Rice Genomics and Genetics 2025, Vol.16, No.1, 14-23
http://cropscipublisher.com/index.php/rgg

Case Study Open Access

Improving Rice Grain Quality Through Integrated Nutrient Management

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Rice Genomics and Genetics, 2025, Vol.16, No.1 doi: 10.5376/rgg.2025.16.0002

Received: 02 Dec., 2024

Accepted: 10 Jan., 2025

Published: 20 Jan., 2025

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Preferred citation for this article:

Shen Y.C., 2025, Improving rice grain quality through integrated nutrient management, Rice Genomics and Genetics, 16(1): 14-23 (doi: 10.5376/rgg.2025.16.0002)

Abstract Improving rice grain quality is a key objective in modern agriculture, aiming to meet the diverse consumer demands for nutrition, appearance, and palatability. This study reviews the effects of Integrated Nutrient Management (INM) on major rice quality traits, including milling quality, appearance, eating quality, and nutritional composition. A field trial was conducted in a representative rice-producing area of Jiangsu Province, China, to evaluate the potential of INM strategies in enhancing grain quality. The experiment combined organic fertilizers, controlled-release fertilizers, and scientifically timed fertilization schedules to achieve precise nutrient regulation. Results showed that INM significantly improved the head rice recovery rate, reduced grain chalkiness, and promoted the accumulation of protein, zinc, and iron. Additionally, eating quality indicators such as gel consistency and taste scores were enhanced, while rice yield remained stable. This study highlights the importance of integrating precision fertilization with soil health management and aims to provide a practical foundation for the sustainable production of high-quality rice.

Keywords Rice grain quality; Integrated nutrient management; Milling quality; Nutritional composition; Sustainable agriculture

1 Introduction

Rice is a staple food for nearly half of the global population, making its quality a critical factor in modern agriculture. The quality of rice grains is influenced by various factors, including the methods of stand establishment, water management, soil type, and nutrient management. These factors collectively impact the nutritional content, grain weight, and milling quality of rice, which are essential for meeting the dietary needs of a growing population (Midya et al., 2021; Zahra et al., 2022).

Integrated Nutrient Management (INM) has emerged as a promising approach to enhance rice grain quality by optimizing the use of both organic and inorganic fertilizers. This method not only improves the yield and nutritional quality of rice but also contributes to soil health and sustainability (Mangaraj et al., 2022; Urmi et al., 2022; Chowdhury et al., 2024). The application of INM has shown significant improvements in rice yield and nutrient use efficiency, which are crucial for maintaining soil fertility and ensuring long-term agricultural productivity (Sharma et al., 2019; Urmi et al., 2022).

Integrated nutrient management ensures a balanced nutrient supply to crops and improves soil health by combining chemical, organic and biofertilizers. This study will evaluate different nutrient management strategies, explore their impact on rice quality, analyze the specific needs of rice cultivation, and strive to find the best combination of organic and inorganic fertilizers to improve rice production systems to maximize yield and nutritional quality, promote food security and sustainable agricultural development.

2 Overview of Rice Grain Quality Traits

2.1 Physical appearance

The physical appearance of rice grains is a critical factor influencing consumer preference and market value. Key traits include the milled rice ratio and chalkiness. The milled rice ratio refers to the proportion of whole grains obtained after milling, which is a significant indicator of milling quality. High milling quality is associated with a higher recovery of whole grains, which is desirable for both producers and consumers (Zhou et al., 2019; Gong et al., 2023). Chalkiness, on the other hand, refers to the opaque areas in rice grains that affect their visual appeal. It is a major determinant of grain appearance and is influenced by genetic and environmental factors (Zhao et al., 2022). Reducing chalkiness is essential for improving the aesthetic quality of rice (Zhao et al., 2022; Gong et al., 2023).

