineering, data science, and social sciences.

9.2. Technology Development Opportunities

Emerging technological innovations present significant opportunities to advance rice nutrient management. The development of affordable, durable, and precise next-generation sensors enables real-time monitoring of soil nutrient status, microbial activity, and plant physiological responses, thereby improving management precision. Engineered nanomaterials facilitate controlled nutrient release, enhance uptake, and serve as carriers for beneficial microorganisms, which can increase efficiency and reduce environmental impacts [129]. Gene editing technologies, such as CRISPR and molecular breeding, enable the targeted modification of traits that influence nutrient use efficiency, rhizosphere interactions, and microbial associations. These approaches may yield rice varieties specifically adapted to advanced management strategies [130]. The design of synthetic microbial communities with complementary functions, rather than relying on single-strain inoculants, can improve establishment success and functional resilience in field conditions [131]. Biodegradable polymers and matrices that respond to environmental cues such as moisture, temperature, pH, or microbial enzymes offer precise control over nutrient release patterns, representing a significant advancement in delivery systems [57]. The use of small-scale, lightweight robots for precision nutrient application, monitoring, and management addresses labour constraints and enhances management accuracy [91]. Advanced algorithms that synthesize multiple data streams to provide real-time, site-specific recommendations and adapt based on feedback represent a frontier in decision support through artificial intelligence and machine learning [89]. Digital twins, or virtual representations of rice fields that integrate soil, crop, climate, and management data, enable scenario testing and optimization prior to real-world implementation, supporting agricultural planning [132]. Finally, augmented and virtual reality tools can assist farmers in visualizing soil properties, nutrient status, and management options, thereby facilitating the adoption of complex recommendations through mixed reality interfaces [88].

10. Conclusions

Achieving simultaneous improvements in rice productivity, soil quality, and environmental sustainability necessitates a fundamental shift in nutrient management strategies. This review evaluates six advanced approaches: site-specific nutrient management, controlled-release fertilizers, integrated nutrient management, digital agriculture applications, microbial biofertilizers, and conservation agriculture-based methods. These methods consistently increase nutrient use efficiency by 20-50 percent and enhance soil properties, generating cumulative benefits over time. Successful adoption requires adapting to local conditions, integrating complementary practices, effective transition management, robust knowledge dissemination, and supportive policy frameworks. In the context of global rice production, which must increase yields, reduce environmental impacts, and adapt to climate change, these strategies offer critical pathways for sustainable intensification. By aligning food security, environmental protection, and farmer livelihoods, they contribute to the development of resilient and sustainable food systems. The evidence presented demonstrates that next-generation nutrient management strategies represent more than incremental improvements—they constitute a paradigm shift toward knowledge-intensive, precision-based approaches that can address the interconnected challenges of productivity, sustainability, and climate adaptation in rice cultivation. The integration of these approaches, rather than their individual application, holds the greatest promise for transforming rice production systems to meet future food security demands while preserving environmental integrity.

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Table 1
Comparison of Next-Generation Nutrient Management Strategies for Rice

