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Rice Ratooning: A Revolutionary Approach for Resource-efficient and Sustainable Practice for Promising Future of Rice

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Ratoon rice, a unique method of cultivating a second crop from primary harvested stubble, is gaining recognition for its potential to revolutionize rice production sustainability and resource efficiency. This comprehensive study aimed to assess the effectiveness of ratoon rice cropping systems compared to traditional methods, focusing on grain yield, quality, economics, and overall sustainability. To achieve better yields in ratoon crops, it is crucial to adopt suitable management practices for both the main crop and the ratoon crop. These practices encompass land preparation, use of suitable cultivars, water management, precise fertilizer application, appropriate cutting stubble height, and effective control of insects and diseases. Results unveiled that with proper management, ratoon rice yields were on par with approximately 60% of the main crop while utilizing only 50% of the labor and resources. The ratoon rice system demonstrated multiple benefits, including farmer profitability, improved crop quality, and reduced greenhouse gas emissions. Despite its promising potential, the widespread adoption of ratoon rice faced limitations such as inconsistent and lower ratoon crop yields, and the lack of suitable cultivars and specialized rice mechanical harvesters. Addressing these challenges, critical agronomic practices were identified, encompassing nutrient and water management, stubble cutting height, variety selection, and integrated technologies for disease and insect control. Ratoon rice is crucial for promoting widespread adoption and securing ratoon rice as a viable solution for the future of rice cultivation.

Keywords: Agronomic practices; crop yield; economic benefits; ratoon rice; resource efficiency; sustainability, quality.

1. INTRODUCTION

Rice (*Oryza sativa* L.) stands as a crucial source of nutrition worldwide, second only to wheat, with an estimated 165.25 million hectares devoted to rice cultivation and a total production of 502.9 million metric tonnes [1]. As one of the most vital staple crops, rice accounts for approximately 21% of the world's caloric intake [2]. Recent decades have witnessed a surge in the adoption of intensive agricultural practices, such as inorganic fertilizers, herbicides, mechanization, and improved cultivars, contributing to significant yield growth. However, this intensification has also led to rising production costs and adverse environmental effects, necessitating the exploration of solutions that can enhance production while minimizing environmental impacts and ensuring farmer profitability [3]. Considering the challenges faced by conventional rice cropping systems, exploring alternate planting techniques becomes imperative. In the realm of multiple rice cropping systems, the predominant approach has been double-season rice, widely practiced in Asia. This system, along with other multiple cropping methods like triple-season rice and ratoon rice, has demonstrated the potential to boost overall rice production per land area, significantly contributing to the global rice supply [4]. Ratoon rice cultivation involves harvesting a second crop, known as the ratoon crop, from the stem nodes on the rice stubbles left after harvesting

the main crop has emerged as a viable alternative to traditional double-season rice has garnered significant attention in recent times. This unique approach offers the advantage of obtaining two harvests from a single planting, thereby reducing production costs and increasing resource use efficiency compared to conventional double-season rice cropping systems. Various studies have shown that ratoon rice can significantly contribute to enhancing the sustainability and profitability of rice cropping systems. It has been observed that ratoon rice exhibits high economic returns, decreased agricultural inputs, reduced resource consumption, and lower environmental impact [5-6]. Studies indicate that ratoon rice yields approximately 40–50% of those obtained from the primary crop while demanding reduced labor and water resources, ranging between 50 and 70% [7-8]. Ratoon rice cropping offers significant advantages over traditional double-cropping systems, leading to a reduction of 29% in labor and 52% in seed inputs [9-10]. As ratoon cropping requires no nursery supplies or land preparation and has a shorter growth duration (40-90 days) compared to the leading rice crop (85-175 days). This results in 50-60% less labor and reduced crop maintenance costs [11]. However, challenges such as manpower constraints, limited automation, and suboptimal production efficiency have led to a decline in the area planted with double-season rice in recent years. Ratoon rice (RR) is emerging as a game-

