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REVIEW

# Innovation and implement of green technology in rice production to increase yield and resource use efficiency

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## KEYWORDS

Alternate wetting and moderate drying irrigation, green technology, nitrogen application criteria, resource use efficiency, rice, water-nitrogen coupling regulation

## HIGHLIGHTS

- Increased harvest index is pivotal for improving yield and resource use efficiency.
- Increased grain-leaf ratio, sugar-spikelet ratio and proportion of productive tillers are key for green rice production.
- Alternate wetting and moderate drying, three-criteria nitrogen application and water-nitrogen coupling regulation are the efficient practices for green rice production.

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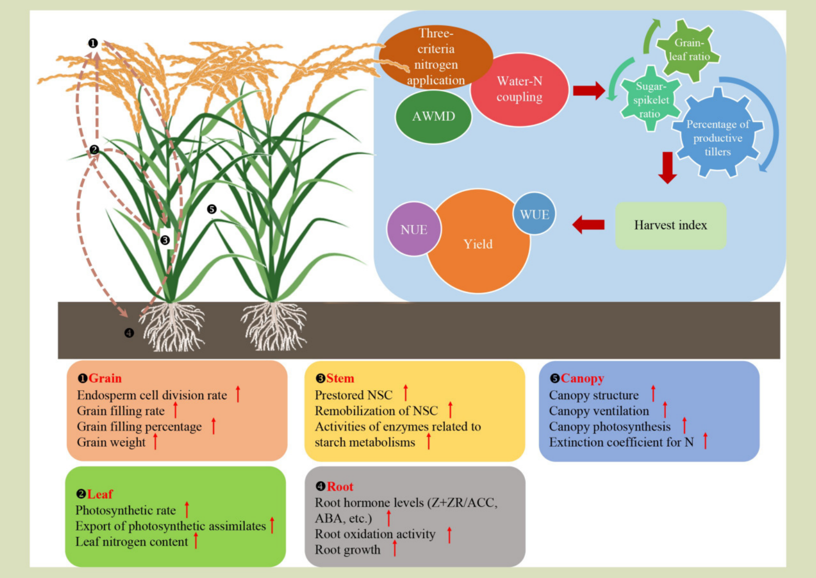
## GRAPHICAL ABSTRACT



## ABSTRACT

Rice is the staple food of nearly half the global population, and its production must steadily increase to meet the growing demand driven by an increasing global population. While an increase in rice production heavily relies on substantial water and fertilizer inputs, which not only decreases water and fertilizer use efficiencies, but also pose significant environmental risks. Therefore, it is an urgent need to enhance yield and resource use efficiency through the development and adoption of innovative, sustainable and environmentally-friendly technologies. This paper reviews progress in green rice production over recent decades based mainly on such research. Firstly, it explores physiological strategies aimed at enhancing yield and improving resource use efficiency in rice production. Secondly, it proposes three key agronomic and physiological strategies to achieve green rice production: optimizing the grain-leaf ratio to balance source-sink dynamics, enhancing the sugar-spikelet ratio to improve sink strength and facilitate non-structural carbohydrates remobilization during grain filling, and increasing ratio of productive tillers to optimize canopy structure. Based on these strategies, a quantitative evaluation of rice population characteristics was undertaken to achieve high yield and resource use efficiency. Thirdly, green technologies for rice production is introduced, including alternate wetting-drying irrigation, three-criteria nitrogen application (based on soil, leaf color and cultivar), and water-nitrogen coupling regulation. Finally, the implication of these technologies is summarized for the major rice-growing areas in China, including Anhui, Heilongjiang, Hubei, Jiangsu, Jilin and Sichuan, and Shanghai. The future prospects for sustainable rice production is then discussed, emphasizing the potential of green technologies to meet the growing demand for rice in an environmentally sustainable way.

## 1 Introduction

China is the largest producer and consumer of rice in the world, and making continuous advancements in rice production essential for ensuring food security and improving living standards both domestically and globally[1,2]. Rice grain yield in China has risen from 2.1 t·ha$^{-1}$ in 1950 to 6.8 t·ha$^{-1}$ in 2020, primarily driven by genetic improvement of cultivars and increased use of fertilizers, pesticides and irrigation[1,3]. In the past, food production achievements in China were largely driven by the intensive agriculture characterized by high-input-high-output thinking, which relied heavily on the extensive use of mineral fertilizers, pesticides and water resources to maximize yields[4]. Although this approach led to substantial increases in production, it also resulted in environmental degradation, resource depletion and a decline in long-term productivity. As a result, this thinking is recognized as unsustainable, necessitating a shift toward more sustainable practices that balance high productivity with environmental conservation[5].

Water scarcity is widely recognized as the major challenge to rice production in many areas of China[6]. This issue arises from several factors, including the unpredictable variability of annual rainfall, the uneven distribution of rainfall throughout the rice-growing season and insufficient precipitation in numerous rice-producing areas. These conditions not only limit water availability during critical growth stages but also exacerbate the vulnerability of rice crops to environmental stresses[1]. China faces substantial water resource challenges, with nearly one-fifth of world population while only about 6% of the global renewable freshwater resources[7]. Over the last two decades, 1.6–2.0 Mha of rice in China have been severely impacted by seasonal droughts due to water shortages[8,9]. Additionally, rice irrigation in China consumes 30%–40% more water, with water use efficiency (WUE) being 40%–50% lower than the global average[2,10]. Compared to standard flooded irrigation, water-saving irrigation technologies are essential for improving WUE and reduce irrigation water consumption.

Excessive nitrogen input and low nitrogen use efficiency (NUE) present another significant challenge to rice production in China. In cereal production in 2010 in China, the N input was 219 kg·ha$^{-1}$ N, and NUE was just under 34%, which was 346% and 68% of the world average, respectively (Fig. 1). With promotion and project support by the Chinese Government, and the combined efforts of scientists, extension technicians and farmers, improved nitrogen management practices have significantly reduced the nitrogen application rate to 166 kg·ha$^{-1}$ N, with NUE (recovery efficiency) reaching 51%. Although this is close to the global average of 56%, it remains significantly lower than that of leading countries such as the USA, where NUE is 72%. Therefore, much greater effort is needed.

