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The tradeoff between increasing productivity and environmental sustainability in super hybrid rice breeding



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Super hybrid rice has significantly enhanced agricultural productivity in China, yet its environmental sustainability implications remain poorly understood. Using the food-carbon-nitrogen-energy-profit (FCNEP) framework, we evaluated five elite varieties (LYPJ, YLY1, YLY2, YLY900, XYL900) cultivated between 1999 and 2017. Field experiments were conducted from 2015 to 2017 across four provinces (Hubei, Hunan, Henan, and Jiangxi Province) in central China under four nitrogen treatments (0, 210, 300, 390 kg N/ha). Our findings reveal that while variety evolution boosted yields and reduced energy footprints (EFs), it also resulted in an increase in the nitrogen and carbon footprint (CF). Compared with LYPJ, newer varieties increased yields by 15.0–21.7% and net profits by 25.9–40.3%, while reducing energy footprints by 16.3–22.7%. However, nitrogen and carbon footprints rose by 8.0–34.5% and 31.0–76.6%, respectively. The composite sustainability score, derived from the FCNEP framework, indicated an initial improvement in sustainability during the early breeding stages of super hybrid rice. However, as breeding advanced, the sustainability score showed a subsequent decline. This study underscores the trade-off between enhancing productivity and maintaining environmental sustainability in superhybrid rice breeding. Future super hybrid rice breeding initiatives should prioritize balancing yield improvements with environmental considerations to promote sustainable agricultural development.

Rice (*Oryza sativa* L.) is a primary food source for half of the world's population, contributing to >20% of global calorie consumption¹. In 2021, global milled rice consumption reached 512 million tons, with China accounting for 32% of the total². However, food security faces major challenges because of a growing global population coupled with declining agricultural productivity caused by extreme weather events such as heat, drought, and waterlogging^{3–5}. Despite these challenges, China has managed to maintain its food security, a feat largely attributable to the rapid development of the super hybrid rice breeding programs and industry^{6,7}.

To meet the self-sufficiency of food supply, a national program on super rice breeding was established in China in 1996. This project was divided into four phases, each with a specific yield target: 10.5 t ha⁻¹ (phase I, 1996–2000), 12 t ha⁻¹ (phase II, 2001–2005), 13.5 t ha⁻¹ (phase III,

2006–2015), and 15 t ha⁻¹ (phase IV, 2016–2020)⁷. Professor Longping Yuan, known as the father of hybrid rice, proposed the ideotype for super hybrid rice, which features a tall erect-leaf canopy, lower panicle position, and greater panicle size⁷. Over the recent decades, significant progress has been made in developing super hybrid rice breeding projects through morphological improvement and the use of inter-subspecific (indica/japonica) heterosis. The yield potential of many super hybrid rice varieties has been consistently surpassed, setting new yield records under optimal management conditions. For example, Liangyoupeijiu achieved a grain yield (GY) of 10.5 t ha⁻¹ at Changsha, Hunan Province, China in 2000; in 2004, Y-liangyou 1 achieved a GY of 12.0 t ha⁻¹ at Longhui, Hunan Province; in 2011, Y-liangyou 2 reached a GY of 13.9 t ha⁻¹ at Longhui, Hunan Province; in 2014, Y-liangyou 900 set a yield record of 15.4 t ha⁻¹ at Xupu, Hunan

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Province^{6,7}. After the yield targets of the first four phases of super rice were achieved, the fifth phase of super hybrid rice high-yield research project was proposed in 2015, with a yield target of 16 t ha⁻¹. As the pioneer super hybrid rice variety, Xiangliangyou 900 achieved a yield record of 16 t ha⁻¹ at Gejiu, Yunnan Province in 2017⁷. The evolution of rice yield potential over these years reflects a continual integration of novel traits aimed at achieving high yields.