changer in rice production, meeting the global demand while addressing environmental concerns [12] by allowing more frequent harvests on existing land without intensive activities, RR proves to be an eco-friendly solution for the future [13]. Rapidly gaining popularity, RR has seen an average yield increase of 26.1% to 71.43%, making it a lucrative option for farmers [14-15]. From an environmental perspective, RR requires lower water and pesticide inputs compared to traditional rice cycles. To ensure a secure and sustainable rice production, strategies to improve the viability and profitability of various rice cropping systems are urgently needed. RR cultivation has been proven to improve farmer revenue, enhance agricultural productivity, reduce labor and input requirements, and sustain crop production [16]. In recent years, the planting area of ratoon rice has rapidly expanded, making it a significant cropping system not only in China but also in other countries like the United States, Japan, Brazil, India, the Philippines, and Thailand [17-19]. Ratoon rice is a promising cultivation system practiced on a commercial scale in the United States [18]. Rice ratoon technology presents an ideal solution for a viable and economic choice, especially in the mid-altitude valley ecosystem of the North-eastern Himalayan region in India [8]. Researchers have also made significant advancements in understanding the factors influencing ratoon rice performance, including crop management practices, stubble height, and the adoption of new hybrid cultivars and high-yielding technologies [20-21]. Previous studies have primarily focused on optimizing agronomic management practices to achieve high ratoon

crop yields. Key techniques include variety selection [22], timing of sowing/planting [23], timing of main crop harvest [24], cutting height of the main crop [18], and efficient fertilizer and water management [25-26]. This review article aims to comprehensively assess the benefits and challenges associated with ratoon rice cultivation, examining its impact on agronomic aspects and resource efficiency. Furthermore, we will explore the recent advancements and strategies to improve the sustainability and productivity of ratoon rice systems.

2. CLIMATIC CONDITIONS OF RATOON RICE

The success of ratoon rice production hinges upon key factors such as temperature, solar radiation, and humidity, which influence the grain yield and flowering of the ratoon crop. The Influence of daily mean temperature and sunshine duration emerges as the key climatic factors impacting the grain yield of ratoon rice [27]. It thrives in regions with an average annual temperature exceeding 18°C, a daily mean temperature above 23°C for the first 30 days post-harvest ensures successful flowering of the ratoon crop. Optimal climatic conditions for ratoon rice success with the initiation of axillary bud benefits from an optimum temperature of 25°C-28°C and relative humidity of 83% [28]. Higher daily mean temperature, solar radiation, and sunshine duration after the heading of the ratoon crop positively impact ratoon crop yield [29]. Appropriate planting time is crucial for effective water management, as well as to optimize the impact of temperature and solar

Table 1. Different strategies of crop season for maximizing the yield

Strategy	Way to enhance ratoon rice	References
Planting Date	Early sowing and transplanting maximize dry matter accumulation	[32]
	Avoid chilling damage to ensure ratoon crop maturity with precise timing	[33-34]
	Early planting increases grain filling percentage and grain yield	[5, 35-36]
Seeding Methods	Pot seeding enhances seedling plasticity and minimizes transplanting shock	[37- 38]
	Dry seeding improves root systems and stress resistance	[39-41]
Planting and Harvesting Dates	Early planting optimizes thermal and radiation resource utilization	[42]
	Delays in main crop planting led to delayed ripening stage and reduced ratoon yield	[43]
Thermal Energy	Ratoon rice suits regions with insufficient thermal energy for double-season rice	[44-45]

radiation on the growth of main crops and ratoon crops. For rice seed germination, the minimum, optimum, and maximum temperatures are 8–10°C, 30–32°C, and 42°C, respectively [30]. The ideal temperature for rice seed germination is 20–35°C, 25–31°C for tillering, 25–28°C for panicle differentiation, and 20–25°C for grain ripening [31]. If temperatures are too low during the late stages of the main crop growth, it can lead to increased grain sterility and hinder the proper development of ratoon crops. Hence, careful consideration of planting time and seeding methods is vital for ensuring optimal conditions and maximizing crop productivity (Table 1). As the grain ripens, the optimum temperature decreases to 20°C to 25°C. It is crucial to avoid exposing rice plants to low temperatures during the late main crop growth stage, as it can increase grain sterility and hinder ratoon development. Utilizing rice cultivars with short growth duration, along with dry bed-raised seedlings, early sowing, and timely transplanting, contributes to success in specific regions [29]. Early planting and precise timing lead to increased dry matter accumulation, enhanced grain yield, and improved quality, fostering a flourishing ratoon rice harvest. Understanding climatic influences and employing innovative agricultural techniques are essential for improved ratoon rice yield and sustainable crop production.