Balancing the need to increase food production with the imperative to conserve resources and protect ecosystems requires innovative physiological strategies and approaches. In

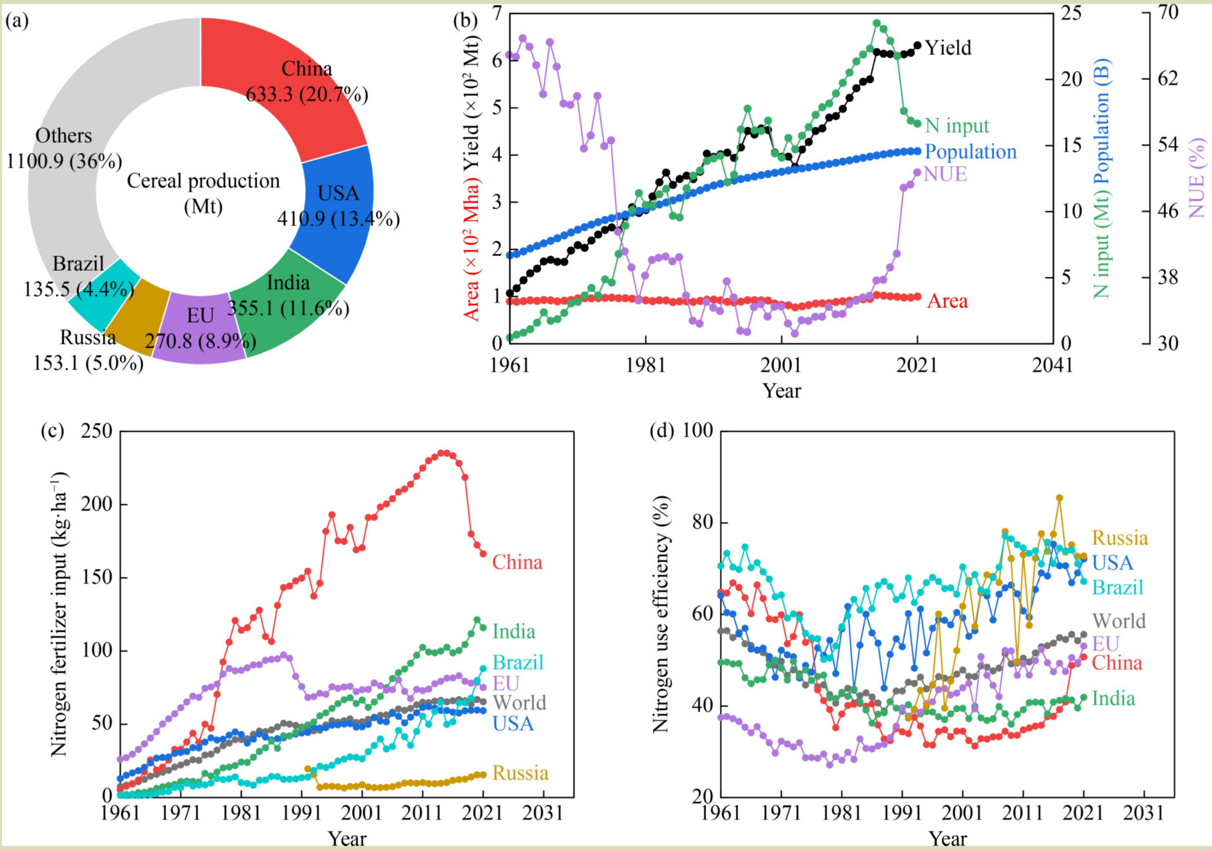


**Fig. 1** Changes in cereal production, nitrogen fertilizer input, nitrogen use efficiency (NUE), planting area, and population in China and the world from 1961 to 2021. (a) Percentage of cereal production by major countries and regions in 2021; (b) changes in planting area, cereal crop yield, population, nitrogen input and NUE in China from 1961 to 2021; (c) nitrogen fertilizer input per area for major countries and regions of cereal production from 1961 to 2021; (d) NUE for major countries and regions of cereal production from 1961 to 2021. Data sourced from the Food and Agriculture Organization of the United Nations[11].

grain crops, harvest index (HI) is yield as a proportion of yield (e.g. grain) to total aboveground biomass (B)[12,13]. HI, which represents the proportion of total biomass allocated to grain production, is a critical indicator of the efficiency with which plants convert dry matter into harvestable grain. This efficiency is pivotal, as HI directly reflects resource use efficiency, including water and nutrient use efficiencies[4,14]. Therefore, improving the HI has a synergistic effect, simultaneously boosting crop yield and enhancing the water and nutrient use efficiency. This relationship highlights the importance of HI in developing more sustainable and productive cropping systems. By focusing on strategies that increase HI, it is possible to achieve increased yields without a proportional increase in resource inputs, making it a critical factor in the pursuit of sustainable green agriculture. Therefore, in this paper, we focus on the role of HI in increasing grain yield, WUE and NUE. We also discuss the physiological strategies to increase HI. Then, we summarize the innovations and implementation of green technologies that are designed to improve the HI in rice. Also, we suggest the future prospects for sustainable rice production, emphasizing the potential of green technologies to meet the growing demand for rice in an environmentally responsible way.

## 2 Physiological approaches to regulate HI to increase grain yield and resource use efficiency

### 2.1 Role of HI in increasing grain yield, WUE and NUE

Historically, yield increases from the 1940s to the 1960s were driven by improvements in HI, while gains since the 1960s have primarily resulted from increased biomass. With HI maintained at 0.5, further yield increases beyond 6 t·ha$^{-1}$ are proposed to rely on increasing biomass[15]. However, HI in rice has been noted to vary widely, ranging from 0.17 to 0.63[16,17], indicating that there is potential for yield improvements through the improvement of HI. Modern rice cultivars that produce increased yields tend to have increased HI, which is attributed to their efficient transfer of photosynthates to the grain[18]. Yang and Zhang[4] reported that during the breeding of midseason *japonica* rice cultivars, both the increase in biomass growth and the improvement in HI has been significant in increasing grain yield. This finding highlights the importance of HI not only in historical yield gains but also as a key factor for future yield improvements.

Water productivity ($WP_T$) in rice is defined as the ratio of grain yield (Y) to the amount of water transpired (Tr). Since Y is the product of HI and total aboveground biomass (B), $WP_T$ can also be expressed as $WP_T = HI \times B / Tr$. The transpiration efficiency (B / Tr) in rice remains relatively constant at around 1.5 g·kg$^{-1}$[19]. Therefore, efforts to reduce transpiration often result in a reduction of biomass, posing a challenge in improving WUE without negatively impacting overall crop productivity. This highlights the importance of strategies that enhance HI as a approach to improve $WP_T$ without compromising biomass production. Therefore, by increasing HI, it is feasible to simultaneously increase grain yield and WUE[2]. Historically, crop breeding has improved WUE by increasing HI[20], highlighting the importance of HI in enhancing WUE in rice.

Nutrient productivity (Np) in rice, defined as grain yield per unit nutrient absorbed (Nr), similarly, can be expressed as $Np = HI \times B / Nr$. Nutrient production efficiency (B / Nr) tends to remain relatively consistent for a specific rice cultivar and nutrient application rate under specific weather conditions[21]. For example, in the lower reaches of the Yangtze River, the B/Nr ratio is typically about 100 g·g$^{-1}$ for *japonica* rice and 110 g·g$^{-1}$ for *indica* rice when nitrogen is applied at a rate of 180–300 kg·ha$^{-1}$[3]. This stable nutrient production efficiency indicates that substantial gains in Np and nutrient use efficiency can be achieved by focusing on improving HI. In fact, Raun and Johnson[22] reported that increasing NUE relies heavily on rice cultivars with increased HI. HI is not only significantly correlated with NUE but also with the use efficiencies of phosphorus and potassium[4]. This correlation underscores the pivotal role that HI has in the broader context of nutrient use in rice, indicating that improving HI could result in improved utilization of multiple essential nutrients.

