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Meta Analysis Open Access

Meta-Analysis of Rice Yield Improvement Techniques: Lessons from Global Practices

Chao Wang
Zhuji City Agricultural Technology Extension Center, Zhuji, 311800, Zhejiang, China
Corresponding email: 1170828465@qq.com

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Abstract Rice (*Oryza sativa* L.) is a staple food for over half of the world's population, making its yield improvement crucial for global food security. This meta-analysis synthesizes findings from various studies to evaluate the effectiveness of different rice yield improvement techniques. The analysis covers water management practices, responses to elevated atmospheric CO_2 and ozone concentrations, biochar applications, and nutrient management strategies. Water management techniques such as alternate wetting and drying have been shown to reduce methane emissions significantly but may slightly decrease yields. Elevated CO_2 levels generally increase rice yields, although this effect can be mitigated by elevated ozone levels and higher temperatures. Biochar application improves soil health and increases rice yields while reducing greenhouse gas emissions. Nutrient management, particularly the interaction between nitrogen and potassium, enhances canopy performance and overall yield. The findings underscore the importance of integrated, location-specific approaches to rice cultivation that consider environmental impacts and sustainability.

Keywords Rice yield improvement; Water management; Elevated CO_2; Biochar application; Nutrient management

1 Introduction

Rice (*Oryza sativa* L.) is a fundamental staple food for nearly half of the world's population, making it one of the most crucial crops for global food security (Ainsworth, 2008; Awad et al., 2018; Guo et al., 2021). The demand for rice is continuously increasing due to the growing global population, necessitating significant improvements in rice yield to meet future food requirements (Guo et al., 2021; Ye et al., 2021). As a primary source of nutrition, rice plays a vital role in the diets of billions of people, particularly in Asia, where it accounts for a substantial portion of daily caloric intake (Vishwakarma et al., 2023). The importance of rice extends beyond nutrition, as it also contributes to the economic stability of many developing countries where rice farming is a major livelihood (Ara et al., 2016).

Achieving sustainable improvements in rice yield is fraught with challenges, including environmental stresses, climate change, and the need for efficient agricultural practices. Climate change, characterized by rising temperatures and increased greenhouse gas emissions, poses a significant threat to rice production. Elevated levels of carbon dioxide (CO_2) and ozone (O_3) have been shown to impact rice yields negatively, with elevated O_3 reducing yield by 14% and elevated temperatures negating the benefits of increased CO_2 (Ainsworth, 2008). Additionally, water management practices, such as non-continuous flooding, while reducing methane emissions, can also lead to a slight decrease in yield (Aloryi et al., 2022). Soil health and nutrient management, particularly the interactions between nitrogen and potassium, are critical for improving canopy performance and overall yield (Iqbal et al., 2016). Furthermore, the genetic complexity of rice and the need for stable, high-yielding varieties that can withstand biotic and abiotic stresses add to the challenge (Vishwakarma et al., 2023).

This study synthesizes the global research on rice yield improvement techniques to identify effective strategies and practices that can be widely applied across the globe. It evaluates the impact of environmental factors, such as climate change and greenhouse gas emissions, on rice yield, assesses the effectiveness of various agricultural practices-including water management and nutrient optimization- in enhancing rice productivity, and explores advancements in genetics and biotechnology with potential for yield improvement. By integrating findings from multiple studies, this research seeks to provide a comprehensive understanding of the determinants of rice yield and offer actionable recommendations for policymakers, researchers, and farmers to achieve sustainable rice production.

2 Methodology

2.1 Data collection and criteria for inclusion

The data for this study were collected from a comprehensive bibliographic search of research papers published between 2001 and 2022. The search focused on studies that investigated various techniques for improving rice yield, including quantitative trait loci (QTL) analysis, genome-wide association studies (GWAS), and field management practices. A total of 462 QTLs from 47 independent studies were retrieved, and 563 QTLs from 67 rice populations were analyzed for traits under water deficit conditions (Aloryi et al., 2022). Additionally, data on greenhouse gas emissions and yield responses to elevated CO_2 and O_3 concentrations were included (Ainsworth, 2008). Studies were selected based on their relevance to rice yield improvement, the robustness of their methodologies, and the availability of quantitative data.

2.2 Statistical approaches used for study

The study employed several statistical techniques to synthesize data from multiple studies. QTL projection was performed using a reference map, and meta-QTL (MQTL) analysis was conducted to identify stable and robust QTLs with reduced confidence intervals (CI) (Khahani et al., 2021; Aloryi et al., 2022). For genome-wide association studies, meta-GWAS was used to detect significant loci affecting yield and its component traits (Su et al., 2021). Dose-response analysis was applied to assess the impact of high temperatures on rice yield and quality (Xiong et al., 2017). Additionally, statistical methods were used to evaluate the effects of various field management practices on greenhouse gas emissions and yield (Wang et al., 2012; Feng et al., 2013; Zhao et al., 2019). The results were synthesized to provide a comprehensive understanding of the genetic and environmental factors influencing rice yield.