2.2 Nutritional properties

Nutritional properties of rice are increasingly important as consumers demand healthier food options. Key nutritional traits include protein content and mineral composition. Protein content is a vital nutritional quality, as rice is a staple food for a large portion of the global population, and enhancing its protein content can help address malnutrition (Chowdhury et al., 2024; Sadhu and Kole, 2024). Minerals such as iron and zinc are also crucial, and biofortification efforts aim to increase their levels in rice to combat deficiencies (Sadhu and Kole, 2024). Integrated nutrient management, which combines organic and inorganic fertilizers, has been shown to improve the nutritional quality of rice, enhancing both protein and mineral content (Chowdhury et al., 2024).

2.3 Eating and processing quality

Eating and processing quality are determined by traits such as gel consistency and amylose content. Gel consistency measures the firmness of the rice after cooking, with softer gels being preferred in many cultures (Zhou et al., 2019; Gong et al., 2023). Amylose content is another critical factor, as it influences the texture and stickiness of cooked rice. Varieties with different amylose levels cater to diverse consumer preferences, with high amylose rice being less sticky and more suitable for certain culinary applications (Gong et al., 2023; Sadhu and Kole, 2024). The gene Wx, located on chromosome 6, plays a significant role in regulating amylose content and gel consistency, making it a target for breeding programs aimed at improving these quality traits (Sadhu and Kole, 2024).

3 Principles of Integrated Nutrient Management

3.1 Synergy between organic and inorganic nutrients

Integrated Nutrient Management (INM) emphasizes the synergistic use of both organic and inorganic fertilizers to enhance crop yield and soil health. Studies have shown that combining organic materials such as farmyard manure, green manure, and compost with inorganic fertilizers can significantly improve nutrient uptake and use efficiency in rice cultivation. This synergy not only boosts crop yields but also enhances soil properties, such as organic carbon content and microbial activity, which are crucial for long-term soil fertility (Urmi et al., 2022; Paramesh et al., 2023; Chowdhury et al., 2024; Walia et al., 2024). For instance, the application of 50% recommended doses of inorganic fertilizers supplemented with organic manures has been shown to improve soil microbial populations and nutrient availability, leading to better crop performance (Gosal et al., 2018; Saha et al., 2018; Walia et al., 2024).

3.2 Precision fertilization and nutrient balance

Precision fertilization involves the careful management of nutrient inputs to match the specific needs of crops, thereby optimizing nutrient use efficiency and minimizing environmental impacts. INM practices that integrate organic and inorganic sources help maintain a balanced nutrient supply, which is essential for sustaining high crop yields and preventing nutrient depletion in soils. Research indicates that the substitution of a portion of inorganic fertilizers with organic sources can lead to a more balanced nutrient profile in the soil, enhancing the availability of essential nutrients like nitrogen, phosphorus, and potassium (Figure 1) (Saha et al., 2018; Majhi et al., 2021; Bhardwaj et al., 2023). This balanced approach not only supports crop productivity but also mitigates the risk of nutrient leaching and soil degradation (Gosal et al., 2018; Urmi et al., 2022).

3.3 Soil health and fertility maintenance

Maintaining soil health and fertility is a cornerstone of sustainable agriculture, and INM plays a vital role in achieving this goal. The integration of organic amendments such as compost and farmyard manure with inorganic fertilizers has been shown to improve soil structure, increase organic matter content, and enhance microbial activity, all of which contribute to better soil health (Majhi et al., 2021; Patra et al., 2022; Paramesh et al., 2023). Long-term studies have demonstrated that INM practices can lead to significant improvements in soil quality indicators, such as soil organic carbon, microbial biomass, and nutrient availability, thereby supporting sustainable crop production (Sharma et al., 2019; Patra et al., 2022; Walia et al., 2024). By fostering a healthy soil ecosystem, INM not only enhances current crop yields but also ensures the long-term sustainability of agricultural systems.