## 2.2 Physiological strategies for enhancing HI

### 2.2.1 Increasing the grain-leaf ratio

The grain-leaf ratio expressed as the number of spikelets per unit leaf area (spikelets cm$^{-2}$) at heading[4], indicates whether the photosynthetic capacity (source) is sufficiently balanced with its grain-filling demands (sink)[23]. Source organs (leaves) produce photosynthates, while sink organs (spikelets) use these photosynthates for grain growth and development. A greater grain-leaf ratio indicates that spikelets have a greater capacity to actively extract photosynthates from the leaves. This efficient extraction improves the coordination between photosynthetic production and grain filling, ultimately leading to increased grain yield. Studies have demonstrated that populations with a greater grain-leaf ratio typically exhibit a superior source-sink relationship, which is crucial for determining rice productivity[4]. This improved relationship is closely associated with enhanced photosynthetic efficiency in the leaves[23]. The increased grain-leaf ratio allows for more efficient allocation of photosynthates, ensuring that the assimilates produced during photosynthesis are rapidly and effectively translocated from the leaves and stems to the developing grains. This process is vital for increasing the HI of rice, as it ensures that a greater proportion of the biomass is directed toward grain production rather than being retained in vegetative parts[2,23,24]. Increasing the grain-leaf ratio is a promising strategy to improve HI and overall rice productivity. This approach focuses on optimizing the balance between source (leaf) and sink (spikelet) organs, ensuring efficient photosynthate allocation.

### 2.2.2 Enhancing the sugar-spikelet ratio

The sugar-spikelet ratio, expressed as the amount of non-structural carbohydrates (NSCs) in the stems to the total number of spikelets at anthesis, with NSCs being given as mg per spikelet [25]. A larger value of this trait at heading indicates more reserves of photosynthetic assimilate at the vegetative stage. These pre-stored NSCs contribute significantly to grain development, providing between a sixth to a third of the total assimilates required for grain filling[25]. In addition to directly supplying the grains with essential carbohydrates, these NSCs serve a pivotal role in regulating sink activity, a process that determines the efficiency of grain filling. These carbohydrates influence hormonal balances, energy status, and activities of the enzymes involved in converting sucrose to starch in the developing seeds[25]. Specifically, NSCs help trigger the grain-filling process by mediating the synthesis of key hormones like abscisic acid and cytokinins, which regulate sink strength[26].

Studies have demonstrated that increasing the sugar-spikelet ratio can significantly enhance sink activity at the beginning of grain filling. This enhancement leads to increased endosperm cell division rates, grain-filling rates, filled-grain percentages, grain weights and overall grain yields, thereby increasing the HI[25,27,28]. The sugar-spikelet ratio is positively and significantly correlated with several critical factors that influence rice yield and grain quality[4]. One of the key relationships is with the division rate of endosperm cells. The accelerated cell division rate is essential for increasing the potential grain size and weight, ultimately leading to improved yield. Additionally, a increased sugar-spikelet ratio enhances the remobilization of NSCs from vegetative tissues. This remobilization process is crucial for ensuring that grains receive a steady supply of assimilates, particularly when photosynthetic activity declines in the later growing season. By sustaining grain filling through pre-stored carbohydrates, rice plants can achieve an increased yield. Also, a greater sugar-to-spikelet ratio typically leads to a more favorable source-sink balance, and it is correlated with HI[25]. Such relationships demonstrate that increasing the sugar-spikelet ratio is another important strategy for enhancing HI in rice.

The increased NSC reserves in stems and sheaths ensure that more resources are available for developing grains, leading to improved grain filling and increased grain weight. This approach complements strategies that enhance the grain-leaf ratio, together providing a comprehensive method to optimize source-sink relationships in rice and achieve increased productivity.

#### 2.2.3 Increasing the proportion of productive tillers

The proportion of productive tillers is expressed as the ratio of productive tillers to the maximum number of tillers at jointing stage[23]. A greater proportion of productive tillers indicates a decrease in non-productive tillers, thereby reducing the unnecessary consumption of water and nutrients for unproductive growth. This leads to more efficient use of resources. Increased productive tillers also enhance the overall canopy structure, increase ventilation and light penetration[21,23]. This structural improvement facilitates improved dry matter production from heading to maturity, which is a key determinant of increased yield[24,29,30]. Additionally, a greater proportion of productive tillers improves the extinction coefficient of nitrogen within the canopy, allowing for more efficient canopy photosynthesis. This directly contributes to increased yields and enhances photosynthetic NUE[31].

In addition, studies have demonstrated that the proportion of productive stems and tillers is positively and significantly correlated with key factors such as the grain-leaf ratio, sugar-spikelet ratio, and HI[4]. These relationships indicate that a greater proportion of productive tillers not only improves resource allocation and use but also enhances overall grain yield and crop performance by optimizing critical physiological processes.

By focusing on increasing the proportion of productive tillers, rice growers can achieve improved resource allocation, superior canopy structure, and ultimately increased yield potential. This strategy complements other approaches, such as enhancing the grain-leaf and sugar-spikelet ratios, providing a holistic method to optimize rice plant productivity and resource use efficiency.

### 2.3 Characteristics of rice population of high yield and resource use efficiency

By enhancing key physiological traits such as the grain-leaf ratio, sugar-spikelet ratio, proportion of productive tillers, and harvest index, significant improvements can be made in both grain yield and resource use efficiency. These traits are interconnected and collectively form a strong foundation for optimizing the overall performance of rice populations. For example, increasing the grain-leaf ratio ensures a more efficient source-sink relationship, enabling improved utilization of assimilates for grain development. Similarly, a greater sugar-spikelet ratio promotes efficient carbohydrate remobilization during grain filling, which is essential for achieving increased yields. A greater proportion of productive tillers minimizes resource wastage on non-productive growth, and improves water and nutrient use efficiency, while also contributing to a stronger canopy structure that supports increased dry matter production. In early research[2,3,9,30,32,33], not only was the importance of these parameters highlighted as pivotal factors in developing rice populations with high yield and resource efficiency, but also were quantitatively assessed the characteristics of such populations, and the key parameters of a high-yielding and resource use efficient rice population are presented in Table 1. The integration of these parameters into breeding and management practices can facilitate the development of resilient and high-yielding rice populations that support sustainable agriculture.

