



REVIEW ARTICLE

Ratoon rice under a changing climate: Physiological responses and management strategies

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Abstract

Ratoon rice has gained attention as a sustainable strategy for maintaining rice productivity under changing climatic conditions, where rising temperatures, irregular rainfall, droughts, floods and other extreme weather events threaten crop productivity and global food security. Ratoon rice has emerged as a resource efficient and climate smart production method as it makes use of the regenerative ability of plants to generate a second harvest from stubble of the main crop. Compared to conventional rice cultivation, ratoon rice requires less labor, reduced inputs and a shorter growing period while improving land, water and nutrient use efficiency. However, the physiological responses of rice plants to changing environmental conditions are important for the success of ratoon crops. Bud regeneration, carbohydrate reserve mobilisation, hormonal regulation, photosynthetic efficiency and source sink relationship play a critical role in determining ratoon establishment and yield under climatic stress. Ratoon rice is more resilient to heat, drought, flooding and other environmental challenges when the appropriate management techniques such as optimal stubble height, balanced nutrition, effective irrigation and plant growth regulators are used. Furthermore, improving soil health through organic amendments and beneficial microbial interactions contributes to greater stress tolerance and sustainable productivity. Ratoon rice production is still limited despite its potential due to automation issues, yield instability and climate related hazards. To enhance the adaptation under shifting climatic conditions, future research should concentrate on creating climate-resilient ratoon cultivars, precision nutrient and water management technologies and decision support systems. This review summarises the physiological response of ratoon rice to climate change and highlights effective management strategies that can enhance productivity, resource use efficiency and sustainability, thereby supporting resilient rice production and long term food security.

Keywords: climate change; main crop; physiological response; ratoon rice; stubble management; sustainable production

Introduction

Rice (*Oryza sativa* L.) is one of the most important staple food crops in the world, providing food for more than half of the world's population and playing a crucial role in food security, particularly in Asia and Africa (1). Cultivated rice comprises two domesticated species, *O. sativa* (Asian rice) and *oryza glaberrima* (African rice) (2). Rice is grown in more than 100 nations worldwide, with Asia accounting for approximately 90 % of production, with China and India leading the way in both production and consumption. Global rice production as reported by Food and Agricultural Organization (FAO) in 2024, has reached approximately 820.22 million tonnes, with Asia contributing nearly 90 % of the total output, highlighting its significant role as a staple food crop and its contribution to global food security and agricultural economy. Rice provides not only calories but also an essential source for carbohydrates, vitamins and minerals; however, its nutritional value varies depending on the variety and the level of processing (3).

However, rice production systems are increasingly threatened by climate change, which is characterised by an increase in the frequency of extreme weather events such as droughts and floods, unpredictable rainfall patterns and rising Mean atmospheric temperature. These changes directly affect crop growth, phenology and yield stability. For instance, elevated temperatures during the reproductive stage can reduce spikelet fertility and grain filling, while water stress conditions can limit tiller development and biomass accumulation (4). Global demand for rice is projected to increase by more than 200 million tonnes by 2050 (5). This growing demand necessitates improving the productivity under constrained environmental conditions through the adoption of innovative and sustainable production strategies that enhance yield without placing additional pressure on natural resources (4). A rice-rice cropping system comprises an integrated set of agronomic practices, including crop selection, sequencing, tillage, water and nutrient management, pest control and residue handling, adapted to specific agro-ecological and socio-economic conditions (6). The goal of

modern rice cropping systems is often to balance increased grain yield with minimised negative environmental impacts, emphasising resource-use efficiency and climate resilience. These systems are influenced by multiple factors such as climate, soil characteristics, water availability, labour, market access and policy frameworks (7).

Rice production must increase substantially by 2050 to meet the food demand of a growing global population. However, expansion of rice-growing areas is constrained by limited land, water scarcity, labour shortages, climate change and increasing environmental concerns such as methane emissions from flooded rice fields. Therefore, future rice production must rely on sustainable intensification rather than land expansion (8). Ratoon rice is a resource efficient and sustainable option that can increase rice production while reducing labour, water use, production costs and greenhouse gas emissions compared with conventional rice systems (9). In this context, ratoon rice has emerged as a promising climate-smart agricultural practice. Ratoon rice involves the cultivation of a second crop from the regrowth of stubble remaining after the harvest of the main crop, thereby eliminating the need for replanting and reducing labour, water and input requirements (10). This system enhances resource-use efficiency, shortens the cropping cycle and provides additional yield with relatively lower production costs. Studies have reported that ratoon rice systems can significantly reduce water use and input requirements while maintaining acceptable yield levels, making them particularly suitable under resource-limited and climate-stressed conditions (11, 12).

The success of ratoon rice largely depends on its physiological ability to regenerate new tillers from dormant axillary buds present in the stubble. This process is regulated by factors such as carbohydrate reserves, hormonal balance and environmental conditions, including temperature and moisture availability (13). Under changing climatic conditions, understanding these physiological responses becomes critical for optimising ratoon crop performance and ensuring yield stability. Although ratoon rice cultivation has received considerable research attention, most existing reviews have focused primarily on agronomic management or yield performance, without offering an integrated understanding of the physiological responses driving regeneration and their response to climate change. Therefore, this review aims to synthesise current knowledge on the physiological mechanisms underlying ratoon rice regeneration and to examine how these

processes are influenced by climate change. It also discusses key management strategies that can enhance ratoon rice productivity and sustainability under variable environmental conditions.