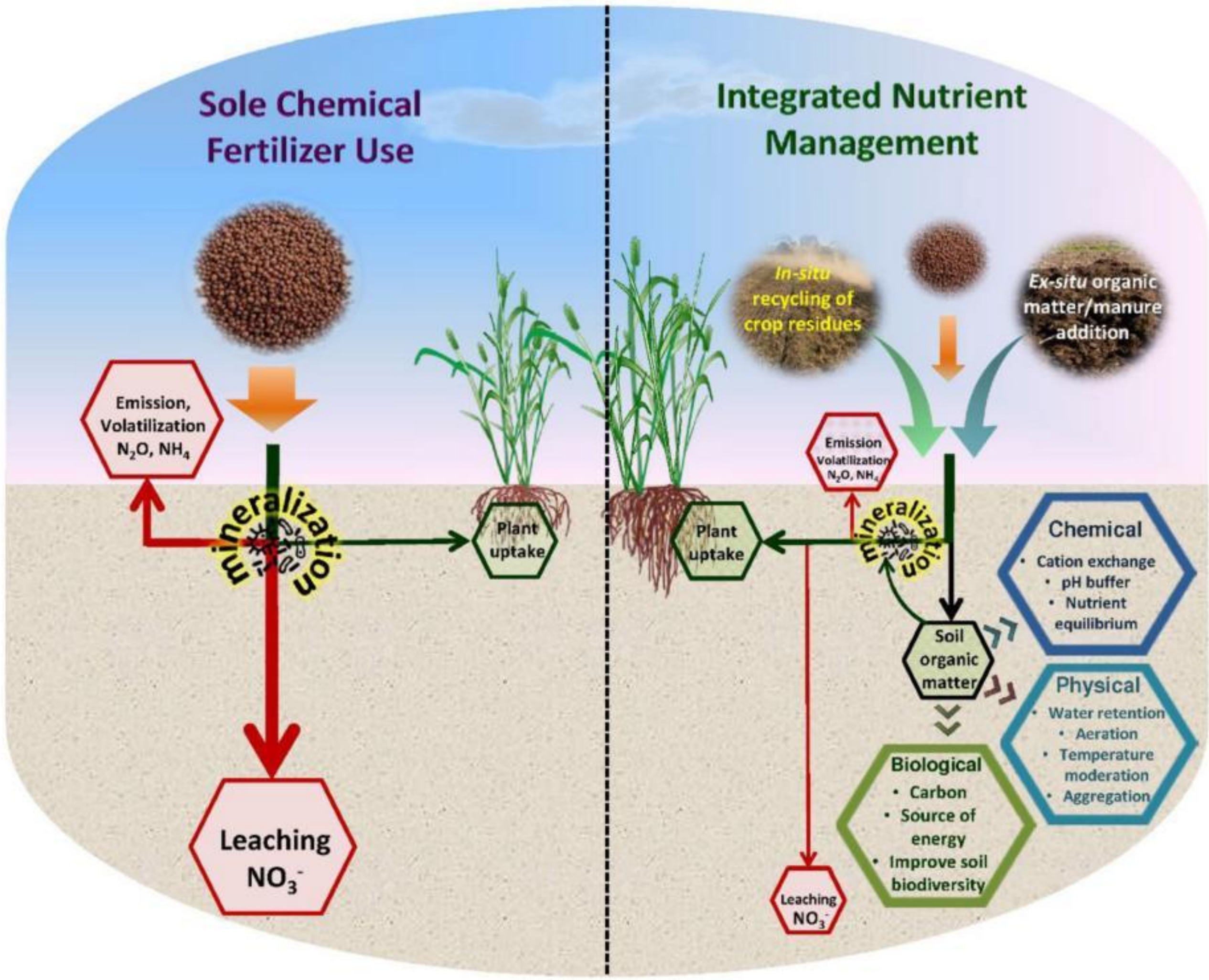

Figure 1 Contrasting influences of sole chemical fertilizer vs. integrated nutrient management on the nitrogen pools, mineralization, leaching, and volatilization fluxes (Adopted from Bhardwaj et al., 2023)

4 Case Region and Field Application Example

4.1 Case selection 1

4.1.1 Major rice-producing area in Yangzhou, Jiangsu Province

Yangzhou, located in Jiangsu Province, is a significant rice-producing area characterized by a subtropical climate with distinct seasons, which is conducive to rice cultivation. The region's soil types include clay, loamy, and sandy soils, each affecting rice root development and grain quality differently under various irrigation regimes (Can et al., 2021). The cropping system in Yangzhou often involves rice monoculture, but there are also integrated systems like rice-green manure rotation and rice-duck co-culture, which are gaining popularity due to their environmental benefits (Figure 2) (Gao et al., 2023).