## 3 Innovations of crop management practices to increase grain yield and resource use efficiency

### 3.1 An alternate wetting-drying regime

To address water scarcity and enhance WUE in rice

**Table 1 Characteristics of the rice population with high yield and high resource use efficiency (grain yield > 10 t·ha$^{-1}$)**

| Trait | Value |
|---|---|
| Total spikelets (× 10$^4$ m$^{-2}$) | > 4.8 |
| Percentage of filled grains (%) | > 82 |
| 1000-grain weight (g) | > 26 |
| Percentage of productive tillers (%) | > 80 |
| Leaf area index at heading stage (m$^2$·m$^{-2}$) | 7.5–8.0 |
| Total leaf area duration (m$^2$·d·m$^{-2}$) | > 500 |
| Dry weight of above-ground biomass at harvest (t·ha$^{-1}$) | > 20 |
| Increase of dry weight of above-ground biomass from heading to maturity (t·ha$^{-1}$) | > 8.0 |
| Grain-leaf ratio at heading (spikelets cm$^{-2}$) | > 0.60 |
| Sugar-spikelet ratio at heading (mg per spikelet) | > 8.0 |
| NSC remobilization (%) | > 45 |
| Root-to-shoot ratio | > 0.20 |
| Root bleeding intensity at heading (g·m$^{-2}$·h$^{-1}$) | > 18 |
| Harvest index | > 0.50 |

production, a range of water-saving regimes have been developed and tested over years. Such as aerobic rice system[34,35], the system of rice intensification[36], non-flooded mulching cultivation[37], and alternate wetting-drying (AWD) irrigation[38]. All these systems have demonstrated the potential to substantially reduce irrigation water use, thereby improving WUE. However, despite the water savings associated with these approaches, they often result in significant trade-offs in terms of grain yield[14,34,39]. For example, the aerobic rice and rice intensification systems have provided substantial reductions in water usage, however, they have also face challenges in maintaining high yield levels comparable those achieved in standard flooded systems. This yield penalty is a major challenge, especially in areas where food security is a critical concern.

Of these water-saving technologies, AWD irrigation has emerged as one of the most widely adopted practices, particularly in China, where it has been implemented on more than 12 Mha of rice fields annually[40–42]. For AWD, it is based on the principle of alternating between flooded and non-flooded conditions in rice fields throughout the growing season. The drying intervals between irrigations in AWD vary greatly, typically ranging from 1 to 10 days, depending on factors such as soil type and climatic conditions. The frequency of irrigation and the duration of the non-flooding phase in AWD is often determined by the practical experience of farmers, which can sometimes result in fields being allowed to dry beyond the optimal level. Prolonged soil drying stress can result in stunted growth, reduced tiller formation, and delayed grain filling, which ultimately compromises overall crop performance. Therefore, it is still debatable if AWD can simultaneously achieve the dual goals of increasing grain yield and conserving water resource[42–45]. Studies have regularly highlighted that the extent of soil drying in AWD is the critical factor influencing rice yield[40,45–47].

Adoption of moderate AWD (AWMD) irrigation, in which soil drying is carefully controlled, is a promising approach to simultaneously enhance water savings and grain yield. By managing soil moisture in a way that does not significantly inhibit photosynthesis and allows plants to rehydrate overnight, rice yield could increased. Studies have demonstrated that by maintaining soil water potential above –15 kPa at a depth of 15–20 cm or midday leaf water potential around –0.80 MPa during drying periods, grain yield, WUE and nutrient use efficiency can be increased, without impairing leaf photosynthesis in rice[9,42].

The mechanisms by which AWMD irrigation achieves these results are mainly attributed to its ability to prevent excessive vegetative growth, improve canopy structure and root development, and regulate hormone levels, such as increased abscisic acid levels during soil drying and elevated cytokinin levels upon rewetting. These hormonal changes improve the remobilization of carbon from vegetative tissues to grains, leading to increased yields, WUE and NUE[9].

The challenge is how to optimally control soil drying under AWMD irrigation. Several methods have been proposed to manage this process, including fixing the number of non-flooding days, setting thresholds based on leaf water potential (LWP), soil moisture content, soil water potential (SWP) or monitoring visual symptoms from plant leaves and/or soil[38,43,44,48]. Theoretically, LWP provides the most accurate index of plant water status, as it directly reflects the hydration levels of plants. However, due to the complexity of accurately measuring LWP, SWP is often recommended as an alternative irrigation index[40]. SWP provides useful insights into soil water conditions, yet it can be difficult for most small farmers to employ tension meters to monitor it consistently. A more practical solution for farmers is to use a simple perforated water tube to measure the depth of the water table below soil surface.

We have recently developed a method of monitoring the water table beneath the soil surface as a practical irrigation indicator by installing polymerized vinyl chloride (PVC) tubes directly into the field (Fig. 2). The inner and outer diameters of the PVC tube is 19 and 20 cm, respectively. To allow water entry, 0.5 cm diameter holes are drilled in the lower 25 cm of the tube, spaced at vertical intervals of 1 cm and lateral intervals of 3 cm. The tube is inserted into the soil up to a depth of 30–40 cm, and the soil inside the tube is removed to expose the water table. The timing of irrigation is determined by daily observations of the water depth inside the tube. During most growth stages, when the water depth drops below a certain threshold below the soil surface, a thin layer of water, about 2–3 cm is applied to the field to restore soil moisture.

This approach allows for a dynamic irrigation system that accounts for the varying sensitivity of rice to soil drying across different growth stages. For example, rice plants exhibit greater sensitivity to soil drying during reproductive stages than ripening stages[9]. Besides, the soil water table varies with soil types (e.g., sand, loam and clay) for the same SWP. As a result, irrigation thresholds must be tailored not only to the growth stage but also to the soil type to optimize water management and avoid under or over-irrigation. In Table 2, we present the thresholds of the water table at each growth stage. These thresholds are adapted based on soil type to accommodate the diverse range of hydrological conditions in different fields. For example, a sandy soil might require more frequent monitoring and irrigation adjustments than a loamy or clayey soil, where water retention is typically increased. The PVC tube system provides a straightforward and cost-effective means for farmers to monitor these variations, ensuring that the crop remains properly hydrated throughout the growing season.

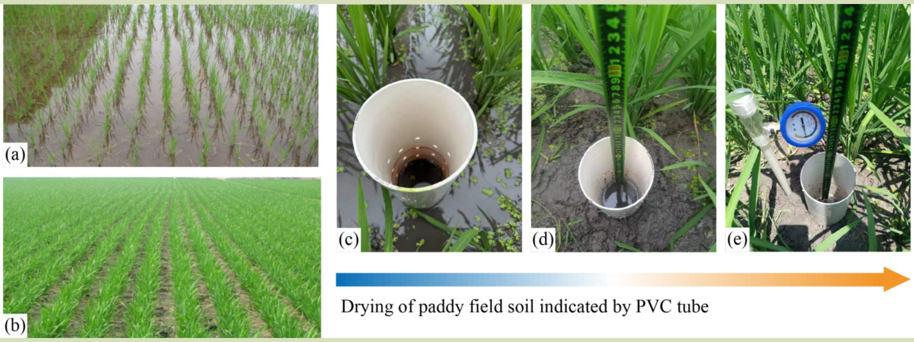


**Fig. 2** Using a polymerized vinyl chloride (PVC) tube to monitor water table level in soil. (a) Rice plants in the field of continuous flooding; (b) rice plants in the field of with alternate wetting-drying irrigation; (c–e) PVC installed in the field to monitor soil water table levels.