Overview of ratoon rice system

Ratoon rice is a form of intensified multi-harvest production where, after harvesting the main crop, the remaining stubble and root system regenerate new shoots that develop into a second crop within the same season, thereby increasing cropping intensity and improving land use efficiency without replanting (14). Ratoon rice farming reduces labour and material expenses by eliminating the need for ploughing, puddling, seeding and transplanting and compared to the main crop, the ratoon crop has a much shorter growth phase, which makes fertilisation and water management easier (15). The ratoon rice system is a feasible choice for increasing system productivity since it can provide better net economic returns and energy efficiency (16). Compared to conventional system of rice cultivation ratoon system is more efficient and economical way of rice production. Tillage, nursery, transplanting, weeding and seed purchases all need a significant amount of labour in the traditional method of rice production (11). Ratoon rice grows more rapidly than the main crop and requires 50 % less labour, 60 % less water and less money to produce at least 50 % of the main crop output, ratooning presents a chance to boost cropping intensity per unit area. These values are not universally fixed and are largely derived from site specific studies, actual figures may vary depending on cultivar, regional agro-climatic conditions and management practices, with reported ranges of 40–60 % yield and 50–70 % reductions in labour and water input (10). The lower production cost primarily results from reduced expenditure on land preparation, transplanting and crop management operations (17). Ratooning lowers air pollution by retaining stubble rather than burning it for a fresh crop. Furthermore, shallow impounding with aeration and draining the fields following the major crop harvest aid in lowering greenhouse gas emissions such as nitrous oxide (N₂O) and methane (CH₄) (9). Comparison of conventional and ratoon rice production systems, with the major advantages and limitations are given in Fig. 1.

Ratoon rice impact has been studied in many countries such as India, Japan, USA, Philippines, Brazil, Colombia, Swaziland, Thailand, Taiwan. It is commercially done on 50 % of the rice land in Texas, USA (18). In the Southern United States, where double

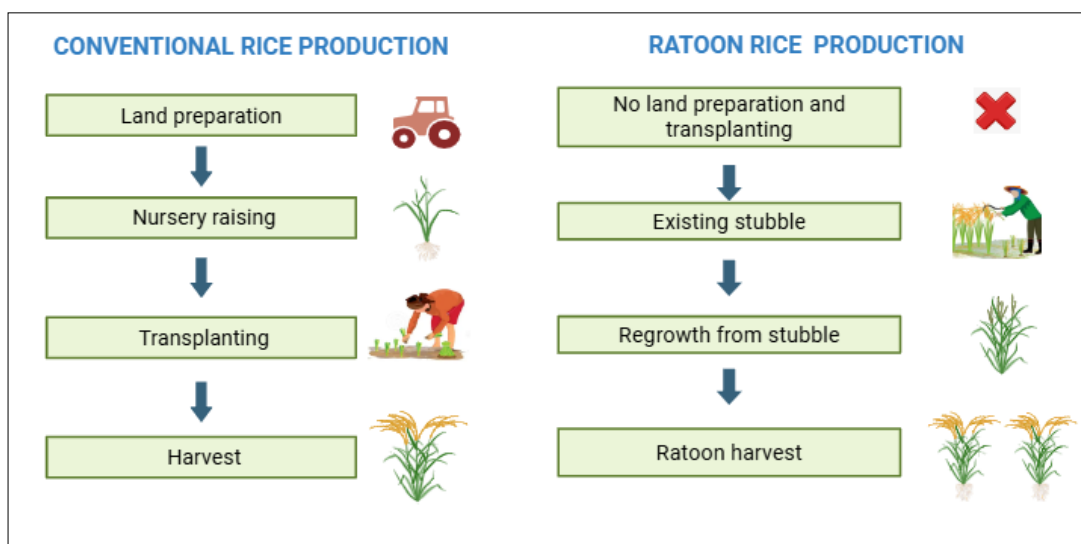


Fig. 1. Comparison of conventional and ratoon rice production systems, highlighting the use of existing crop stubble for regrowth and ratoon harvest without land preparation and transplanting (www.biorender.com).

cropping rice is impossible due to low temperatures, ratoon rice gained popularity with the introduction of short duration rice cultivars (14). Rice ratooning has been implemented in countries located in tropical and temperate regions, such as China, Indonesia, Japan, the Philippines. In China, the planning area for rice ratooning has reached over 1.0 million hectares owing to mechanised rice ratooning technology that allows the harvesting of the first crop mechanically (19). In India, rice ratooning is practiced in Karnataka, Andhra Pradesh, Bihar, Kerala, Odisha, Tamil Nadu, Uttar Pradesh and West Bengal (20). In India, there have also been reports of rice ratooning from Assam but ratooning and double cropping of rice have not yet been documented at the mid and high altitudes of India's North East Hills region (21).

Climate change and rice production

Climate change studies on global rice production revealed an alarming condition for its sustainable production and distribution around the world. The availability of land and water resources for rice farming may alter in the future due to rising temperatures and changes in rainfall distribution patterns (22). Rice growth and yield are significantly impacted by changes in key climate variables such as temperature, precipitation, solar radiation and carbon dioxide (CO₂) concentration (23). Temperature is an important environmental factor influencing the growth and development of rice, especially in the case of global climate change, where changes in temperature have increasingly affected the growth cycle and rate of development of rice. The developmental rate of rice greatly increases with increasing temperature in all growth stages. The optimal temperature for maximum growth speed and minimum overall development period throughout all growth stages was determined to be 28 to 31 °C and the threshold temperature is 18 to 35 °C (24). Lower temperature causes decrease in ratoon yield and panicle density by delaying crop emergence, harvest and ratoon development (25). Spikelet sterility and poor grain filling are caused by rising temperatures, especially high night-time temperatures, which can reduce yield by up to 4.4 % for each degree Celsius above 27 °C (26). Rice crop productivity is expected to decrease by 15–35 % in Africa and Asia and 35 % in the Middle East due to temperature induced adversities (27).