Jiangsu Province, including Yangzhou, predominantly cultivates japonica rice varieties, which have seen improvements in grain yield and nutrient use efficiency over the decades (Meng et al., 2022). However, challenges remain in maintaining high grain quality, particularly under high nitrogen levels, which can deteriorate eating and cooking quality due to increased protein content (Gu et al., 2015). Efforts to improve grain quality focus on optimizing nitrogen management and breeding practices to balance yield and quality.

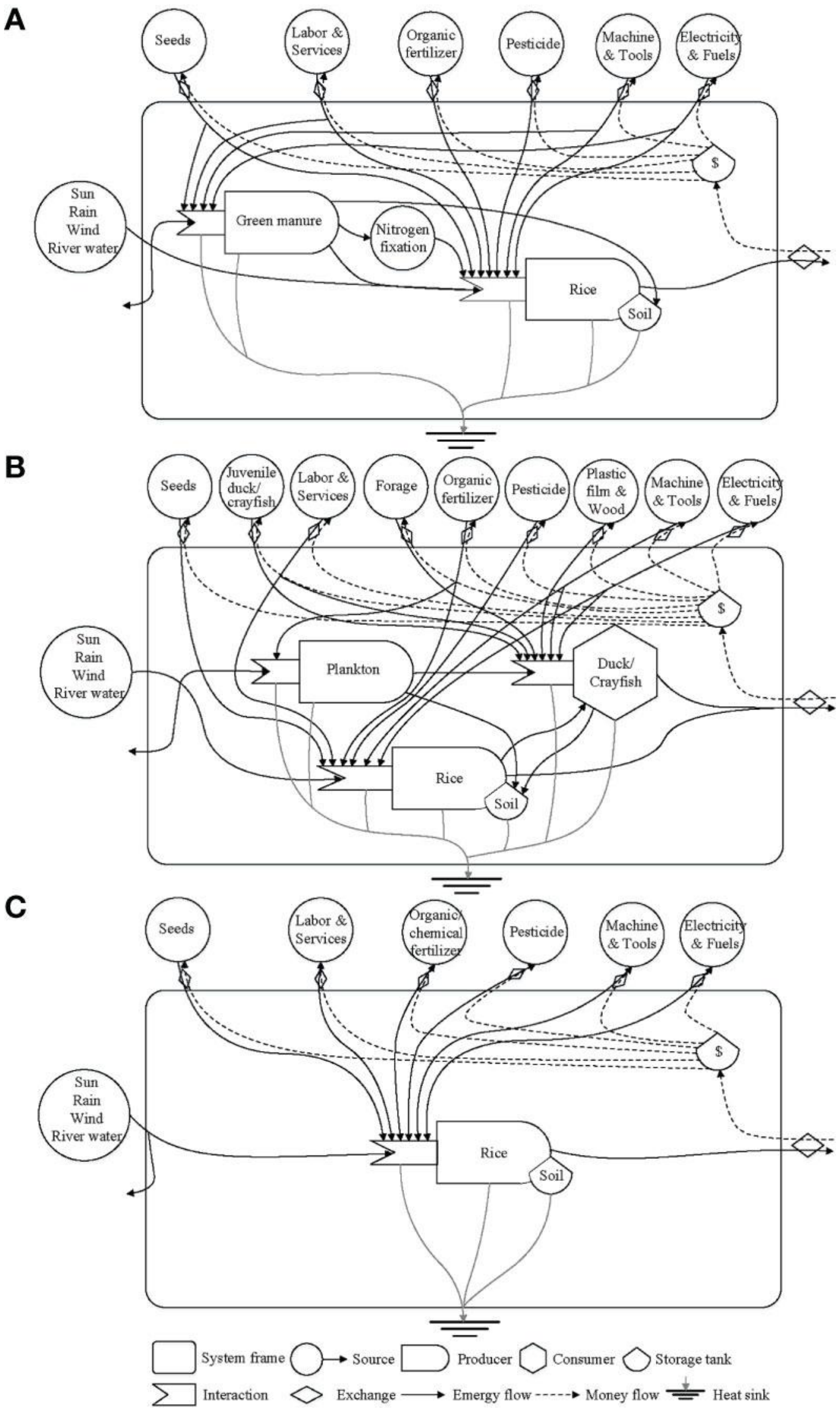

Figure 2 Aggregated energy flow diagrams of rice-green manure rotation (A), rice-duck/crayfish co-culture (B) and organic/conventional rice monoculture (C) (Adopted from Gao et al., 2023)

Integrated nutrient management in Yangzhou involves optimizing nitrogen application rates and timing to enhance yield and nitrogen use efficiency while minimizing environmental impacts (Guo et al., 2017). This approach has been shown to increase yield and partial factor productivity of nitrogen by adjusting application strategies, thus contributing to sustainable rice production. The integration of organic and inorganic fertilizers is also practiced to improve soil health and rice grain quality (Zahra et al., 2022).

4.1.2 Field management and nutrient application design

Field management in Yangzhou involves the use of integrated crop management practices that combine increased plant density and optimized nutrient management to maximize grain yield (Wang et al., 2017). The design of nutrient application includes the use of both organic and inorganic fertilizers, with a focus on reducing nitrogen rates and improving application timing to enhance nutrient use efficiency and grain quality (Wang et al., 2019). This approach aims to achieve high yield and quality while reducing environmental impacts.

4.1.3 Data collection and quality evaluation methods

Data collection in the field involves monitoring grain yield, nitrogen use efficiency, and grain quality parameters such as milling quality, appearance quality, and nutritional content (Gu et al., 2015; Can et al., 2021). Quality evaluation methods include assessing the milling quality (e.g., brown rice percentage, milled rice percentage), appearance quality (e.g., chalky kernels percentage), and nutritional quality (e.g., protein and micronutrient content) (Gu et al., 2015). These evaluations help in understanding the impact of integrated nutrient management on rice grain quality and guide further improvements in cultivation practices.