**Table 2 Irrigation threshold for water table in the rice fields at different growth stages and soil types**

| Soil type | Depth to water table below soil surface (cm) | | | |
|---|---|---|---|---|
| | Mid-tillering | Jointing | Heading | Maturity |
| Sand | 8–10 | 12–20 | 10–14 | 12–16 |
| Loam | 10–14 | 18–25 | 14–18 | 15–20 |
| Clay | 12–16 | 25–30 | 18–22 | 20–25 |

Compared to a continuous flooding, AWMD irrigation not only conserves water by reducing excess irrigation but also promotes the grain-leaf ratio, sugar-spikelet ratio, proportion of productive tiller and HI, and accordingly increase grain yield, WUE and NUE. This irrigation strategy thus offers a viable approach to optimizing rice production and resource efficiency. In addition, rice paddies contribute 15%–20% of global anthropogenic methane emissions, with even more emissions when wheat residues are incorporated in wheat-rice rotation systems which is common in East and Southeast Asia[42]. Organic matter in the soil, such as organic fertilizers, root exudates, plant residues and weed residues, can be used by methanogens to produce methane. The flooded, anaerobic conditions in paddies promote methane production by methanogenic microorganisms[49]. AWMD irrigation can substantially decrease methane emissions, and the reduction is primarily due to the intermittent drying phases of AWMD irrigation, which create aerobic conditions in the soil. The aerobic conditions inhibit methanogenic microorganisms responsible for methane production and increase the activity of methanotrophs, which oxidize methane, thus lowering methane emissions[49–51]. It is also observed that AWMD irrigation could markedly increase soil redox potential, which provides abundant oxidants like Fe(III), the oxidized forms of iron, to reduce methane production, by inhibiting methanogenic bacteria[51]. Thus, the AWMD irrigation reduces methane, global warming potential, and greenhouse gas intensity by 48.3%–57.9%, 44.0%–56.3%, and 44.9%–62.9%, respectively, in comparison with a continuously flooded regime[9,42].

## 3.2 Three-criteria nitrogen application

Nitrogen fertilizer is essential for crop yield, and its application and management strategy is one of the primary drivers behind increasing crop productivity. The primary challenge lies in optimizing nitrogen application rates and timing, which depend on soil fertility, the nitrogen requirements of rice at various growth stages and the specific nitrogen demanding characteristics of a given rice cultivar[3]. To address these challenges, we developed a nitrogen application method that synchronizes the supply of available soil nitrogen with the nitrogen demands of rice plants. This newly developed three-criteria method for N application accounts for soil fertility, the plant N status at various growth stages, and genetic differences in N requirements of rice plants. The approach adjusts N application to rice based on three criteria: soil fertility, leaf color as an indicator of plant nitrogen status, and the specific cultivar being grown[4].

### 3.2.1 Soil fertility

The total N rate is determined by first calculating the difference between the target grain yield and the yield supported by the indigenous N supply from the soil, and the value was divided by the agronomic NUE (i.e., the grain yield increase per unit of nitrogen applied) (Fig. 3). Once calculated, the total amount of N is distributed among basal, tillering and panicle stages (applied at panicle initiation and/or pistil and stamen differentiation stages) according to the nitrogen requirements of rice plants at various growth stages.

### 3.2.2 Leaf color

The nitrogen application rate at the rice growth stages of tillering, panicle initiation, and pistil and stamen differentiation are adjusted by monitoring the leaf color ratio. This ratio is determined by comparing the relative color value of the third fully expanded leaf to the first fully expanded leaf

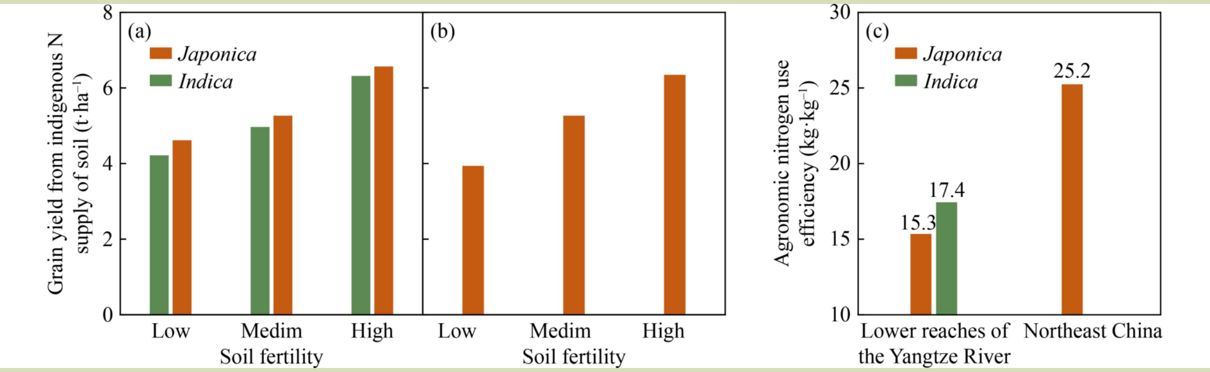


**Fig. 3** Grain yield from indigenous nitrogen supply of soil in the lower reaches of the Yangtze River (a) and Northeast China (b); agronomic nitrogen use efficiency of rice for the lower reaches of the Yangtze River and Northeast China (c).

from the top of the stem. Adjustments are made to ensure that nitrogen supply aligns with the nitrogen demand of rice plants at these critical stages.

The darkness of leaf color is an important indicator to evaluate plant N status. The SPAD chlorophyll meter has been widely used as a rapid, accurate, and non-destructive tool to evaluate leaf N content and overall plant nitrogen status, thereby guiding fertilizer management[52]. Generally, a fixed threshold of SPAD value has been used across various growth stages for a particular cultivar[52]. However, the SPAD threshold value can differ between rice cultivars, so it needs to be experimental calibration for each cultivar[53]. For example, the thresholds of SPAD value of *japonica* rice cultivars generally greater than that of *indica* cultivars, typically ranging from 37 to 39 for *japonica* and 35 to 37 for *indica* rice, respectively[54]. A SPAD value of ~35 corresponds to a leaf nitrogen content of ~1.4 $\text{g}\cdot\text{m}^{-2}$ N leaf[53]. The recently-bred elite rice cv. Yongyou 2640, has great yield potential compared with existing rice cultivars. In this cultivar, SPAD readings can reach up to 48, corresponding to a leaf nitrogen content of 2.2 $\text{g}\cdot\text{m}^{-2}$ N, with grain yields of 12–13 $\text{t}\cdot\text{ha}^{-1}$ under optimized nitrogen management regimes[31,33]. Also, the accuracy of SPAD-based leaf nitrogen predictions can be influenced by several external factors. Environmental conditions, such as ambient light intensity, and intrinsic leaf characteristics, including chlorophyll distribution and the proportion of nitrogen allocated to chlorophyll, all impact SPAD readings[55]. These uncertainties necessitate further refinement of SPAD-based diagnostic methods.