Next to temperature, rainfall plays a crucial role in rice production and showing a significant positive relationship between rainfall and rice output. Adequate rainfall supports rice growth and productivity, while low rainfall can result in drought stress and decreased production, excessive rainfall can induce flooding, nutrient loss, pest outbreaks and yield reduction (28). China's rice production was positively impacted by average rainfall, especially over the long term. A 10 % increase in average rainfall improved rice production by roughly 0.46 % (29). The different rainy and dry seasons of the tropical monsoon climate present serious difficulties for irrigated rice farming. This seasonal variation makes managing water resources more difficult and puts more strain on agricultural water usage which accounts for most of the water consumption in tropical regions (30). The CH₄ emissions from flooded rice systems can be amplified by warming and increased CO₂. In comparison to the main crop, ratoon rice significantly reduces CH₄ emissions due to its shorter growth period, lower temperatures and lower carbon inputs. By reducing both area-scaled and yield-scaled greenhouse gas emissions compared with double rice systems, ratoon rice has the potential to be a climate-smart method for maintaining rice production while lowering its carbon footprint (31).

Physiological basis of ratoon rice

The physiological basis of ratooning is crucial to understand the regeneration pattern of new tillers and panicles after the harvest of the main crop. Ratoon rice yield depends on how well photosynthesis, grain development and nutrient movement work together in the plant (32). Regeneration rate or number of effective panicles is the primary factor influencing the ratoon crop yield. High ratoon yield depends on efficient bud sprouting and subsequent panicle development (13). In ratoon rice, the performance of the second crop largely relies on the timely activation of dormant buds, high photosynthetic efficiency of newly formed leaves and effective remobilisation of nutrients from the stubble of the main crop (33). Following harvest, adventitious roots regenerate from the basal nodes of the remaining stubble, improving water and nutrient uptake required for bud sprouting and tiller development. A vigorous regenerated root system maintains water and nutrient absorption, supports sustained photosynthesis and ultimately contributes to higher ratoon productivity (34). Bud sprouting and ratoon yield development are crucially regulated by physiological and biochemical variables, especially plant hormones and nutrient dynamics. Gibberellins (GA) and abscisic acid (ABA) contribute to node specific responses, whereas cytokinins (CTK) are found to be important regulators that favourably affect bud length and number of the nodes in the plant (35). High stubble dry weight and non-structural carbohydrates (NSC), which include soluble sugars and starch, serve as the primary energy reserves mobilised during ratoon bud regeneration) at main crop harvest strongly support ratoon yield (36). Stem NSC reserves are a major carbon source for the grain filling and peak grain filling stage coincides with depletion of reserves (37). Ratoon season rice shows much higher translocation efficiency of stem NSC to grain and greater assimilate allocation to grains, raising harvest index by 5–12 % (32). The physiological basis of ratoon rice crop is shown in Fig. 2.

Despite a much lower leaf area index (LAI) and biomass, ratoon rice has higher net assimilation rate and grain/leaf ratio, so yield is tightly determined by source-sink capacity and transport efficiency (38). While leaf-cutting restricts assimilate supply and inhibits regeneration, agronomic techniques like spikelet thinning increase assimilate availability and encourage bud growth. Therefore, assimilate distribution and total ratoon productivity are determined by the equilibrium between source capacity and sink demand (13). The ability of ratoon crops to regenerate is impacted by source-sink management, as evidenced by the fact that leaf-cutting reduced the regeneration rate of ratoon rice while spikelet-thinning enhanced it by more than 20 % (39).

Physiological responses of ratoon rice to climate change

The global production of major cereal crops, including rice, is predicted to be negatively impacted by recent and anticipated climatic changes, particularly rising temperatures. Low temperatures during the last phases of the primary crop were the main issues limiting the practice of ratooning, according to experimental studies on the potential of ratooning in Portugal, India and the United States (40). Ratoon rice is extremely climate sensitive and its performance is largely dependent on temperature, humidity and solar radiation. Ratoon success is highest in regions with an average yearly temperature over 18 °C, a daily mean above 23 °C during the first 30 days following harvest and ideal bud initiation at 25–28 °C and 83 % relative humidity (15). These threshold values largely represent genotype averaged estimates, as genotypic