Strategy	Key Technologies	Yield Impact	NUE Improvement	Soil Quality Impact	Environmental Benefits	Implementation Challenges
Site-Specific Nutrient Management	Nutrient Expert, Rice Crop Manager, Leaf Color Charts, Real-time N Management	+5-15%	+30-50% (AE), +5-15% (RE)	Moderate positive impact on biological properties and pH stability	Reduced N losses by 10-30%, decreased GHG emissions	Knowledge intensity, spatial variability, infrastructure limitations
Controlled-Release Fertilizers	Polymer-coated urea, Nitrification inhibitors, Urease inhibitors, Double inhibitors	+5-11%	+10-30%	Reduced soil acidification, possible enhanced microbial diversity	-30% N_2O emissions, -40-60% NH_3 volatilization	Cost premium, variable economic returns, and product quality concerns
Integrated Nutrient Management	Combined organic-inorganic systems, Green manures, Composts, Crop residue management	+15-25%	+10-20%	Significant improvements in SOC, physical structure, biological activity	Reduced environmental footprint, enhanced C sequestration	Labor requirements, biomass availability, knowledge intensity
Digital Agriculture	Remote sensing, IoT sensors, Smartphone apps, Machine learning, VRT	+5-15%	+10-20%	Indirect benefits through precision management	-15-30% N losses, -10-20% GHG emissions	Digital divide, data standardization, validation needs, cost-benefit uncertainty
Microbial Biofertilizers	N-fixing microbes, P-solubilizers, Mycorrhizal fungi, PGPR, Microbial consortia	+5-30%	Equivalent to 20-50 kg N/ha and 10-40% improved P uptake	Enhanced soil biological properties, increased enzyme activities	Reduced chemical inputs, potential GHG mitigation	Inconsistent field performance, formulation limitations, and quality control challenges
Conservation Agriculture	Direct seeded rice, Reduced tillage, Residue retention, Cover crops	-5% to +10% (transition period) +10-15% (long-term)	+10-30% after transition period	Major improvements in SOC, aggregation, porosity, biological activity	Reduced erosion, enhanced C sequestration, improved water quality	Transition yield penalties, equipment needs, knowledge intensity

Note: AE = Agronomic Efficiency, RE = Recovery Efficiency, NUE = Nitrogen Use Efficiency, SOC = Soil Organic Carbon, GHG = Greenhouse Gas, VRT = Variable Rate Technology, PGPR = Plant Growth-Promoting Rhizobacteria

Table 2
Nitrogen Use Efficiency (NUE) in Rice Cultivation Under Different Management Strategies

Management Strategy	Average NUE (%)	Range (%)	Reference
Conventional practice	30-40	20-50	[9]
Site-specific nutrient management	45-55	35-65	[48]
Controlled-release fertilizers	50-60	40-70	[64]
Nitrification inhibitors	45-65	40-75	[58]
Urease inhibitors	40-55	35-65	[67]
Integrated nutrient management	45-50	35-60	[79]
Conservation agriculture (after transition)	40-50	35-65	[6]
Digital N management	45-60	40-70	[88]
Microbial biofertilizers	35-45	30-55	[101]

Table 3
Impact of Next-Generation Nutrient Management Strategies on Soil Quality Parameters in Rice Systems

Soil Quality Parameter	Site-Specific Management	Controlled-Release Fertilizers	Integrated Nutrient Management	Conservation Agriculture	Biofertilizers
Soil organic carbon	↑	↑	↑↑↑	↑↑↑	↑↑
Soil pH	↑	↑↑	↑↑	↑	↑
Bulk density	→	→	↓↓	↓↓↓	↓
Aggregate stability	→	→	↑↑	↑↑↑	↑
Water holding capacity	→	→	↑↑	↑↑↑	↑
Microbial biomass	↑	↑	↑↑↑	↑↑	↑↑↑
Enzyme activities	↑	↑	↑↑	↑↑	↑↑↑
Earthworm populations	→	→	↑↑	↑↑↑	↑
Nutrient stratification	→	→	↑	↑↑↑	→

Note: ↑ = slight increase, ↑↑ = moderate increase, ↑↑↑ = significant increase, → = minimal change,
↓ = slight decrease, ↓↓ = moderate decrease, ↓↓↓ = significant decrease

Table 4
Economic Analysis of Next-Generation Nutrient Management Strategies in Rice Systems

Strategy	Initial Investment Cost	Operating Cost Change	Yield Benefit	Net Return Increase	Benefit-Cost Ratio	Payback Period
Site-specific nutrient management	Low-Medium	-10% to +5%	+5–15%	$80–150/ha	2.5:1 to 4:1	1–2 seasons
Controlled-release fertilizers	Low	+30–80%	+5–11%	$50–120/ha	1.2:1 to 2:1	1–3 seasons
Integrated nutrient management	Medium	+10–30%	+15–25%	$100–200/ha	2:1 to 3.5:1	2–3 seasons
Digital agriculture technologies	High	+5–20%	+5–15%	$70–180/ha	1.5:1 to 3:1	2–4 seasons
Microbial biofertilizers	Low	+5–15%	+5–30%	$60–150/ha	2.5:1 to 5:1	1 season
Conservation agriculture	Medium-High	-20% to +10%*	-5% to +15%**	$50–200/ha***	1.5:1 to 4:1	2–5 seasons