Alternatively, plant N status of a plant can be evaluated by examining the spatial distribution of N within the canopy[31]. In situations where N is limited, plants tend to translocate N from older, lower leaves in the canopy to the newer, upper leaves. This process creates a steeper nitrogen gradient within the canopy, reflecting the plant adaptation to stress and prioritization of young, photosynthetically active leaves. Based on this, we found that the relative SPAD value (RSPAD), calculated by taking the ratio of the SPAD value of the third fully expanded leaf (counting from top to bottom) to the SPAD value of the top fully expanded leaf on the main stem (Fig. 4). This approach accounts for the uneven distribution of nitrogen within the canopy, making it a more accurate for assessing N status than standard SPAD measurements. The RSPAD approach overcome uncertainty due to genetic differences between different cultivars. Therefore, the nitrogen application rate at growth stages of tillering, panicle initiation, and pistil and stamen differentiation can be adjusted by comparing the relative leaf color with the thresholds at different growth stages[3,56].

### 3.2.3 Cultivar

Nitrogen application strategies from panicle initiation to grain filling are tailored to meet the specific requirements of rice cultivars with varying panicle sizes (Table 3). Rice cultivars can be classified by their panicle sizes and the nitrogen strategy needs to be adjusted accordingly[28]. For rice cultivars with smaller panicle sizes (⩽ 130 spikelets per panicle), a flower-promoting fertilizer is recommended to enhance the early development of spikelets, thereby increasing the potential grain yield. Conversely, for cultivars with larger panicles (⩾ 160

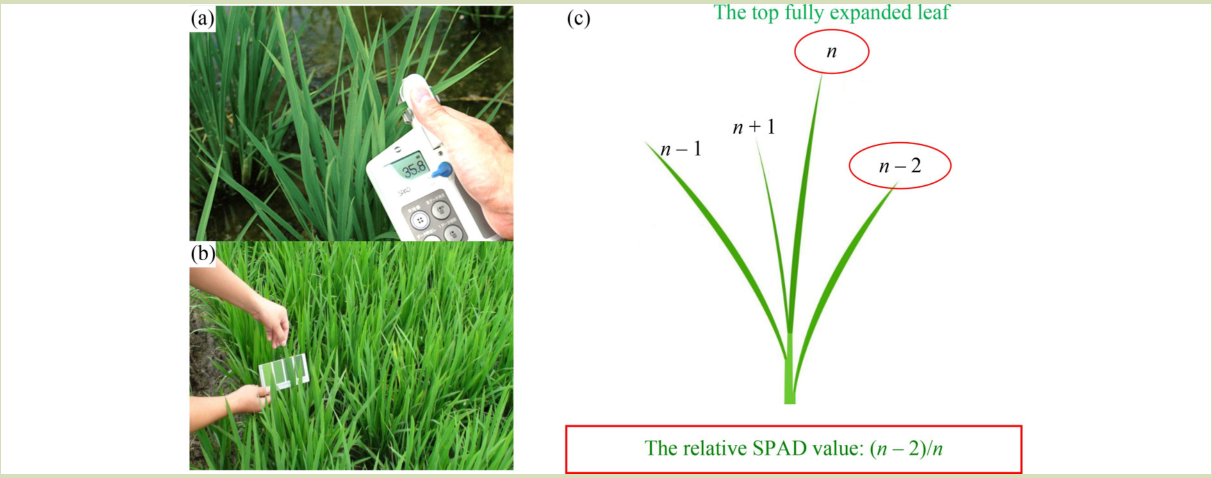


**Fig. 4** Schematic illustrating how to calculate the relative SPAD value (RSPAD) based on SPAD chlorophyll meter (a) or leaf color chart (b), and the RSPAD was calculated as the ratio of the SPAD value of the third fully expanded leaf (counted from top to bottom, $n - 2$) *vs.* the value of the top fully expanded leaf of the main stem (c). Leaf number $n$ refers to the emergence order of leaves.

**Table 3 Topdressing with N fertilizer for panicle development and grain filling based on the rice cultivars differing in panicle sizes**

| N fertilizer | Growth stage | RSPAD value | Percentage of total N rate (%) | | |
|---|---|---|---|---|---|
| | | | Large-panicle cultivar (Spikelets $\geqslant 160$) | Small-panicle cultivar (Spikelets $\leqslant 130$) | Medium-panicle cultivar ($130 <$ Spikelets $< 160$) |
| Flower-promoting fertilizer | Panicle initiation | $\mathrm{RSPAD} > 1$ | 0 | 25 | 15 |
| | | $1 \geqslant \mathrm{RSPAD} > 0.9$ | 5 | 30 | 20 |
| | | $\mathrm{RSPAD} \leqslant 0.9$ | 10 | 35 | 25 |
| Flower-protecting fertilizer | Pistil and stamen differentiation | $\mathrm{RSPAD} > 1$ | 25 | 0 | 10 |
| | | $1 \geqslant \mathrm{RSPAD} > 0.9$ | 35 | 10 | 20 |
| | | $\mathrm{RSPAD} \leqslant 0.9$ | 40 | 15 | 25 |
| Grain filling-promoting fertilizer | Grain filling | $\mathrm{RSPAD} > 0.95$ | 0 | 0 | 0 |
| | | $\mathrm{RSPAD} \leqslant 0.95$ | 5 | 0 | 0 |

spikelets per panicle), a flower-protecting fertilizer is used to avoid spikelet degeneration, which helps to sustain increased grain yields. For rice cultivars with medium-sized panicles (130–160 spikelets per panicle), either flower-promoting or flower-protecting fertilizers can be applied, depending on the specific growth characteristics of the cultivar and the prevailing environmental conditions. This N application strategies allow for more precise and effective management of crop nutrition, ensuring that N supply is aligned with the spikelet development to produce increased yields under varying conditions[28].

Compared to the standard methods of nitrogen application used by Chinese farmers, the three-criteria nitrogen application provided a marked increase in grain yield, HI and NUE. These advancements are strongly correlated with improvements in key physiological traits, including the grain-leaf ratio, sugar-spikelet ratio and the proportion of productive tillers[4]. By optimizing N application in rice based on soil fertility, leaf color and cultivar, this innovative approach promotes improved nutrient use and enhances the overall performance of the rice crop.

## 3.3 Water-nitrogen coupling regulation technology

The presence of water in the soil significantly influences nitrogen availability and its efficiency in crop production. Soil moisture directly influences key processes such as volatilization, nitrification and urease hydrolysis, which influence the fate of nitrogen in the soil[57]. The availability of nitrate and ammonium to plants is also determined by soil water content, as it alters the aeration status of the soil.

Effective management of soil moisture and nitrogen fertilizer has the potential to enhance crop growth, yield, WUE and NUE through a synergistic effect[2]. For example, by adopting AWMD irrigation along with a moderate N rate (200 $\mathrm{kg \cdot ha^{-1}}$ N), synergistic water-N effects can be achieved, promoting improved plant performance[30]. Also, combining site-specific nitrogen management (SSNM) with AWMD irrigation, known as SSNM-AWMD, has been shown to significantly improve grain yield, NUE and WUE compared to using SSNM or AWMD irrigation alone[32,58].