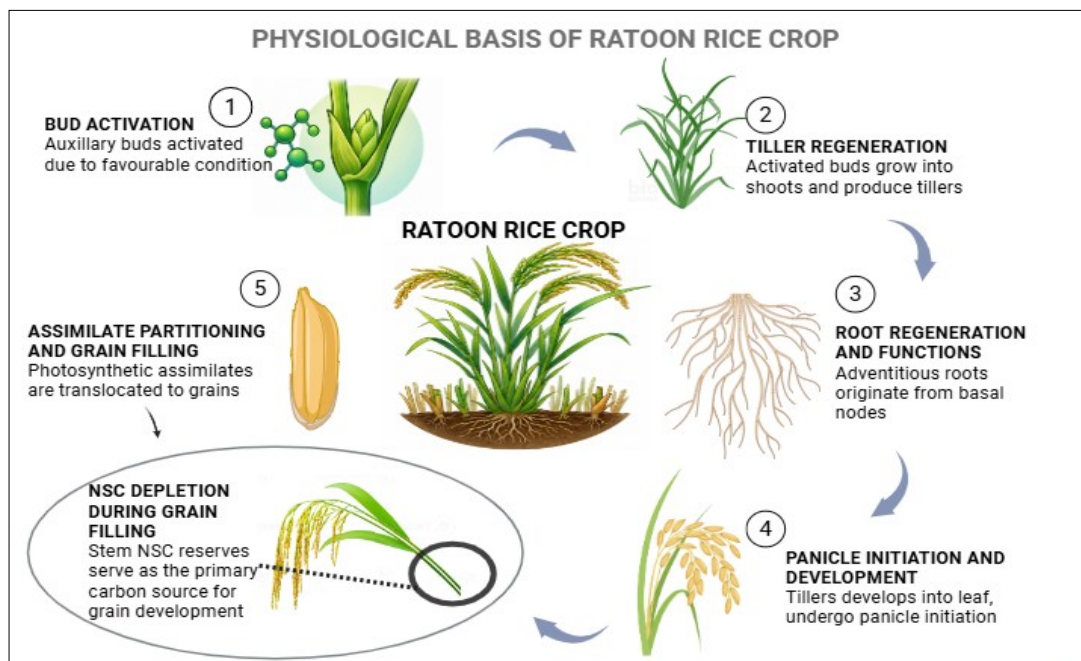


Fig. 2. Physiological basis of ratoon rice regeneration. The major physiological processes involved in ratoon crop development, including (1) bud activation, (2) tiller regeneration, (3) root regeneration and function, (4) panicle initiation and development and (5) assimilate partitioning and establishment and grain development (www.biorender.com).

variation in bud dormancy, tillering ability and heat tolerance during regrowth has been reported to influence ratoon success thresholds (41).

Although hormonal and reactive oxygen species (ROS)-mediated pathways are well documented in rice stress physiology and developmental regulation, their specific roles in ratoon regeneration remain insufficiently characterised. Studies from conventional rice indicates that hormone-ROS interactions contribute to developmental regulation, with ABA, jasmonic acid (JA) and hydrogen peroxide (H_2O_2) participating in the regulation of dormancy and germination. Similarly, ethylene signalling has been associated with coleoptile emergence through the activation of ROS-scavenging genes. At the source-sink level, molecular regulation of sucrose allocation has been linked to transporters such as *O. sativa* sucrose transporter 1 (OsSUT1). However, whether these hormone-ROS signalling networks and sucrose transport mechanisms play similar roles during post-harvest bud activation, tiller regeneration and source-sink re-establishment in ratoon rice largely unexplored (42).

Major abiotic stresses that disrupt rice physiological, molecular, biochemical and morphological responses include heat stress and drought. This leads to significant crop losses and quality compromises (43). Ratoon rice under climate change responds mainly through photosynthesis, stomatal regulation, chlorophyll maintenance, water relations and carbohydrate translocation, greater assimilate allocation to grains and enhanced expression of sucrose transport and stress responsive genes, supporting rapid recovery after the main crop (32). Recovery in ratoon rice depends on surviving basal buds, root viability, stem carbohydrate reserves and post stress assimilate transport (44). Drought and heat stress reduce stomatal conductance, CO_2 uptake, photosynthesis, chlorophyll content and leaf water status, while increasing oxidative stress and antioxidant enzyme activity (45). Under heat stress, the rice flower buds are unable to mobilise vital nutrients such as carbohydrates and other derived products (43). High temperatures during grain filling can reduce quality by causing spikelet infertility,

lower grain weight, increased chalkiness and reduced amylose content (15). When main crops were drought stressed, ratoon tillering depended on stem carbohydrate reserves and soil moisture at harvest (44). During water stress in ratoon crop, leaf water content and stomatal conductance decrease resulting in reduced photosynthesis and biomass (45). Under drought, stomatal conductance, transpiration and net CO_2 assimilation may decline substantially, with the magnitude of reduction varying among cultivars/genotypes, reflecting differences in drought tolerance and gas exchange regulation (46).

Rising atmospheric CO_2 concentration increase global average temperatures, contributing to climate change and elevating the risk of floods and droughts. Elevated levels of carbon dioxide reduce transpiration while enhancing canopy photosynthesis, thereby promoting plant growth and improving grain yield (47). Rice cultivation could benefit from increased carbon dioxide concentrations and management strategies that offset the adverse effects of climate change (23). Rice fields are important sources as well as sinks of greenhouse gases (GHGs), which are created and consumed through biochemical processes including photosynthesis, decomposition, nitrification, denitrification, methanogenesis and methane oxidation (48).

Influence of stubble management

Stubble height, defined as the stem length remaining after harvest of the main crop, plays a direct role in regulating ratoon tiller regeneration, ratoon grain yield and the overall carbon footprint and energy efficiency of the production system (49). Cutting height has a significant impact on ratoon performance by affecting the bud retention and the availability of stored carbohydrates. Extremely low cutting height weakens ratoon establishment and delays bud sprouting by reducing assimilate reserves. High stubble height, on the other hand, encourages early tiller emergence but may lower grain production because of ineffective remobilisation. So ideal cutting height is crucial to balance regeneration and attain maximum production (50). Due to an abundance of non-structural carbohydrates in the stubble, plants harvested at the regular time

produced a high first crop yield with just a minor decrease in the second crop. Combining a high cutting height with high nitrogen (N) and regular harvests increased leaf area index and non-structural carbohydrate reserves, which produced more spikelets and improved grain filling (51).