* Operating costs typically increase during the transition period (1-3 seasons) and then decrease in the longer term
** Yields may decrease during the transition period but increase in the longer term
*** Net returns may be negative during the transition period but increase substantially in the longer term

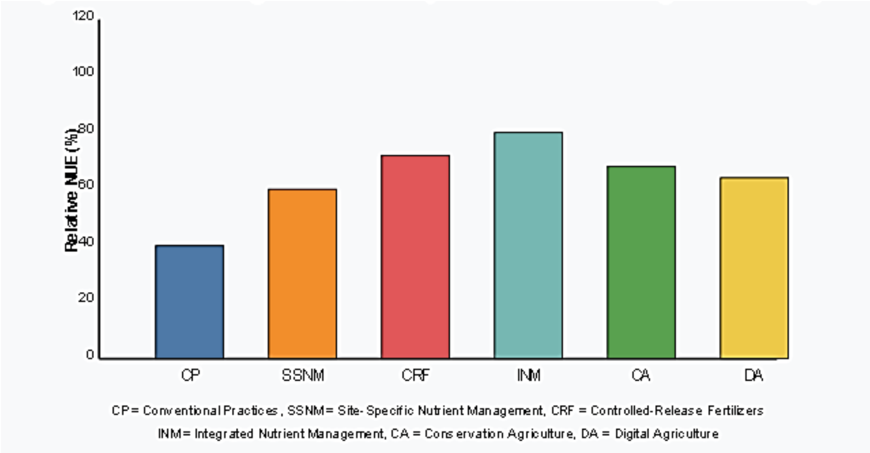

Figure 1: Relative Nitrogen Use Efficiency Under Different Management Strategies

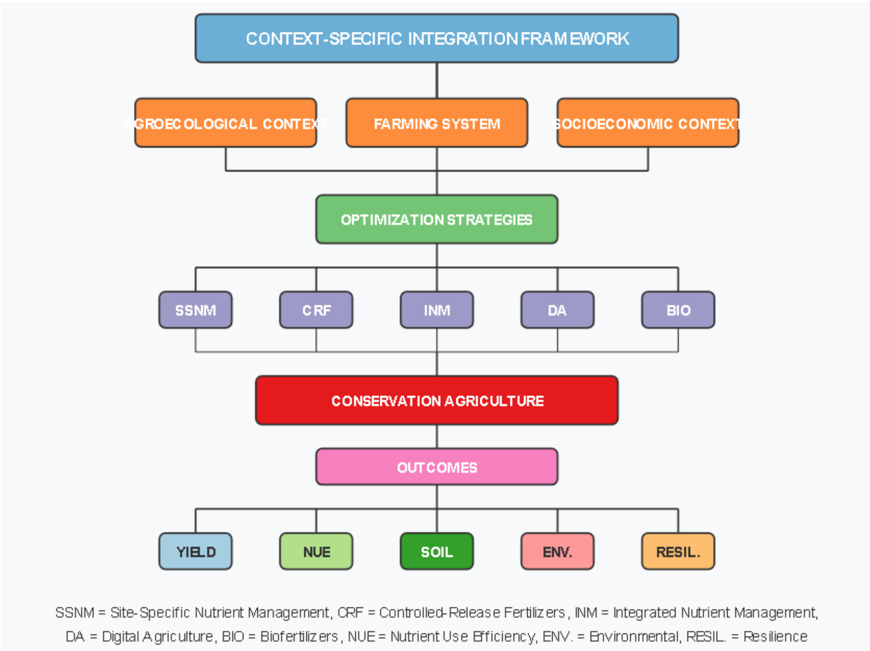

Figure 2: Conceptual Framework for Integrated Next-Generation Nutrient Management