3. UNDERSTANDING THE VARIETAL CHARACTERISTICS FOR ENHANCING RATOON RICE PRODUCTION

The selection of rice varieties with crucial traits is a vital task, as it directly influences grain yields in both the main and ratoon seasons. Specifically, prioritizing rice cultivars with strong ratooning ability is essential as this trait plays a critical role in achieving high grain yield. The selection of rice cultivars with high ratooning ability is the linchpin for successful and sustainable ratoon rice production (Table 2). This comprehensive exploration of rice variety traits and their influence on ratooning ability offers valuable insights for farmers and breeders seeking to optimize ratoon rice production. The selection of appropriate rice cultivars with strong ratooning ability, suitable growth duration, and specific morphological and physiological traits can significantly contribute to sustainable crop productivity.

Ratoon rice cultivation holds the promise of significantly augmenting grain yield and stability by understanding the critical relationships

between ratooning ability and various crop indices, coupled with the selection of high-performance cultivars, farmers can unleash the true potential of ratoon rice. Practical strategies like postponed N fertilizer application and alternate wetting and drying irrigation enhance root activity and improve yields in ratoon rice cultivation (Table 3). Apart from ratooning ability, other significant characteristics profoundly impact the success of ratoon rice production. Moreover, different agronomic practices and cultivation techniques can be utilized in the forefront for enhancing rice ratoon productivity.

4. GROWING RATOON RICE VARIETIES: CULTIVATING SUCCESS ACROSS COUNTRIES

Ratoon rice varieties are gaining recognition and momentum in multiple countries due to their potential to boost cropping intensity and rice productivity. The primary objective of rice farmers is to achieve higher yields in the main crop prior to ratoon crop. To accomplish this, they use high-yielding cultivars that also possess good ratooning ability. Several studies [56-58] have reported variations in ratooning capabilities among different rice genotypes (Table 4). Interestingly, principal crop early maturing genotypes showed an average 68% higher grain yield compared to the early maturing genotypes of ratoon crops. The lower yield of the ratoon crop was primarily attributed to the number of grains per panicle or panicle size.

Ratoon cultivation is gaining attention as a viable strategy to enhance rice yields not only in the Philippines and Pakistan but also in India [60]. Likewise, promising research outcomes in Bangladesh have shown the potential of ratooning practices to improve rice production [61]. However, to address challenges related to yield variability and stability, it remains crucial to focus on developing improved ratoon varieties [62]. By doing so, sustained and efficient rice production can be achieved, contributing to food security and economic growth across the region.

5. NITROGEN MANAGEMENT FOR ENHANCED RATOON YIELD

Nitrogen (N) fertilizer management is a critical factor influencing the growth and yield of ratoon rice crops. To achieve higher grain yield in the ratoon season, the application of N fertilizer is strategically timed and tailored based on the

stubble height and growth duration of the ratoon crop. The ratoon crop biomass production is significantly influenced by N fertilizer management practices, impacting plant canopy light interception, radiation use efficiency, and N utilization [63]. The bud-promoting N fertilizer serves a dual role in ratoon rice production, prolonging leaf senescence during main crop

grain filling and boosting leaf N content and photosynthetic rate [64]. Precise N fertilizer management is key to unlocking the ratooning ability and grain yield of the ratoon crop (Table 5). Various studies have investigated the impact of N fertilizer application on ratoon rice attributes, and the findings offer valuable insights for optimizing N management practices.