4.2 Case selection 2: major rice-producing area in Deqing County, Zhejiang Province

Deqing County is located in the north of Zhejiang Province, in the hinterland of the Yangtze River Delta, with a subtropical monsoon climate. It has four distinct seasons, sufficient light, abundant rainfall, warm and humid. The territory is densely covered with water systems and fertile land, which is suitable for rice growth. Rice is the most widely planted grain crop in Deqing County. In 2024, the planting area of rice in the whole county reached 6000 hectare, dominated by high-quality rice varieties, such as' ningxiangjing 9 ',' zhehexiang 2 'and' zheyou 18 '. In recent years, the model of "rice duck co breeding" has been vigorously demonstrated and popularized, which has greatly improved the quality of rice (Figure 3). The "rice duck co breeding" model, which is dominated by ducks, forms an ecosystem with rice, insects, other microorganisms, field weeds, etc., uses duck manure as natural fertilizer instead of chemical fertilizer, makes full use of the omnivorous nature of ducks, feeds on rice flowers, weeds, pests, etc., and avoids the spraying of chemical insecticides, fungicides and herbicides, so as to produce high-quality green rice.

Figure 3 "Rice duck co breeding" model in Deqing (Photographed by Yuchao Shen)

5 Effects of Integrated Nutrient Management on Grain Quality

5.1 Appearance improvement under different treatments

Integrated nutrient management (INM) has been shown to enhance the appearance of rice grains by improving plant growth parameters such as tiller number and panicle length, which contribute to a more uniform and appealing grain size and shape. For instance, the combination of inorganic fertilizers with organic sources like cow dung has resulted in better plant growth and yield, leading to improved grain appearance in black rice (Chowdhury et al., 2024). Additionally, the use of poultry manure and other organic amendments has been associated with increased grain yield and improved physical characteristics of rice grains (Kaur et al., 2023).