Stubble height affects ratoon rice regeneration and productivity by interacting with environmental parameters such as temperature, solar radiation, water availability and humidity. A stubble height of 20–30 cm is generally optimal under well irrigated, standard harvest and adequate N conditions, where lower stress reduces the need for stored reserves and shorter stubble promotes active crown buds, whereas 30–45 cm is preferable under rainfed or drought conditions, as taller stubble retains greater carbohydrate reserves and photosynthetic leaf sheath area while protecting ratoon buds from heat and moisture stress (52). Therefore, increasing ratoon establishment, grain yield and resource use efficiency requires managing stubble height in accordance with local environmental conditions (53). However, the interaction between stubble height and water availability in regulating carbohydrate reserves, bud activation and ratoon tiller development remains poorly understood, highlighting the need for environment specific stubble height optimisation.

Mechanised harvesting can seriously damage rice stubble in ratoon rice systems, mainly because the wheels or tracks of the harvester crush part of the field as they pass over it. Common harvesters used in China roll over more than 40 % of the field on average and this crushed stubble contributes very little to the second harvest, since the damaged stubble either fails to grow or produces a smaller crop. As a result, ratoon rice harvested by machine typically yields 3.8–20.1 % less than manual harvest (54). The problem is often made worse by wet, muddy fields at harvest time, which can cause heavier machines to sink and crush stubble even more and by leftover straw that not spread out properly, which can trap moisture and cause the stubble to rot instead of sprouting again (55).

Nutrient management strategies

Nutrient management strategies for ratoon rice focus on optimising N timing and rate, while balancing phosphorus (P) and potassium (K) and integrating water, soil and residue management to improve ratoon ability, yield and nutrient use efficiency across the main and ratoon crops (56). The splitting pattern technique in N management offers a strategy for the timing and splitting of applications based on crop growth stage, cropping season, variety employed and crop establishment method, as well as a suggestion for the overall N fertiliser demand (57). The number of regenerated tillers and panicle per m² increased under high N availability and contributed to greater ratoon rice productivity (58). Common management techniques for ratoon rice include applying N at bud initiation (N bud: 75 kg N ha⁻¹ applied 12 days after heading of the main crop) and regenerated tiller growth (N tiller: 75 kg N ha⁻¹ applied 2 days after main crop harvest). Applying N at the tiller stage greatly increased ratoon crop productivity and grain quality as compared to N bud. Applying N at the bud initiation decreased non-structural carbohydrate reserves, which may have hindered ratoon tiller regeneration even though raised the N content in the stubble. (59) found that N tiller is a better method for increasing ratoon rice yield, whereas straw nutrient status and main crop panicle quantity affect N bud's efficacy. However, different studies report varied ideal N rates for tiller promoting and bud promoting (60). Phosphorus is involved in the

storage and transfer of high energy compounds, the most prevalent of which is adenosine triphosphate (ATP) in rice. It also plays a regulatory role in plant metabolism, affects enzyme activity and is a component of several plant structural units, including phosphoproteins and nucleic acids (61). Phosphorus in ratoon rice appears to matter most as a part of balanced nutrient management, not as a stand-alone lever. In ratoon rice, reduced N plus moderately added P outperformed N only fertilisation (62). In addition to P, K is a crucial plant nutrient that increases crop resilience to pests and diseases, promote root growth and plant vigour and helps avoid lodging (57).

In ratoon production systems, environmental stress like drought and temperature extremes severely impair the crop's physiological capacity to absorb, translocate and utilise essential nutrients for optimal grain yield. So, strategic nutrient management approaches that optimise N application rates and provide correct nutrient balance to improve agronomic N use efficiency rather than excessive N that reduces overall efficiency. Optimised management of fertilisers, coupled with irrigation and soil amendments under drought stress, is essential for maintaining yield (14). The main and ratoon crops' grain filling is susceptible to stress from hot and low temperatures, respectively, which can result in erratic yields and decreased nutrient use efficiency. Temperature extremes hinder efficient nutrient usage and emphasise the need for appropriate nutrient and moisture management by impairing assimilate translocation, lowering starch synthesising enzyme activity and shortening the grain filling period (63).

Water management strategies

Water-saving irrigation practices have been shown to maintain grain yield while significantly improving water productivity (64). So, water management is another important factor influencing ratoon rice output and grain quality as irrigation regimes directly influence tiller formation, N uptake, grain filling processes. In a ratoon rice study, maintaining the groundwater level 12 cm below the soil surface produced the highest grain yield by improving root activity and nutrient uptake, whereas deep water 20 cm above ground increased tiller number but reduced 1000 grain weight in Tarai areas (65). Because of inadequate assimilate partitioning, deep water conditions frequently result in lower grain weight and yield even though they may increase the number of tillers. Split N application in combination with alternate wetting and drying irrigation has been found to be a very successful method that increases yield by more than 25 % while lowering greenhouse gas emissions (66). Even though alternate wetting and drying (AWD) irrigation uses less water, it fails in extremely hot weather, necessitating the use of adaptive irrigation techniques with heat-tolerance measures (67). Although the performance of ratoon rice is weather dependent, it exhibits much higher water use efficiency and water productivity compared to traditional double cropping systems under climate variability. Compared to conventional double cropping, ratoon rice double cropping enhances water productivity by 60 to 87 % (30). Ratoon has been identified as an effective climate resilience strategy in rice, enabling partial recovery of grain yield following drought induced panicle abortion and lodging caused by heavy rainfall and flooding, with optimum recovery achieved through appropriate stubble management and timely ratoon initiation which is a flood mitigation strategy (44). Further technical advancements are needed for practical application under climate induced water scarcity (64).