Table 2. Key varietal characteristics for Successful ratoon rice production

Rice Varietal Traits	Improved Ratooning Ability	References
High-yield ratoon rice varieties	Suitable growth duration (within 135 days), good ratooning ability	[46]
	Strong lodging and high-temperature resistance, high leaf area duration, low rice shattering	
Rice cultivars for high ratoon yield	High leaf area index (LAI), low grain-leaf ratio, high dry weight per stem-sheath at maturity stage of the main crop	[47]
Rice cultivars with strong ratooning ability	Strong tillering ability, more panicles per unit land area, few spikelets per panicle	[48-50]
	High ratio of leaf area to grains at full heading in the main season	
Hybrid rice for higher grain yield in main and ratoon seasons	Higher carbohydrate content in the stubble, more vigorous root system at the harvesting of the main crop	[48, 51-52]

Table 3. Indicators for the high regeneration ability for rice ratoon production

Characteristics	Improved specific attributes	References
Practical strategies for elevated crop performance	N fertilizer application in the main crop benefits root activity and delayed leaf senescence	[53]
	Alternate wetting and drying irrigation improve root morphological and physiological traits	[54]
Effective cultivation techniques	Short to medium duration rice varieties, early seeding and transplanting, early main crop harvest, and high stubble maintenance	[21]
	Evaluation of plant senescence characteristics during grain filling stage and lodging resistance of main crop is crucial for variety selection	[53,55]

Table 4. Factors contributing to the improved productivity of ratoon crop

Characteristics	Different studies on enhancing the yield
Total yield	Rice cultivars with high total yields in both main and ratoon seasons are preferable. Selection of cultivars with 160-190 spikelets per panicle can result in high total yields [27,59].
Spikelets per Panicle	An important indicator for selecting high-yield rice cultivars. Cultivars with fewer spikelets per panicle exhibit strong ratooning ability, while those with more spikelets have higher yield potential in the main crop. Optimal spikelets per panicle for both seasons fall within the range of 160-190 [27,59].
Axillary bud regeneration	Cultivars with strong axillary bud regeneration capability are preferred for ratooning [35, 5]

Table 5. Effect of nitrogen application rate on ratoon crop

N Fertilizer Application	Enhancement in Ratoon Rice Attributes	References
Bud-promoting N fertilizer application	Increased leaf N content, photosynthetic rate, and transport of photosynthetic products to grains	[64-65]
Application of 100 kg N ha ⁻¹ at 15 days after heading of the main crop	Increased ratoon crop yield by 12.7% – 55.4%,	[63, 66]
Bud-promoting N rate increased from 0 to 103.5 kg N ha ⁻¹	Ratoon crop yield increased from 3.78 to 4.36 t ha ⁻¹	[67]
Bud-promoting N with application rate of 170 and 125 N kg ha ⁻¹	Enhanced grain yield of the ratoon crop compared with control	[68]
Early application of bud-promoting N fertilizer	Improved grain yield, especially in heavy-panicle type cultivars	[65]
Tiller-promoting N applied 1–2 days after harvesting the main crop	Promoted growth of regenerated tillers, improved head rice yield, and reduced chalkiness in ratoon crop rice	[69]

It is evident from the studies that proper N fertilizer management significantly enhances the ratoon crop's growth and yield. The timing, rate, and combination of bud-promoting and tiller-promoting nitrogen play a crucial role in promoting bud initiation, tiller growth, and panicle development, ultimately contributing to higher grain yield in ratoon rice production. We explore the crucial role of N fertilizer application in stimulating bud initiation, tiller growth, and panicle development for both low-stubble and high-stubble ratoon rice systems. The timing of fertilizer application should be carefully considered, with early application at the full-heading stage being recommended for enhanced ratooning bud survival.

6. OPTIMIZING WATER MANAGEMENT FOR BETTER RATOON CROP YIELD

Water management is crucial for boosting ratoon crop yield in ratoon rice system. Moderately draining paddy fields during the main crop growing season is an effective and widely recommended strategy [70]. Water management strategy for a ratoon crop differs from that of a normal transplanted crop (Table 6). Critical stages, such as grain filling during the main crop, are essential for promoting the initiation and growth of axillary buds. Decreasing soil moisture content at the maturity of the main crop is beneficial as it improves soil hardness, reducing rolling damage to stubbles caused during harvesting of main crop [71].