5.2 Nutritional enrichment and enhancement

INM practices significantly enhance the nutritional quality of rice grains. The integration of organic and inorganic fertilizers has been shown to increase the protein content and essential micronutrients such as potassium in rice grains. For example, a study found that a combination of 75% inorganic fertilizer and 25% cow dung resulted in higher protein and potassium content in black rice (Chowdhury et al., 2024). Moreover, the use of poultry manure has been linked to improved nutrient uptake, including nitrogen, phosphorus, and potassium, which are crucial for enhancing the nutritional profile of rice grains (Urmi et al., 2022; Kaur et al., 2023).

5.3 Improvements in palatability and processing traits

5.3.1 Gel consistency and taste evaluation

The application of INM can positively affect the gel consistency and taste of rice, which are important for consumer preference. The balanced nutrient supply from both organic and inorganic sources can lead to better starch quality, influencing the texture and taste of cooked rice. Although specific studies on gel consistency and taste evaluation are limited, the overall improvement in grain quality through INM suggests potential benefits in these areas (Zhang et al., 2020).

5.3.2 Variations in amylose content

INM practices can influence the amylose content of rice, which is a key determinant of cooking and eating quality. The integration of organic amendments such as farmyard manure with chemical fertilizers has been shown to affect the starch composition of rice grains, potentially leading to variations in amylose content. This can result in rice with desirable cooking properties, such as a softer texture and better taste (Walia et al., 2024).

5.3.3 Performance across different processing applications

Rice grains produced under INM systems have shown improved performance in various processing applications. The enhanced grain quality, including better nutritional content and physical characteristics, makes them suitable for diverse processing needs. The use of organic amendments like poultry manure has been associated with increased grain yield and quality, which can translate into better performance in milling and other processing applications (Urmi et al., 2022; Kaur et al., 2023).

6 Yield and Agronomic Performance

6.1 Yield-quality trade-off coordination

Integrated nutrient management (INM) practices have shown significant potential in balancing the trade-off between yield and quality in rice production. Studies indicate that combining organic and inorganic fertilizers can enhance both yield and nutritional quality. For instance, the application of 75% inorganic fertilizer with 25% cow dung resulted in the highest grain yield and improved nutritional quality in black rice, demonstrating a successful coordination between yield and quality (Chowdhury et al., 2024). Similarly, the use of integrated crop management practices has been shown to increase grain yield while maintaining or improving the nutritional quality of rice, suggesting that INM can effectively manage the yield-quality trade-off (Wang et al., 2017; Zhang et al., 2018).

6.2 Plant height and grain setting under different regimes

The application of integrated nutrient management significantly influences plant height and grain setting. For example, a study in Tamil Nadu reported that the combined application of inorganic fertilizers and vermicompost resulted in higher plant height and improved grain setting, as evidenced by increased numbers of productive tillers and filled grains per panicle (Udhaya et al., 2024). Additionally, the use of integrated crop management practices, which include optimized nutrient management, has been shown to enhance plant growth parameters such as plant height and tiller number, contributing to improved grain setting.

6.3 Overall field performance and stability

Overall field performance and stability are crucial for sustainable rice production. Integrated nutrient management has been shown to improve field performance by enhancing yield stability and agronomic efficiency. For instance, the use of INM practices in a rice-wheat cropping system in the Indian subcontinent resulted in significant yield gains and improved soil health, indicating enhanced field performance and stability (Sharma et al., 2019). Furthermore, the integration of organic and inorganic inputs has been shown to improve soil quality and crop productivity, contributing to the overall stability of the cropping system (Sarkar et al., 2024). These findings suggest that INM practices can lead to sustainable improvements in rice production by enhancing both yield and agronomic stability.