While the continuous record-breaking yields of super hybrid rice are impressive, it is important to note that these achievements often come with significant trade-offs. Super hybrid rice often requires increased use of fertilizers and water resources to show higher yield potential⁸. However, excessive fertilizer use not only increases agricultural production costs but also has potential adverse environmental impacts, such as excessive nutrient loss or eutrophication, biodiversity loss, or heightened greenhouse gas emissions^{9–11}. In addition, the significant water consumption for agriculture can worsen the strain on groundwater and water resources, creating difficulties for sustainable agriculture and ecological equilibrium¹². However, to the best of our knowledge, no study has yet examined the environmental sustainability of representative super hybrid rice varieties used in the five phases under different agricultural management. Understanding the environmental impacts of these high-yielding varieties is crucial for guiding super hybrid rice breeding and developing sustainable agricultural strategies that balance productivity with environmental conservation.

In recent years, the agricultural ecological footprint has gained significant attention as a measure of the sustainability of agriculture^{13,14}. Many studies have adopted various ecological footprint indicators, such as CF, nitrogen footprint, and EF, to evaluate the impact of agricultural production on the environment^{15–17}. The CF of a crop encompasses the carbon emissions and environmental impacts generated by its production practices throughout the growing season¹⁸. In recent years, China's agricultural production technologies, including the use of fertilizers and pesticides, have not only led to greenhouse gas emissions after application in the fields but also generated significant amounts of greenhouse gases during their upstream production processes¹⁹. Furthermore, the development of agricultural machinery and increasingly sophisticated irrigation techniques have also contributed to high carbon emissions due to their reliance on fossil fuels²⁰. Nitrogen Footprint (NF), is an indicator that represents the total amount of reactive nitrogen (Nr) lost to the environment as a result of human activities²¹. Xue et al.²² studied the N₂O emissions of the double-cropping rice planting system in southern China and found that NH₃ volatilization is the main pathway for nitrogen fertilizer production. They concluded that reducing fertilizer inputs and improving the efficiency of agricultural inputs are effective ways to reduce nitrogen emissions. In the process of agricultural production, activities such as cultivation, irrigation, fertilization, operation of agricultural machinery, harvesting, and transportation all involve the input and output of energy^{23,24}. These activities reflect both the utilization of energy resources and the impact on the environment. These indicators provide objective measures of the environmental impact of agricultural production. Incorporating life cycle assessment (LCA) to calculate ecological footprints in agricultural production processes is currently one of the most effective approaches^{5,24–27}. By considering these indicators comprehensively, a more complete evaluation of agriculture's impact on the environment can be achieved.

Here, we leverage a comprehensive 3-year field experiment dataset that encompasses extensive details on GY, yield components, greenhouse gas emissions, resource use efficiency, etc. We then conducted a comprehensive assessment of the agricultural sustainability of super rice varieties developed between 1999 and 2017 using a framework based on the food-carbon-nitrogen-energy-profit (FCNEP) nexus to evaluate and assess whether the advancements in super rice breeding are consistent with agricultural sustainability. The objectives are to (1) evaluate the yield performance and resource use efficiency of super rice varieties under different nitrogen management; (2) assess how food production and carbon, nitrogen, EF, and profit change across five-phase super hybrid rice varieties at four sites under different nitrogen treatments; and (3) offer insights for optimizing breeding

strategies and agricultural practices to ensure a harmonious balance between yield enhancement and environmental preservation.

Methods

Experimental site and test material

Field experiments were conducted across central China from 2015 to 2017, with the locations of each experimental site shown in Supplementary Fig. 1. These sites experience hot summers and cool/cold winters, differing notably in growing season rainfall and solar radiation. Throughout the rice growing season (April to October), temperatures range from 12.3°C to 35.1°C. Hunan Province receives an average annual growing season solar radiation of 2738.5 MJ m⁻², compared with 3057.9 MJ m⁻² in Hubei Province, 3144.6 MJ m⁻² in Jiangxi Province, and 2683.3 MJ m⁻² in Henan Province. Annual total rainfall averages 1096.1 mm in Hunan Province, 967.9 mm in Hubei Province, 1412.2 mm in Jiangxi Province, and 1488.3 mm in Henan Province. Detailed soil properties in the upper 20 cm at each experimental site are provided in Supplementary Table 1.