Agronomic and crop management practices

Ratoon rice crop uses the stubble of the main crop to produce a second crop, so management of the main crop strongly determines the ratoon performance (68). Key practices include optimised density, careful harvesting, targeted nutrition and growth regulators and integrated weed pest management suited to climate stress (69). Adequate plant density and spacing are the requirements for good ratoon yield because they influence tiller number and resource use per unit (20). Cultivar selection is important in case of good ratoon yield. Hybrids and long-duration inbred cultivars that are harvested at a 30 cm stubble height and planted on schedule with standard transplanting enhances ratoon productivity and regeneration capacity (68). Integrated cultivation models adjusting planting density together with N and water management significantly increases ratoon grain yield and N agronomic efficiency by improving root traits and stubble characteristics (70). Varieties suitable for ratooning in India are given in Table 1.

In perennial mid-season rice-ratoon forage systems, higher planting density increases both grain and ratoon forage yield, as low density gives the lowest ratoon yield (71). Another important factor affecting ratoon rice performance is the method of harvesting. Manual harvest allows careful control of stubble height and has achieved ratoon yield upto 7.2 Mg ha⁻¹ in Chongqing, but labour constraints are drawback (63). Another method particularly in large scale production systems, is mechanised harvesting. Despite increasing productivity, it is frequently results in mechanical damage to rice stubble, which lowers ratoon crop yield by 3.8 to 20.1 % as compared to hand harvesting. Regeneration is significantly hampered by the degree of rolling and poor stubble management. Effective axillary bud sprouting and subsequent tiller development depend on maintaining the proper stubble height and reducing rolling damage. To promote ideal ratoon crop growth, effective harvesting procedures such as threshing, cleaning and straw management are also required (54). Ratoon crop output is greatly influenced by key crop management strategies, with harvest timing and nitrogen management being important variables. Mowing the main crop at the heading or milk-ripening stages and adding around 270 kg N ha⁻¹ improve ratoon recovery and yield by increasing stubble biomass, carbohydrates reserves and canopy light interception (72). Additionally in ratoon crop foliar application can help to delivers nutrients rapidly to leaves and developing panicles,

which is especially useful where root uptake is limiting. In ratoon crop well timed foliar sprays can supplement these internal reserves and strong regrowth and grain filling (73).

In addition to agronomic management, effective weed and pest control is essential for maximising yield. Weeds and insect pests are major constraints in rice-ratoon rice systems and their impacts may worsen under climate change. Early herbicide application in the main crop improved productivity, nutrient uptake, energy use efficiency and profitability, highlighting the importance of timely weed management for sustaining ratoon performance (74). Insect pests such as rice water weevil and stem borers cause significant yield losses in rice-ratoon systems. While insecticidal seed treatments and foliar sprays improve main crop yields, they often provide little benefit to ratoon crops. Therefore, climate smart pest management should integrate chemical control with resistant varieties, biological control, habitat management and farmer training to ensure sustainable and environmentally friendly pest control (75). Representative foliar formulations are presented in Table 2.

Soil health and microbial interactions

Soil health and microbial interactions are essential to sustain high yields in ratoon rice, where regrowth depends on stubble root systems and the surrounding rhizosphere. In ratoon fields, soil organic matter, beneficial microbes and their response to climate driven stresses jointly regulate nutrient cycling and plant resilience. In ratooning rice, higher extractable and dissolved organic carbon and microbial biomass carbon are closely associated with enriched microbial functional genes for carbon fixation and degradation and with higher ratoon yield (76). Bio fertilisers and mycorrhiza, especially Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), can enhance soil fertility and rice growth by increasing N,P and K availability, improving nutrient uptake and sustain soil health, with combined AMF+PGPR inoculation raising rice yield and postharvest soil nutrient status (77). A symbiosis between rice, AMF and other microbes is maintained via root and microbial exudates and AMF and related bacteria in the rice mycorrhizosphere have a significant impact in plant growth and soil structure. Soil microbes mediate nutrient transformation, organic matter decomposition and stress tolerance at the soil-plant-climate interface (78). In rice systems, integrated nutrient management that provides organic and mineral sources increases the abundance,

Table 1. Rice varieties suitable for ratooning in India

Variety	Region	Ratoon characteristics	Reference
IR-64	Meghalaya, Assam, Eastern Himalaya	Strong ratoon and high system yield	(21)
Binadhan-11	Assam	Best ratoon yield cluster	(71)
Sayjihari	Assam	High ratoon yield	(72)
DRR-44	Assam	Good ratooning ability	(72)
Sahsarang-1	Meghalaya, Eastern Himalaya	Highly promising ratoon yield	(21)

Table 2. Foliar nutrition for ratoon rice

Foliar Spray Type	Dosage and spraying time	Effect on Ratoon Rice	References
Rice - Si Spray	1 % Potassium silicate at tillering, panicle initiation, grain formation	Increased rice grain and straw yield	(76)
Foliar EDTA-Se at heading + 7 d after heading (main)	800 mL of 12.66 mg L ⁻¹ EDTA-Se at heading stage	Increased rice yield by 6.45 %; improved milled rice rate; chalky rice rate	(77)
Foliar sodium selenite, Se-Met (ratoon season)	100 mg L ⁻¹ At booting stage (3 sprays at 2 days interval)	Increases Se and trace elements in grain and straw; improved photosynthesis.	(78)
(main) Plant extracts (<i>Gliricidia</i> + Banana bract) at high temperature- Ratoon	1 : 10 dilution (2 weeks after harvesting of main crop)	Increased grain yield; and high profitability	(79)
Plant growth regulators	Cytokinin – Benzyl amino purine (25 ppm – 3days after harvest)	Promoting axillary bud sprouting and ratoon tiller regeneration	(80)

diversity and activity of soil microbiomes more than sole synthetic fertilisers, improving nutrient availability, soil structure and plant tolerance to drought, salinity, heavy metals and other climate related stresses (79). In ratoon rice, rhizosphere microbial activity and functional genes for carbon and phosphorous cycling are directly tied to nutrient indices and yield, underscoring that managing soil organic matter and microbial consortia under changing climates is essential for sustaining ratoon productivity (76).