2.3 Limitations and sources of bias in the study

Several limitations and potential sources of bias were identified in this study. The heterogeneity of the studies included, such as differences in experimental conditions, genetic backgrounds, and environmental factors, could introduce variability in the results (Khahani et al., 2021; Su et al., 2021; Aloryi et al., 2022). Publication bias may have affected the selection of studies, as research with significant findings is more likely to be published. The reliance on reported data without access to raw data may limit the accuracy of the study. Additionally, the interaction between different field management practices and site-specific conditions was not always accounted for, which could influence the generalizability of the findings (Huang et al., 2015; Zhao et al., 2019). Despite these limitations, the study provides valuable insights into the techniques for improving rice yield and highlights areas for future research.

3 Overview of Global Rice Yield Improvement Techniques

3.1 Conventional breeding approaches

Conventional breeding approaches have significantly contributed to the development of high-yielding rice varieties. The selection of high-yielding varieties involves identifying and propagating rice strains that exhibit superior yield potential under optimal conditions. This method has been a cornerstone of rice improvement strategies, particularly during the Green Revolution, which introduced semi-dwarf rice types that significantly increased yield potential (Khush, 2013). Hybrid rice technology has been another pivotal conventional breeding approach. By crossing two genetically diverse rice varieties, hybrid rice exhibits heterosis or hybrid vigor, resulting in higher yields compared to inbred varieties. Field experiments in China and Japan have demonstrated that the best recent Chinese hybrids have a yield potential about 10% higher than the best recent inbred cultivars in Japan (Horie et al., 2005). This technology has been instrumental in achieving yield gains and meeting the rising global demand for rice.

3.2 Biotechnological interventions

Genetic engineering has opened new avenues for enhancing rice yield by directly modifying the plant's genetic makeup. Techniques such as molecular marker-assisted selection (MAS) and genetic engineering have been employed to introduce desirable traits such as improved photosynthesis, stress tolerance, and nutrient use efficiency. These interventions have the potential to break the yield ceiling by enhancing the plant's physiological and metabolic processes (Altaf et al., 2021; Vishwakarma et al., 2023).

The CRISPR-Cas9 gene-editing technology has revolutionized rice breeding by allowing precise modifications at specific genomic loci. This technology has been used to enhance traits such as yield, stress tolerance, and disease resistance. CRISPR-Cas9 enables the development of rice varieties that can thrive under suboptimal conditions, thereby contributing to sustainable yield improvements (Nutan et al., 2020).

3.3 Agronomic practices

Integrated nutrient management (INM) involves the judicious use of chemical fertilizers, organic manures, and bio-fertilizers to optimize nutrient availability and uptake by rice plants. Studies have shown that INM can significantly enhance grain yield by improving plant density, leaf area index, and radiation use efficiency. For instance, integrated crop management practices in China have resulted in a 13.5% increase in grain yield compared to traditional farming practices (Wang et al., 2017; Cheng et al., 2021).

Effective water management is crucial for maximizing rice yield, especially in regions with limited water resources. Techniques such as intermittent irrigation and the System of Rice Intensification (SRI) have been shown to improve water use efficiency and yield. SRI, in particular, involves practices like transplanting young seedlings and applying compost, which enhance root growth and nutrient uptake, leading to higher yields (Kassam et al., 2011).

3.4 Sustainable and climate-resilient approaches

Developing stress-tolerant rice varieties is essential for ensuring stable yields under adverse environmental conditions such as drought, salinity, and extreme temperatures. Advances in molecular biology have facilitated the identification and incorporation of genes responsible for stress tolerance into high-yielding rice varieties. These stress-tolerant varieties are crucial for maintaining productivity in the face of climate change (Long, 2014; Nutan et al., 2020).

Organic and low-input farming practices focus on reducing the reliance on synthetic inputs and promoting sustainable agricultural practices. These methods include the use of organic fertilizers, crop rotations, and biological pest control. While these practices may result in slightly lower yields compared to conventional methods, they offer long-term benefits such as improved soil health, reduced environmental impact, and enhanced resilience to climate change (Figure 1) (Cheng et al., 2021; Verma et al., 2021; Ye et al., 2021).