Experimental design

The experimental design comprised four nitrogen fertilizer treatments: 0 kg ha⁻¹ (N1), 210 kg ha⁻¹ (N2), 300 kg ha⁻¹ (N3), and 390 kg ha⁻¹ (N4). Five representative varieties from different phases were used: Liangyoupeijiu (LYPJ), Y-liangyou 1 (YLY1), Y-liangyou 2 (YLY2), Y-liangyou 900 (YLY900), and Xiangliangyou 900 (XLY900). Details of these test varieties can be found in Supplementary Table 2. The experiment followed a split-plot design, with nitrogen fertilizer treatments as the main plot and varieties as the subplots. Each plot measured 30 m² and was replicated three times. Urea (46%), calcium superphosphate (12%), and potassium chloride (60%) were used as fertilizers. On the day before transplantation, phosphorus (N2: 58 kg ha⁻¹, N3: 83 kg ha⁻¹, and N4: 108 kg ha⁻¹) was applied to all subplots. Potassium (N2: 12 kg ha⁻¹, N3: 17 kg ha⁻¹, and N4: 19 kg ha⁻¹) was evenly distributed across the basal and panicle initiation stages.

The nitrogen application ratio for base, tiller, and panicle initiation stages was 5:2:3. Base fertilizer was applied one day before transplanting, tiller fertilizer 5–7 days after transplanting, and panicle initiation fertilizer during early panicle initiation. Phosphorus fertilizer was applied as basal once, while potassium fertilizer was split into two applications: the first before transplanting and the second during panicle initiation.

Pre-germinated seeds were carefully sown in designated seedbeds. After 28–35 days of nurturing, healthy seedlings were meticulously transplanted into field plots at a density of 20 cm × 20 cm. To optimize growth conditions, diligent field management practices were implemented: systematic drainage and sun-drying were conducted when the tiller count reached ~85% of the expected panicle yield. Additionally, the controlled alternation between wet and dry conditions was maintained from jointing to maturity stages. Throughout the crop's growth cycle, chemical treatments were applied to effectively manage insect pests and diseases. Cultivation protocols were consistently applied across all locations and years to ensure reliable and uniform results.

Measurement of nitrogen use efficiency and GY

At maturity, 12 plants were selected from each plot, with three replicates per treatment. These plants were harvested and transported to the laboratory, where their roots were carefully removed. The harvested rice material was then separated into stems, leaves, and spikes, and placed in labeled paper bags. To ensure accurate measurements, the bags were heat-treated at 105 °C for 15 mins and subsequently dried at 80°C until a constant weight was achieved.

GY was assessed within a 5 m² area per plot and adjusted to a standard water content of 0.14 g H₂O g⁻¹. Additionally, we sampled the 12 diagonal hills within this area to examine traits including panicle number, spikelets per panicle, grain filling rate, and 1000-grain weight. Nitrogen agronomic efficiency (AE_N) was calculated using the ratio of GY increase to nitrogen application²⁸.

Measurement of Leaf photosynthetic characteristics

The Leaf photosynthetic characteristics were assessed at 10:00–13:00 at the heading stage. The measurements were conducted using the LI6400XT portable photosynthesis system (LI-COR Environmental, Lincoln, NE, USA) equipped with a Leaf Chamber Fluorometer (6400-40, LI-COR, USA), which served as the light source²⁹. During the assessment, environmental conditions were maintained at a temperature of 25°C, photosynthetically active radiation (PAR) of 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$, and ambient CO_2 levels of 400 $\mu\text{mol mol}^{-1}$. Using this setup, four photosynthetic parameters were evaluated, including net photosynthetic rate (Pn), intercellular CO_2 concentration (Ci), stomatal conductance (Gs), and transpiration rate (Tr).

CH₄ and N₂O sampling and measurement

In 2016 and 2017, CH₄ and N₂O gas samples were collected using a static closed chamber method³⁰. Chambers of two different sizes were used throughout the rice growth: smaller chambers (60 cm × 60 cm × 80 cm) until the seedlings reached 80 cm in height, and larger chambers (60 cm × 60 cm × 120 cm) thereafter. Gas samples were collected between 9:00 and 11:00, and 14:00 and 17:00 each day. As our focus was on the effects of different rice varieties on CH₄ and N₂O emissions, we started measurements 25 days after transplantation, when tillers were mostly above the soil surface. These measurements were taken from the tillering stage to maturity. CH₄ and N₂O concentrations were analyzed using a gas chromatography system (GC 2010 Plus, Shimadzu, Japan) equipped with a flame ionization detector (FID) and electron capture detector (ECD). The column and FID temperatures were held at 55 °C and 200 °C, respectively, while the oven and ECD were maintained at 35°C and 300°C. Cumulative CH₄ and N₂O emissions were calculated based on the averages of emissions between consecutive measurements³¹.