To quantitatively reveal the interactive/synergistic effects of water ($W$) and nitrogen fertilizer ($N$) on yield ($Y$), experiments were conducted at various levels of soil moisture and nitrogen rates, and data was collected and fitted to a mathematic equation $Y = y_0 + aW + bN + cW^2 + dN^2 + eWN$, where $y_0$ is the residual yield and $a$, $b$, $c$, $d$ and $e$ are model coefficients.

Once the quantitative relationship was built, the optimal nitrogen content for plants could be determined based on specific soil water potential, and the ideal soil water potential can be calculated for a given plant nitrogen content. In Fig. 5, we illustrate the quantitative relationship between plant nitrogen content and soil water potential for *japonica* rice cv. Wuyunjing 24. For example, at mid-tillering, when soil water potential at soil depth of 15–20 cm was 0, –10, –20, –30 and –40 kPa, the optimal plant nitrogen content was 2.97%, 2.94%, 2.91%, 2.87%, and 2.84%, respectively (Table 4).

Based on the relationships between soil water potential and soil water table level, and the relationships between RSPAD and plant N status, the soil water table level and RSPAD could be used as indicators to guide irrigation and topdressing of N to achieve increased grain yield, WUE and NUE.

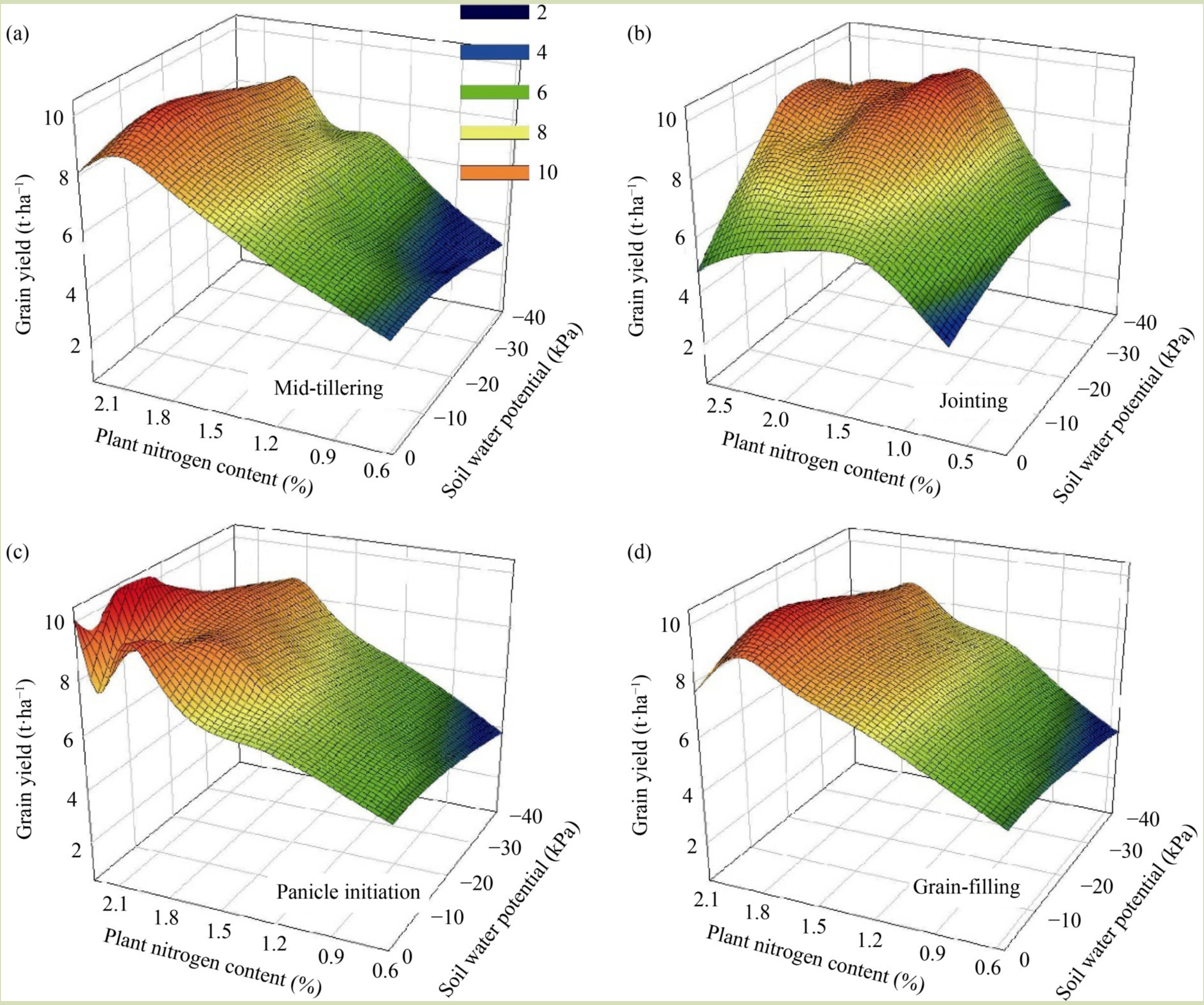


**Fig. 5** Relationship between plant nitrogen content, soil water potential and their effects on grain yield of *japonica* rice cv. Wuyunjing 24 at (a) mid-tillering, (b) jointing, (c) panicle initiation, and (d) grain-filling stages.

**Table 4 Optimum nitrogen content (%) of rice plants under different soil water potentials**

| Growth stage | Soil water potential (kPa) | | | | |
|---|---|---|---|---|---|
| | 0 | –10 | –20 | –30 | –40 |
| Mid-tillering | 2.97 | 2.94 | 2.91 | 2.87 | 2.84 |
| Jointing | 1.88 | 1.97 | 2.06 | 2.15 | 2.23 |
| Panicle initiation | 2.47 | 2.51 | 2.56 | 2.60 | 2.65 |
| Grain filling | 1.87 | 1.76 | 1.65 | 1.54 | 1.44 |

## 4 Implement of green technology in rice production to increase yield and resource use efficiency

The innovative water and N management techniques, such as AWMD, the three-criteria nitrogen application, and the water-nitrogen coupling regulation have significantly enhanced grain yield, HI, WUE and NUE[3,9]. These improvements are closely linked to increases in the grain-to-leaf ratio, sugar-to-spikelet ratio and the proportion of productive tillers, resulting in optimized source-sink relationships. Collectively, these methods enhanced leaf photosynthesis, facilitated the remobilization of pre-stored NSCs from stems during grain filling, improved canopy structure and root development, accelerated endosperm cell division, and enhanced grain filling (Fig. 6).

These innovative technologies have been demonstrated in rice production on a large scale in the regions including Anhui, Heilongjiang, Hubei, Jiangsu, Jilin, Sichuan, and Shanghai, contributing greatly to green rice production in China (Fig. 7). In 2021–2022, these technologies were applied across a total area of 10.3 Mha in these areas, resulting in 9.3% increase in yield, 27% improvement in NUE, and 35% increase in WUE. These advancements resulted in substantial economic returns equivalent to 2.2 billion USD.