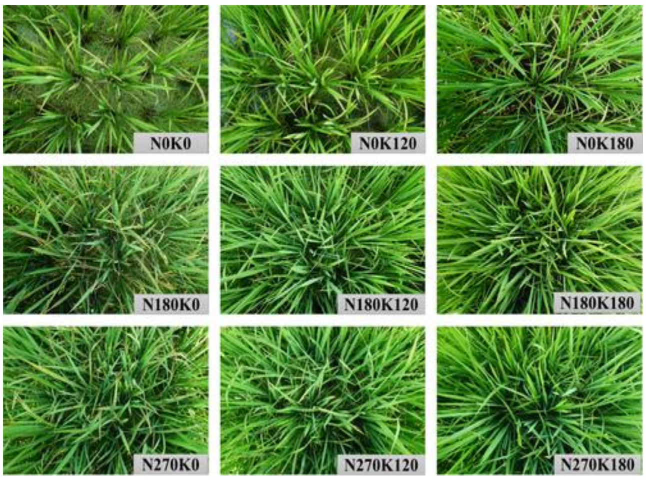

Figure 1 Vertical view of different N and K rate on the leaf development at booting stage (Adopted from Ye et al., 2021)

4 Case Study: System of Rice Intensification (SRI)

4.1 Introduction to SRI and its principles

The System of Rice Intensification (SRI) is an innovative agro-ecological approach to rice cultivation that originated in Madagascar. It focuses on changing the management of rice plants, soil, water, and nutrients to enhance productivity. Key principles of SRI include planting younger seedlings singly rather than in clumps, maintaining wider spacing between plants, and using intermittent irrigation instead of continuous flooding. These practices aim to improve root growth and plant health, leading to higher yields and reduced input costs (Stoop et al., 2002; Chintalapati et al., 2023; Thakur et al., 2023).

4.2 Global implementation and adoption of SRI

SRI has been adopted in various countries across the globe, including India, China, Indonesia, and several African nations. In India, for instance, SRI has been implemented in states like Andhra Pradesh, Tamil Nadu, and Tripura, showing significant yield improvements and water savings (Sinha and Talati, 2007; Majumder et al., 2019). The method has also been evaluated in 27 countries, with 80% of studies reporting higher grain yields compared to conventional practices (Thakur et al., 2023). Despite initial skepticism, SRI has gained traction due to its potential to increase productivity while reducing resource use (Stoop et al., 2002).

4.3 Comparative analysis of yield gains across regions

Studies have shown that SRI can lead to substantial yield gains across different regions. In India, SRI practices resulted in a 32% increase in paddy yields and a 67% increase in net returns compared to conventional methods (Sinha and Talati, 2007). In Kerala, SRI management yielded 3 326 kg/ha, which was higher than farmers' practices but lower than the best management practices (Sarala and Chellappan, 2011). Similarly, in Tripura, SRI provided higher gross and net returns compared to traditional methods. These results highlight the variability in yield gains, influenced by local conditions and implementation practices (Satyanarayana et al., 2006; Sinha and Talati, 2007; Majumder et al., 2019; Li et al., 2024).

4.4 Challenges and criticisms of SRI

Despite its benefits, SRI faces several challenges and criticisms. One major criticism is the increased labor requirement, particularly for weeding and transplanting, which can be a barrier for smallholder farmers. Additionally, the variability in yield gains and the need for precise management practices can make SRI less attractive in regions with less favorable conditions or where farmers lack the necessary training and resources (Dobermann, 2004; Sarala and Chellappan, 2011). Some studies have also questioned the scientific basis of SRI, arguing that the reported high yields may be due to measurement errors or selective data presentation (Figure 2) (Thakur et al., 2023).