Table 6. Comprehensive study of different water management practices with recommendations

Aspect	Key Findings and Recommendations
Effect of soil moisture	Proper water management during the late growth stages of the main rice crop can delay plant senescence, improve root activity, and promote the growth and development of ratooning buds [72]. Adequate drainage during the main crop season significantly improves root activity and enhances ratoon rice yield by up to 15% compared to shallow water irrigation [73]. However, soil moisture below 21% negatively affects ratooning bud growth and causes yield loss.
Alternative wetting and drying (AWD)	Hybrid rice cultivars under AWD conditions produce higher grain yields (5.8%-11.3%) in the main crop season and (11.9%-14.3%) in the ratoon season compared to continuous flooding conditions [74]. Implementing ridge furrow patterns and proper drainage techniques during the main crop season in Southeast China significantly improves root activity, resulting in a higher ratoon rice yield [27, 75-76].
Comparison of water management techniques	Ratoon rice yields generally due to better water management practices, allowing for adequate drainage during the main rice crop season [27]. Properly drained paddy fields during the main crop season improves root activity and creates suitable soil conditions for mechanical harvesting of the main rice crop, ultimately leading to higher ratoon rice yields.

However, mechanical harvesting of the main crop can result in damage negatively impacts bud initiation and regenerated tiller growth, leading to reduced grain yield in the ratoon crop. By understanding and implementing proper water management techniques for both the main and ratoon seasons, farmers with proper water management strategies can significantly enhance the overall productivity and success of ratoon rice production.

7. OPTIMAL HARVESTING TIME FOR MAIN CROP IN RATOON RICE FARMING

The timing of harvesting of the main crop plays a crucial role in improving overall grain yield and ensuring successful heading of the ratoon crop and varies based on the planting region. Early harvesting of the main crop should be avoided as it can lead to yield loss due to poor grain filling. On the other hand, delaying the harvest may expose the ratoon crop to cold stress during the heading stage, adversely affecting its growth and development. For mechanized ratoon rice farming, the optimal harvesting time of the main crop is when around 95% of the grains have reached the yellow-ripe stage and thereby ensures minimal yield loss and prevents significant delays in the heading of the ratoon crop when compared to manually harvested ratoon rice. Harvesting the main crop when axillary buds emerge from the leaf sheath has been found to mitigate the negative effects of high temperature and drought conditions on the growth and development of axillary buds, leads to higher yield of the ratoon crop [27, 45, 51]. Harvesting the main crop too early may result in immature grains and reduce the grain yield in the main season. Conversely, if the main crop is harvested too late, the leaves of the regenerated tillers may be damaged, affecting the grain yield of the ratoon crop. Based on previous studies, it is recommended to harvest the main crop when approximately 90–95% of the grains have matured and acquired a yellow color [77]. Therefore, choosing the optimal harvesting time for the main crop is essential for maximizing grain yield and ensuring successful ratooning. By adopting the right timing, farmers can enhance the productivity and efficiency of ratoon rice farming, contributing to food security and sustainable agricultural practices.

8. RATOON RICE FARMING: YIELD, QUALITY, ECONOMICS, AND SUSTAINABILITY

Ratoon rice yields vary from 1.1 to 4.9 t ha⁻¹, representing 28.6% to 64.3% of main season output as temperature, selection of varieties, and management techniques influence yield fluctuations [62, 78]. We knew proper variety selection and effective management can achieve 3-6 t ha⁻¹ in subtropical and temperate climates [23, 44, 79] and even best practices lead to yield as high as 9.7 t ha⁻¹ [80]. In temperate regions, varieties resilient to low temperatures and shorter development periods are necessary [44]. Factors like planting date, establishment method, stubble cutting height, fertiliser use, and water management also affect ratoon rice yield.

Exemplify superior grain quality with superior milling, aesthetic attributes, and nutritional properties compared to the main crop. It demonstrates increased amylose content, lowered gelatinization temperature, and better gel consistency [81]. Lower temperatures during ratoon rice growth contribute to enhanced grain maturity, appearance, cooking quality, and flavor [82]. Ratoon rice efficiently transports carbohydrates and nitrogen resulted in beneficial compounds like phenolic compounds, lipids, and lysine. However, high temperatures during grain filling can adversely affect ratoon rice quality, leading to spikelet infertility, decreased grain weight, increased chalkiness, and reduced amylose content [83-85]. Despite some challenges, ratoon rice remains an attractive option due to its overall superior grain quality attributes.