Innovative technologies developed in recent years have achieved substantial success, particularly in single-season rice-growing areas, especially in the lower reaches of the Yangtze River. However, other green technologies have also been proven successful in different rice-growing areas, either within China or internationally in recent decades. These technologies include fertilizer application based on soil testing[59], site-specific nitrogen management[53], precise and quantitative fertilization technology[60], three control N application technology[61], the ratoon rice system[62], side-deep fertilization[63], and integrated soil-crop system management[64]. These green technologies have made great contribution to rice production. More experiments and demonstrations are needed to investigate whether these technologies can be used in both in China and internationally.

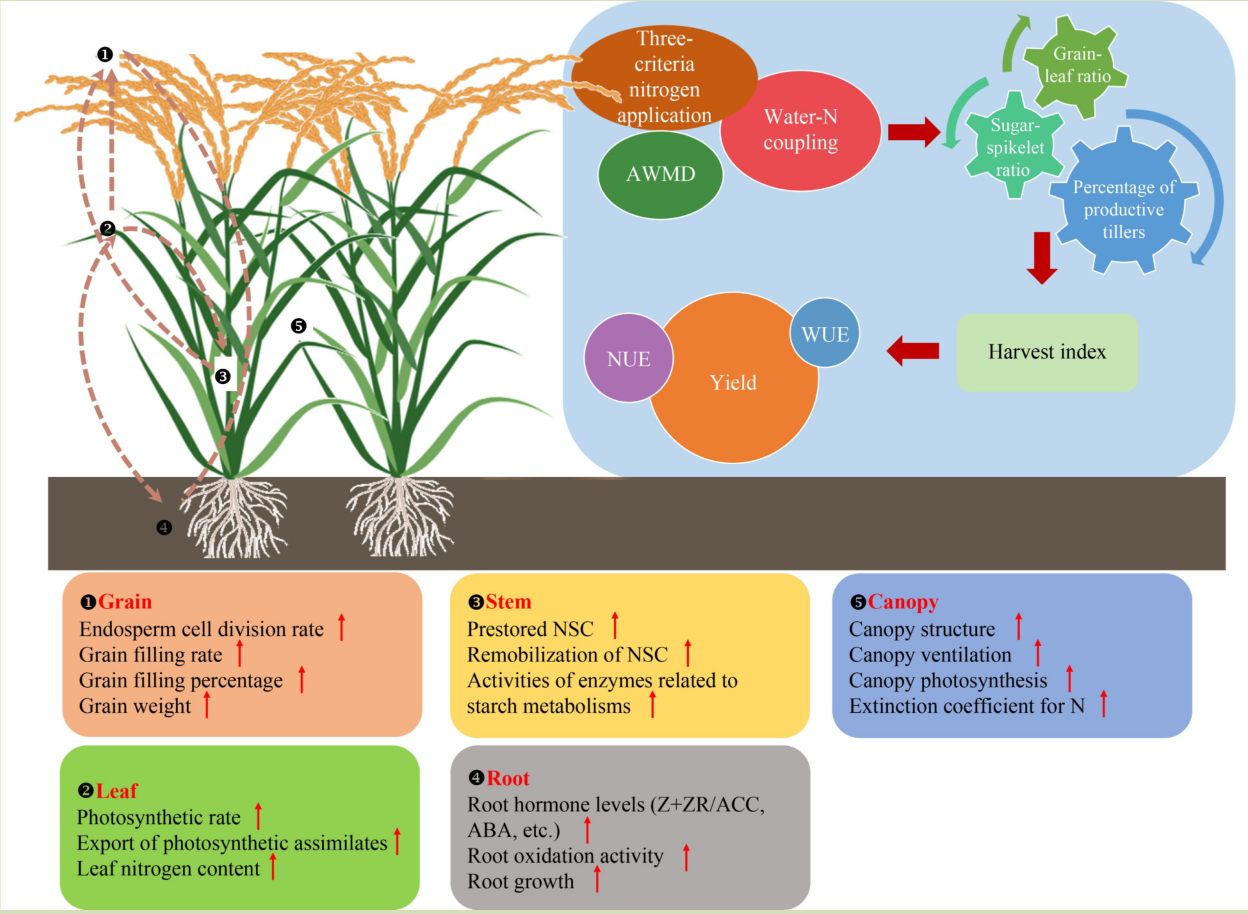


**Fig. 6** Schematic overview of green technologies significantly increase grain yield, water use efficiency (WUE), and nitrogen use efficiency (NUE) and underlying physiological mechanisms. These improvements are closely associated with increases in the grain-leaf ratio, sugar-spikelet ratio and proportion of productive tillers, which increased harvest index (HI) and contributed to increased yield, NUE and WUE. These green technologies improve physiological traits related to the leaf, stem, grain root and canopy.

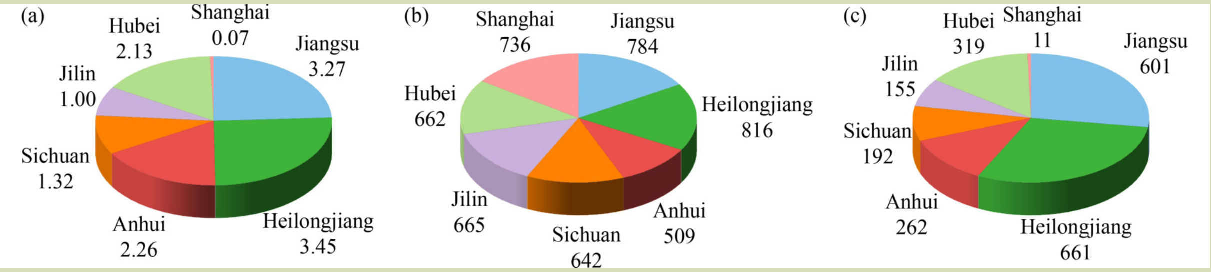


**Fig. 7** Implement of green technologies in Anhui, Heilongjiang, Hubei, Jiangsu, Jilin, Sichuan, and Shanghai, China in 2021–2022. (a) The total extension area ($10^6$ ha) of green technologies in 2021–2022; (b) the average increase of rice yield ($kg \cdot ha^{-1}$) by adopting green technologies; and (c) the total economic benefits (million USD) by adopting green technologies in 2021–2022.

## 5 Conclusions and prospects

Grain yield, nutrient use efficiency and WUE in rice could be simultaneously improved by enhancing HI. Increases in the grain-leaf ratio, sugar-spikelet ratio at the heading time, and the proportion of productive tillers, contributes to a greater HI. AWMD irrigation, three-criteria nitrogen application and water-nitrogen coupling regulation technology are important approaches or techniques to increase HI, and great progresses have been achieved to increased grain yield, nutrient use efficiency and WUE. Further studies are needed to reduce greenhouse gas emissions in rice production to meet the net-zero target, develop data-driven intelligent technologies (or so-called smart agriculture) and simplify agronomic practices to make the production process more efficient and sustainable while reducing the need for labor and other resources.

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### Compliance with ethics guidelines

Junfei Gu, Xianlong Peng, Shiwei Guo, Jianwei Lu, Xiaojun Shi, Yixiang Sun, and Jianchang Yang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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