7 Farmer Practice and Scaling Potential

7.1 Farmer engagement and perception of quality

Farmers' engagement with integrated nutrient management (INM) practices is crucial for improving rice grain quality. Studies have shown that farmers perceive the combination of organic and inorganic fertilizers as beneficial for enhancing soil quality and crop yield. For instance, the use of farmyard manure combined with chemical fertilizers has been reported to significantly improve crop yield and soil fertility, which aligns with farmers' goals of achieving higher productivity and sustainability (Paramesh et al., 2023; Urmi et al., 2022). Additionally, the adoption of INM practices has been linked to improved soil health and nutrient transformations, which are critical factors that farmers consider when evaluating the quality of their produce (Walia et al., 2024).

7.2 Applicability and feasibility of nutrient management

The applicability and feasibility of INM practices are supported by various studies that highlight their effectiveness in different cropping systems. For example, the integration of organic inputs such as vermicompost and poultry manure with inorganic fertilizers has been shown to enhance soil fertility and crop productivity in rice-based systems (Urmi et al., 2022; Kaur et al., 2023). These practices are feasible for farmers as they utilize locally available resources, reducing dependency on costly inorganic fertilizers. Moreover, the use of site-specific nutrient management (SSNM) tools can further tailor nutrient applications to specific farm conditions, enhancing the applicability of INM practices across diverse environments.

7.3 Potential and barriers to regional scaling

The potential for scaling INM practices regionally is significant, given their proven benefits in improving yield and soil quality. However, several barriers exist, including the need for extensive field evaluations to adapt practices to local conditions and the requirement for farmer education and training on the benefits and implementation of INM (Chivenge et al., 2022). Additionally, the integration of digital tools and platforms can facilitate the dissemination of INM practices, although challenges such as the need for farm-specific data and the variability in economic outcomes must be addressed. Despite these barriers, the positive impact of INM on soil health and crop productivity suggests a strong potential for regional scaling, provided that these challenges are effectively managed (Patra et al., 2022; Sai and Chettri, 2020).

8 Concluding Remarks

The integration of organic and inorganic nutrient sources can significantly improve the quality and yield of rice. Research has shown that integrated nutrition management (INM) practices, such as combining poultry manure with nitrogen fertilizer, can increase rice yield by up to 67.3% compared to control treatments without organic amendments. Research has found that INM can improve soil health by increasing microbial activity and nutrient absorption efficiency, which is crucial for sustainable crop production. The use of INM can not only improve crop productivity, but also enhance the nutritional quality of rice. When cow manure is combined with inorganic fertilizers, the protein and potassium content in black rice will increase.

The research findings emphasize the potential of INM to address the challenges of declining soil fertility and stagnant crop yields, particularly in areas with dense rice cultivation. Future research should focus on optimizing the balance between organic and inorganic inputs to maximize yield and soil health benefits. Further exploration is needed to investigate the long-term effects of INM on soil carbon sequestration and nutrient cycling, which is crucial for mitigating the impacts of climate change. The research should aim to develop region specific INM strategies, taking into account local soil conditions, crop types, and available organic resources.

Implement a balanced combination of organic and inorganic fertilizers tailored to specific soil and crop needs to improve yield and soil health. Encourage the use of locally available organic materials such as poultry manure and farmyard manure to improve nutrient absorption and soil microbial activity. Raise farmers' awareness and training on the benefits of INM and the importance of maintaining soil health for sustainable agriculture. Support research programs aimed at understanding the interaction between soil microbiota and nutrient management practices to further optimize INM strategies. Develop policies that incentivize the adoption of INM practices, including subsidies for organic inputs and support for farmer education programs. Integrated nutrient management provides a promising way to improve rice quality and yield, while ensuring the sustainability of the agricultural system. By adopting strategic INM practices, both food security and environmental health can be enhanced simultaneously.

Acknowledgments

The author express deep gratitude to Professor R. Cai from the Zhejiang Agronomist College for his thorough review of the manuscript and constructive suggestions.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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