Soil microorganisms play diverse and specific roles in supporting rice growth and nutrient availability. Certain bacteria, such as *Rhizobium* and *Azotobacter*, along with cyanobacteria and the water fern *Azolla*, can fix atmospheric N and convert it into forms that can be utilised by rice plants, thereby reducing the dependence on N fertilisers. Other beneficial bacteria, including species of *Bacillus* and *Pseudomonas*, can solubilise and mobilise P and K that are otherwise present in less available forms in the soil, thereby enhancing the availability to plants (79). Studies have also shown that rice varieties with better ratooning ability tend to be associated with soil microbial communities that efficiently cycle nutrients, providing a more consistent nutrient supply during crop regeneration (76). However, climate change can significantly affect these microbial communities; extreme temperatures can alter microbial composition and activity, while increasing temperatures may impair soil carbon and nitrogen cycling. Furthermore, the projected increase in the frequency of droughts and floods may impose additional stress on soil microbial communities. Integrated nutrient management, which combines organic inputs such as manure and compost with reduced rate of chemical fertilisers, has been shown to enhance microbial activity, improve nutrient use efficiency and reduce greenhouse gas emissions from rice fields (79).

Yield, quality and resource use efficiency

In 2016, a study examined three methods in central China, utilising 240 farmer fields: middle season rice (MR), double season rice (DR) and ratoon rice. Annual grain yield averaged 7.7 Mg ha⁻¹ for MR, 15.3 Mg ha⁻¹ for DR and 13.2 Mg ha⁻¹ for ratoon rice. Thus, ratoon rice produced 72–129 % more yearly grain production than MR but around 13 % less annual yield than DR. The main crop averaged 7.5 Mg ha⁻¹, while the ratoon crop averaged 5.7 Mg ha⁻¹ resulting in an annual ratoon rice total of 13.2 Mg ha⁻¹. Ratoon rice outperformed MR in terms of annual productivity, input efficiency and profitability, while remaining competitive with DR on net energy and significantly superior on environmental intensity and profit (80).

Main season yield was primarily determined by spikelets per panicle, while ratoon season yield was influenced by grain filling rate, panicles per m² and 1000-grain weight. In the ratoon season, all the three traits were positively associated with yield, however path analysis revealed that grain filling rate had a strongest overall contribution, followed by panicles per m² and 1000 grain weight. Notably, although 1000 grain weight showed the highest direct contribution among the three traits, its total contribution was reduced by the negative indirect effect of panicles per m², whereas grain filling rate benefited from a positive indirect contribution via panicles per m², resulting in its higher overall influence on ratoon yield (81).

According to research on ratoon rice under climate stress, grain quality is typically more sensitive than yield, particularly when heat, shade or water-related stress affects grain filling (82). Climatic

stress mainly affected ratoon rice grain quality through increasing nighttime temperature, shifts in atmospheric CO₂ and harvest time temperature exposure. Higher nighttime degree days above 10 °C consistently reduced grain quality in ratoon rice. Later main crop harvests also worsened several quality traits, likely because later produced grain experienced higher temperatures during grain filling and possibly greater insect and disease pressure (83). Grain quality is strongly influenced by stubble height, variety, planting region, latitude, precipitation and temperature, highlighting the importance of environmental and agronomic factors in determining the quality of ratoon rice. Meta-analysis indicates that ratoon-season rice generally exhibits better grain quality than main crop rice, with higher milled rice and head rice rates, reduced chalkiness and favourable changes in the amylose content and alkali spreading value (82).

The practice of rice ratooning produces high net energy values and cost benefit ratios than middle and double season rice cultivation methods while it generates lower environmental damage through global warming potential (84). Due to the lower cumulative CH₄ emissions during the ratoon season, ratoon rice system's annual cumulative CH₄ emissions were 35.21 % lower than double rice systems, although the annual cumulative N₂O emissions of two cropping systems were comparable (12). Ratoon rice has a lower global warming potential (GWP) and lower greenhouse gas intensity per unit grain yield (GHGI) than the main and double rice seasons (12). The lower greenhouse effect was linked mainly to reduced biomass during the ratoon season, which limits methane production. The ratoon rice cropping pattern is thus described having a lower annual greenhouse gas emissions, lower environmental footprints and better sustainability than double season rice, especially when annual yield is maintained (85).

Constraints and path to overcome the constraints

The production of the succeeding ratoon rice crop in the rice-ratoon-rice system is significantly restricted by inadequate tiller regeneration from the stubble following the harvest of the main rice crop (86). Because there are fewer productive tillers, ratoon output is typically lower than the main crop, typically falling between 40–60 % of the main crop yield (87). Ratoon yield, however, usually accounts for nearly half of the primary crop and yield unpredictability continues to be a significant obstacle to its widespread use. In addition, ratoon is climate sensitive, due to this sensitivity ratoon success may be affected by improper time of planting or delayed main crop development. Adoption of ratoon rice is constrained by lower and unpredictable ratoon crop yields, lack of suitable cultivars and a shortage of specialised mechanical harvesters (15). The absence of specifically designed ratooning varieties, poor agronomic practices, climate change susceptibility and policy preference for double-season rice continue to be significant obstacles. Due to inadequate extension and training, the study also identifies discrepancies between experimental and farmers' field yields (88). There are some crucial agronomic management techniques for raising ratoon output to get around these restrictions. These include choosing the right varieties (hybrids with high regeneration potential), timing planting and harvesting, cutting the main crop at the right height, managing water and nutrients, controlling weeds and using plant growth regulators (9). To overcome these limitations proper agronomic and other management practices should be needed.