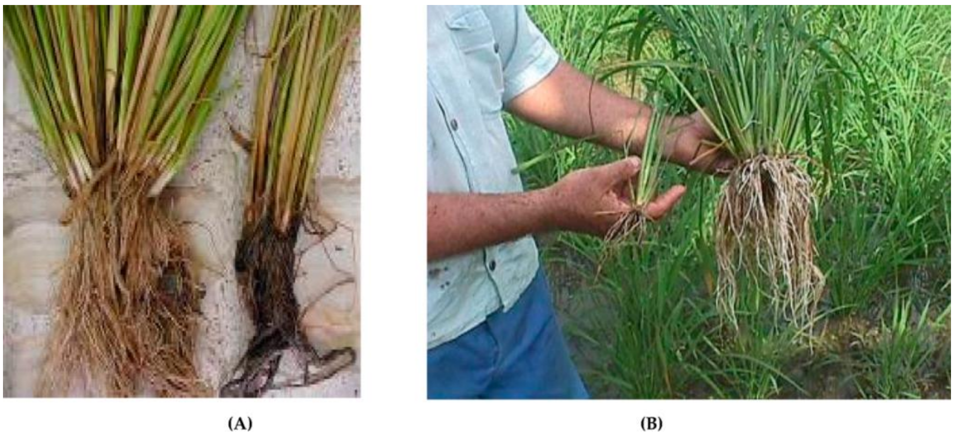

Figure 2 (A) The pair of rice plants grown, respectively, using SRI vs. standard methods of rice cultivation at the Haraz Extension and Technology Development Center in Amol, Iran. The dark color and stunting of the right-hand plant's roots reflect their degeneration due to lack of oxygen. (B) The pair of rice plants grown in Cuba are of the same age (52 days) and the same variety (VN 2084). Right-side plants are grown using SRI and have 43 tillers, and the left one grown using the standard method have only 5 tillers (Adopted from Thakur et al., 2023)

4.5 Lessons learned for future yield improvement practices

The experience with SRI offers several lessons for future yield improvement practices. First, the importance of integrated and interdisciplinary research is evident, as SRI's success relies on the synergy between various agronomic practices (Stoop et al., 2002). Second, the adaptability of SRI to local conditions and its potential for resource savings make it a valuable model for sustainable agriculture (Satyanarayana et al., 2006; Majumder et al., 2019). However, addressing the labor-intensive nature of SRI and providing adequate training and support to farmers are crucial for its broader adoption and success (Dobermann, 2004). Future research should focus on optimizing SRI practices to reduce labor requirements and enhance its applicability across diverse agro-ecological settings (Thakur et al., 2023).

5 Synthesis of Key Findings

5.1 Comparative effectiveness of genetic, agronomic, and socio-economic approaches

Genetic approaches, such as Meta-QTL and genome-wide association studies, have been instrumental in identifying stable QTLs and significant loci that control yield and yield-related traits under various conditions. For instance, Meta-QTL analysis has identified 61 stable QTLs for traits like grain weight and root architecture under water deficit conditions, which are crucial for breeding programs aimed at improving yield in non-flooded cultivation systems (Khahani et al., 2021). Similarly, genome-wide association studies have pinpointed significant loci for component traits like grains per panicle and tillers per plant, which indirectly enhance yield potential (Su et al., 2021).

Agronomic approaches, particularly optimized nitrogen management, have shown significant promise in improving both yield and nitrogen use efficiency. Studies have demonstrated that reducing total nitrogen and late-stage nitrogen application can enhance rice eating quality and nitrogen use efficiency without significantly compromising yield (Cheng et al., 2021). Additionally, optimized management practices, including appropriate water and fertilizer management, have been shown to improve grain yield and nitrogen use efficiency by enhancing post-heading carbon and nitrogen metabolism (Deng et al., 2022). Socio-economic approaches, such as the development of decision support systems like Nutrient Expert (NE) for Rice, have also proven effective. These systems provide science-based fertilizer recommendations that improve yield and agronomic efficiency, thereby increasing profits for farmers.

5.2 Regional variations in yield improvement success

Regional variations significantly influence the success of yield improvement techniques. In China, for example, traditional nitrogen management practices have been heavily reliant on high nitrogen input, which has led to environmental concerns and reduced eating quality. Adjusting these practices has shown promise in balancing yield and quality (Cheng et al., 2021). In contrast, in regions facing water deficit conditions, genetic approaches like Meta-QTL analysis have been more effective in identifying traits that enhance yield under stress (Khahani et al., 2021). In intensive irrigated systems in Asia, continuous agronomic and genetic interventions have been essential for sustaining high annual production. However, these systems have struggled to achieve the yield increases needed to meet growing global demand, highlighting the need for ongoing innovation and adaptation (Ladha et al., 2021). The variability in success across regions underscores the importance of tailoring yield improvement strategies to specific environmental and socio-economic contexts.

5.3 Identification of synergistic strategies

Synergistic strategies that combine genetic, agronomic, and socio-economic approaches have shown the most promise for sustainable yield improvement. For instance, the integration of optimized nitrogen management with genetic improvements in super hybrid rice has led to significant gains in both yield and nitrogen use efficiency (Deng et al., 2022). Similarly, the use of decision support systems like Nutrient Expert, which incorporate agronomic data and genetic insights, has proven effective in enhancing yield and profitability (Xu et al., 2017).

Moreover, the combination of genetic mapping techniques with agronomic practices has facilitated the identification of key traits and management practices that can be targeted for improvement. For example, the identification of stable QTLs for yield-related traits through Meta-QTL analysis, combined with optimized nitrogen management, has provided a comprehensive framework for improving rice yield under various conditions (Khahani et al., 2021; Aloryi et al., 2022).