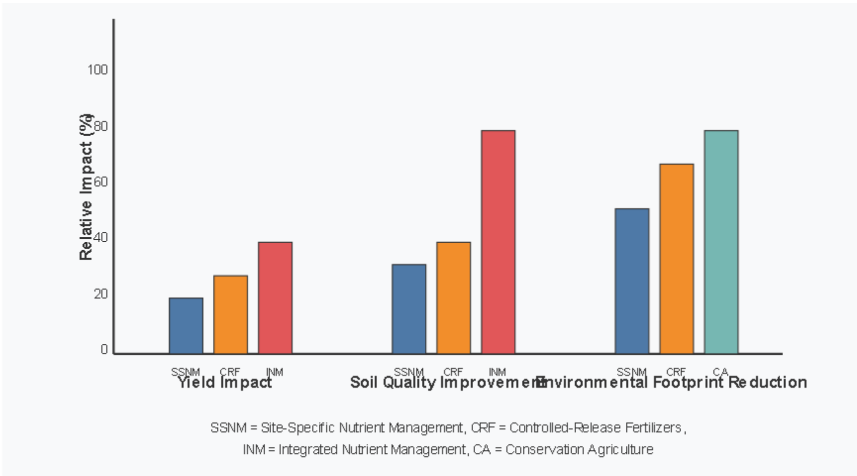

Figure 3: Relative Impact of Strategies on Yield, Soil Quality, and Environmental Footprint

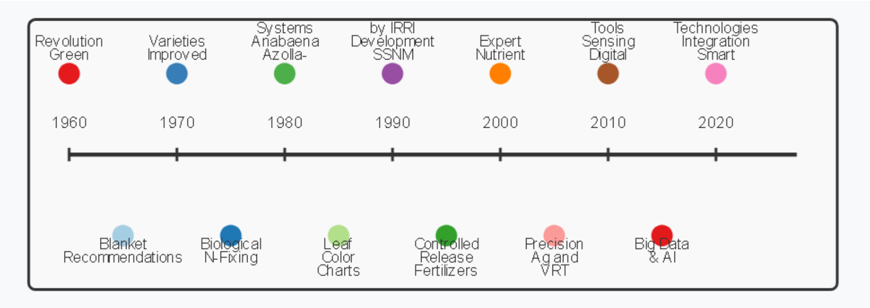

Figure 4: Timeline of Key Developments in Rice Nutrient Management Technologies

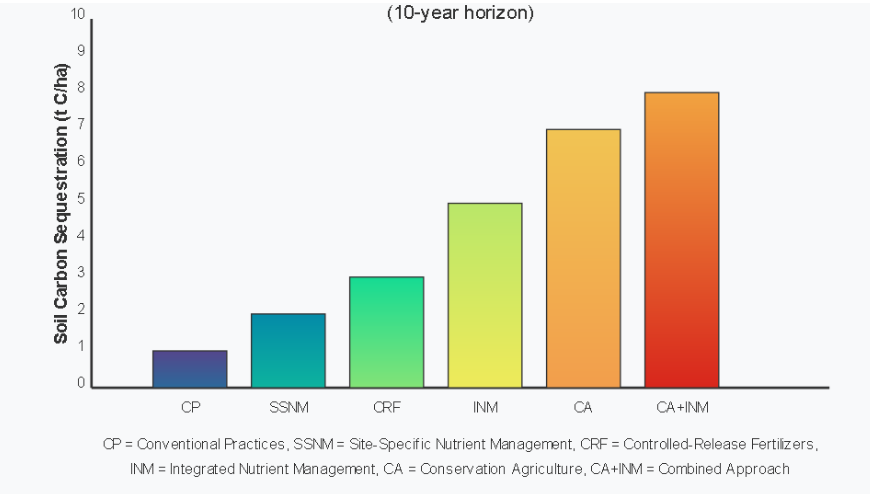

Figure 5: Soil Carbon Sequestration Potential