Future prospects and research directions

Future research directions for ratoon rice under changing climate must prioritise three interconnected domains. First, developing climate-resilient varieties through modern breeding strategies is critical. The “One Rice Breeding Strategy” by International Rice Research Institute (IRRI) and National Agricultural Research and Extension Systems (NARES) partners aims to accelerate climate-resilient variety release, while genome mining of traditional varieties identifies alleles for heat and drought tolerance (89). Future breeding efforts should integrate genome-wide association studies (GWAS), marker assisted selection (MAS), genomic selection, genomic prediction and rapid generation advancement to identify and efficiently deploy favourable alleles for ratooning ability, stress tolerance and yield stability (55). Gene editing technologies such as CRISPER/Cas should also be explored to functionally validate candidate genes and precisely modify traits associated with axillary bud regeneration, climate stress tolerance, plant architecture and nutrient use efficiency (90). Also, develop or select large panicle cultivars that ensure high yield during the main cropping season and complement them with suitable agronomic practices. This approach can enhance panicle density per unit area, improve grain filling and increase grain weight in the ratoon crop, ultimately leading to higher overall annual productivity (81). Future studies should determine which combinations of large panicle architecture, effective panicle density, axillary bud regeneration, root vigour, stem strength and grain filling ability maximise combined main season and ratoon season productivity under contrasting climatic conditions (55).

Second, precision agriculture and digital tools will transform ratoon rice management. Remote sensing, Global Positioning System (GPS)–Geographic Information System (GIS)-based site-specific nutrient management, variable rate applicators and decision support systems like IRRI's Rice Crop Manager optimise water and fertiliser inputs according to spatial-temporal field variabilities, achieving higher nutrient and water-use efficiency than conventional practices (91). Artificial intelligence (AI)-driven pest and disease detection tools enhance crop protection under climate stress (92). Future research should determine whether unmanned aerial vehicle (UAV)-based imaging, hyperspectral sensing, soil moisture monitoring and artificial intelligence can predict ratoon bud activation, tiller regeneration, nutrient deficiency, water stress and pest and disease incidence early enough to enable site specific interventions (92).

Third, policy and sustainability aspects require strategic intervention. Policy changes supporting large-scale ratoon cultivation, subsidies for high-ratooning cultivars with multiple disease resistance and mechanisation incentives compatible with optimised cutting heights (30–40 cm) are essential for rapid adoption in India (17). Beyond agronomic constraints, adoption is limited by the lack of specialised mechanical harvesters that avoid rolling damage to stubble. Farmer's risk attitude shapes technology adoption, with risk averse farmers prefer low cost and stress tolerant varieties (15). Economic research should move beyond estimates of input-cost savings by evaluating net returns, benefit-cost ratios, labour and mechanisation costs, irrigation and nutrient expenditure, price sensitivity and economic risk across different ratoon production systems and climatic environments (80). Carbon credit programs recognising ratoon rice's reduced greenhouse gas emissions through lower irrigation and fossil fuel consumption can

enhance farmer incentives (85). Integrating sustainability metrics with productivity goals ensures ratoon rice contributes to climate adaptation, food security and environmental stewardship while minimising pollutant emissions (93). Long term, multi-location experiments are needed to quantify genotype $\times$ environment $\times$ management interactions and determine how ratoon rice performance, nutrient use efficiency, soil health, greenhouse gas emissions and economic returns respond to increasing heat, drought and flooding (14).

Conclusion

Ratoon rice represents a resource-efficient, climate-smart production method that increases rice productivity in the face of shifting weather patterns. Ratoon systems yield 40–50 % of the main crop while allowing for increased cropping intensity, with a 40 % reduction in growth period, a 60 % reduction in water requirements and a 50 % reduction in labour input when compared to conventional rice. Regeneration capacity is determined by the physiological basis including bud dormancy breakage, carbohydrate reserves in stubble and hormonal regulation by auxins and cytokinins, but climatic change presents serious risks. Ratoon rice production approach also reduces the carbon footprint by cutting greenhouse gas emissions through lower irrigation water needs and reduced fossil fuel use from machinery operations. Effective management of ratoon rice requires optimised cutting height, split nitrogen (N) application, integrated nutrient strategies and water management techniques like alternate wetting and drying. Improved cultivars with multiple disease resistance and high ratooning ability for mechanical harvesting are critical for expanding adoption. Future research must focus on breeding climate resilient cultivars, understanding hormone carbohydrate interactions under cumulative stress and developing best agronomic practices. In addition, strong policy support for large scale adoption is crucial to fully harness the potential of ratoon rice in strengthening food security amid climate variability, while simultaneously reducing greenhouse gas (GHG) emissions and promoting sustainable agricultural system.

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Authors' contributions

AR and VR conceived the idea for the manuscript. AR conducted the literature review and drafted the initial manuscript. MK, SN and VK provided critical feedback on the manuscript. AR and VR prepared the final version. All authors have read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work the author used ChatGPT in order to improve language and readability, with caution. After using the tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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