Ratoon system offers economic benefits with reduced labor, water, seed, pesticide, and fertilizer costs [9-10]. Despite lower yearly output, it yields higher net profit than double-season rice. Ratoon rice is 125.4% more profitable than single-season rice [8]. It also proves energy-efficient for bioethanol production compared to single rice cropping as reduced greenhouse gas emissions make it an eco-friendly choice [14]. It serves as a valuable adaptation strategy for flood-prone areas [86]. Overall, ratoon rice is an economically viable, eco-friendly, and resource-efficient cropping system, enhancing rice production sustainability [87]. Ratoon farming holds promise for increasing grain yield, enhancing grain quality, and realizing economic gains, all while fostering environmental sustainability. Further research and

Table 7. Agronomic Management practices for ratoon rice

Management technique	Findings and Recommendations	References
Variety selection	Hybrid rice cultivars have a higher regeneration rate and dry weight per stem after the main crop harvest.	[52]
	Novel plant type varieties show superior vegetative growth and harvest season output.	[88]
Methods of Establishment	Direct-seeded ratoon rice offers sustainable alternative to transplanted ratoon rice.	[44]
	Ensure proper crop establishment and choose varieties with high lodging and cold tolerance for direct-seeding.	[89]
Nitrogen fertilizer management	Apply lower N rates for main crop, followed by additional N application of bud-promoting fertilizers is recommended around 15 days after heading in the main season to facilitate ratoon bud regeneration.	[24]
	Adjust N rate for bud-promoting fertilizers to optimize ratoon crop grain production.	[26]
	Administer tiller-promoting fertilizers 2 to 5 days after main crop harvest to increase ratoon crop grain production.	[90]
Optimising Water management	Soil drying at maximum tillering and middle-late grain filling stages improves ratoon crop growth.	[33]
	Controlled flooding after main crop harvest encourages tillering in ratoon crops.	[25]
Main season crop harvest & stubble height	Mechanized harvesting minimizes yield losses and damage, improving ratoon rice productivity.	[91]
	Adjust stubble cutting height based on ratooning characteristics and climate conditions of the region	[18]
Control of pests and diseases	Implement separate management strategies for ratoon crops and use pest-resistant cultivars.	[16]
	Consider eco-friendly, non-chemical approaches to reduce environmental contamination and resistance development.	[92]

implementation of effective management practices are essential to optimize ratoon rice farming and ensure its contribution to a sustainable future.

9. MAXIMIZING RATOON RICE YIELD: AGRONOMIC MANAGEMENT TECHNIQUES

Exploring the best agronomic management techniques to enhance ratoon rice grain yield. Selecting varieties with high regeneration capacity and yield potential, incorporating direct-seeded rice, and optimizing nitrogen and water management are key factors. Mechanized harvesting, proper stubble cutting height, and effective pest and disease control also play vital roles in maximizing ratoon rice productivity (Table 7). Integrating these practices will contribute to sustainable rice production and improved crop yields.

10. CONCLUSION

Ratoon rice emerges as a promising and sustainable cropping system, offering economic, environmental, and resource-efficient benefits for rice production. Ratooning is widely practiced in various rice-growing regions except Europe, and typically yields 40 to 60% of the main crop, depending on cultivars and management practices. The economic benefits stem from reduced land preparation and planting efforts, shorter crop cycles, and better utilization of the growing season. By implementing essential agronomic practices such as varietal selection, nutrient and water management, stubble cutting height, harvesting methods, and the application of plant growth regulators, the grain yield of the ratoon crop can be significantly enhanced. To fully unlock the potential of ratoon rice, a strong emphasis on ratoon rice breeding programs is crucial. It is a cost-effective practice with the

potential to significantly increase rice production and overall farming profitability. With continuous advancements in ratoon rice holds the promise of becoming a sustainable alternative for sustaining cropping intensity and ensuring food security with reduced labor and agronomic inputs. By fostering research and promoting adoption, ratoon rice can play a vital role in enhancing global rice production and addressing the challenges of the future.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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