6 Integrated Approaches for Enhancing Rice Yield

6.1 Integration of genetic mapping and agronomic practices

The integration of genetic mapping tools with agronomic management has become increasingly important in modern rice breeding. While genetic mapping alone has allowed researchers to pinpoint loci associated with key traits, its impact is greatly amplified when combined with on-the-ground agronomic knowledge. For instance, Meta-QTL analysis has enabled the identification of stable QTLs linked to yield-related traits across multiple environments, providing breeders with reliable genetic targets (Khahani et al., 2021; Aloryi et al., 2022).

However, these genetic insights do not operate in a vacuum-optimized nitrogen management, for example, is often necessary to fully express the potential of favorable alleles. In many breeding programs, the practical value of QTLs is only realized when they are paired with regionally adapted field practices. This combined approach has proven particularly valuable under variable environmental conditions, where genetic resilience and responsive agronomy must go hand in hand. As such, the synergy between mapping techniques and agronomic strategies represents a crucial step toward closing the yield gap in rice cultivation.

6.2 Regional variations in yield improvement success

Regional variations significantly influence the success of yield improvement techniques. For instance, in China, traditional nitrogen management practices have been adjusted to improve both yield and eating quality, demonstrating the importance of region-specific agronomic practices (Cheng et al., 2021). In contrast, in regions facing water deficits, genetic approaches such as meta-QTL analysis have identified stable QTLs for yield-related traits under water stress conditions, highlighting the need for drought-resistant varieties (Khahani et al., 2021). Additionally, the International Rice Research Institute (IRRI) has focused on accelerating genetic improvements in Asia and Africa to meet the growing demand for rice, emphasizing the role of regional breeding programs (Juma et al., 2021).

6.3 Identification of synergistic strategies

Synergistic strategies that combine genetic, agronomic, and socio-economic approaches have shown the most promise in improving rice yields. For example, the integration of optimized management practices with genetic improvements in super hybrid rice has led to significant yield gains and enhanced nitrogen use efficiency (Deng et al., 2022). Similarly, the combination of genetic insights from genome-wide association studies with practical agronomic interventions, such as adjusting nitrogen application, has been recommended to further enhance rice yield potential (Su et al., 2021). These synergistic strategies underscore the importance of a holistic approach to rice yield improvement, leveraging the strengths of multiple disciplines to achieve sustainable productivity gains.

7 Implications for Future Research and Policy

Despite significant advancements in rice yield improvement, several research gaps remain. One critical area is the need for more localized studies to understand the specific factors contributing to yield gaps in different regions. For instance, studies have shown that yield gaps in Eastern and Southern Africa are influenced by factors such as straw management, weeding frequency, and fertilizer application. Similarly, in China, yield gaps are affected by climatic conditions and soil nutrient content. Therefore, future research should prioritize region-specific studies to identify and address the unique challenges faced by rice farmers in different areas.

Another priority is the development of integrated crop management practices that can enhance resource-use efficiency. Research has demonstrated that high yields and high resource-use efficiencies are not mutually exclusive goals. By focusing on improving soil, plant, and nutrient management measures, it is possible to narrow yield gaps and increase nutrient use efficiency (NUE). Additionally, there is a need for more studies that decompose yield gaps into efficiency, resource, and technology gaps to better target research and development efforts.

Policymakers and practitioners should focus on creating an enabling environment for the adoption of advanced agricultural technologies and practices. Investments in technology transfer and institutional arrangements are crucial for boosting farmers' yields and closing yield gaps. For example, in Southeast Asia, structural changes are needed to accelerate the adoption of improved rice cultivars and production technologies. Moreover, policies should support the dissemination of integrated crop management practices, especially in regions with large efficiency yield gaps. This includes promoting the use of improved rice cultivars, better nutrient and water management techniques, and effective weed control measures. Policymakers should also prioritize investments in agricultural research and development to ensure that the latest innovations are accessible to farmers.

Integrating traditional knowledge with modern agricultural practices can play a significant role in improving rice yields. Traditional knowledge, such as indigenous soil and water management techniques, can complement modern practices to enhance resource-use efficiency and sustainability. For instance, in sub-Saharan Africa, combining traditional practices with modern technologies has shown potential in increasing rice productivity. Efforts should be made to document and validate traditional knowledge and integrate it into modern agricultural extension programs. This can help in developing context-specific solutions that are more acceptable to local farmers. Additionally, participatory research approaches that involve farmers in the development and testing of new technologies can ensure that these innovations are well-suited to local conditions and practices.

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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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