$$F = \rho \times h \times \frac{\Delta C}{\Delta t} \times 273 / (273 + T) \quad (1)$$

$$CE = \sum [(F_n + F_{n+1}) / 2 \times 24 \times t] \quad (2)$$

The greenhouse gas emission rate (F) for N₂O ($\text{g m}^{-2} \text{h}^{-1}$) and CH₄ ($\text{mg m}^{-2} \text{h}^{-1}$) is calculated using the static chamber method. The equation accounts for gas density in the standard state (ρ : N₂O, 1.964 kg m^{-3} ; CH₄, 0.714 kg m^{-3}), chamber height (h), the change in gas concentration over time ($\Delta C / \Delta t$, $\text{mg m}^{-2} \text{h}^{-1}$), and the mean air temperature inside the chamber (T , °C). Seasonal emissions (CE , kg ha^{-1}) are obtained by summing the emission rates (F) between consecutive sampling days (F_n and F_{n+1}) timed at intervals of t (days). The N₂O and CH₄ emission flux at different growth stage of five-phase rice varieties can be seen in Supplementary Figs. 2 and 3.

Calculation of CF of rice production. To assess the potential global warming impact of CH₄ and N₂O emissions, we calculated the global warming potential (GWP) per unit area. The GWP values for CH₄ and N₂O, relative to CO₂, are 25 and 298 over a 100-year period^{32,33}. We then determined the greenhouse gas intensity (GHGI, $\text{kg CO}_2\text{-eq t}^{-1}$), which represents the CF per unit GY. GHGI is calculated by dividing the carbon equivalent emissions (CF, $\text{kg CO}_2\text{-eq ha}^{-1}$) by the GY. The mean and total N₂O and CH₄ emission flux of five-phase rice varieties can be seen in Supplementary Figs. 4 and 5. This metric is useful for evaluating the efficiency of rice production systems^{17,34}.

$$CF = 25 \times CE_{\text{N}_2\text{O}} + 298 \times CE_{\text{CH}_4} \quad (3)$$

$$\text{GHGI} = CF / \text{Grain yield} \quad (4)$$

Nitrogen footprint calculation of rice production. This study assessed the eutrophication potential, which represents the release of eutrophication substances into different ecosystems. We also evaluated the impact of nitrogen losses and emissions on the rice production process, following the ISO 14044 guidelines³⁵. We quantified the nitrogen footprint on the

farm (NF) and the nitrogen footprint intensity (NFI) using Eqs. 5 and 6, respectively. These equations provide an estimate of the nitrogen impact associated with rice cultivation:

$$NF = NE_{\text{inputs}} + EV_{\text{NH}_3} + EV_{\text{N}_2\text{O}} + NL_{\text{NO}_3^-} + NL_{\text{NH}_4^+} \quad (5)$$

$$NFI = NF / \text{Grain yield} \quad (6)$$

NE_{inputs} accounts for nitrogen losses attributed to agricultural inputs. We calculated this by multiplying the actual usage of various inputs by their respective emission factors (see Supplementary Table 3). To capture variety-specific nitrogen emissions, we established a coefficient that considers the average N₂O emission flux and rice growth duration of each variety (Supplementary Fig. 4).

Calculation of EF of rice production. Rice production requires energy input from eight main components, including irrigation water, machinery, diesel, electricity, labor, seeds, fertilizers, and pesticides²⁴. The energy output is determined by the amount of rice grains and straw produced. We convert the quantities of input materials and output products into energy units using established energy equivalents²³ (see Supplementary Table 4). The total energy input is obtained by summing the energies of all inputs, while the total energy output sums up the energies of all outputs. To assess energy performance, we calculate the net energy and energy use efficiency. Additionally, we determine the EF of rice production using the following equations^{23,36,37}:

$$\text{Net energy} = \text{Energy out} - \text{Energy input} \quad (7)$$

$$EF = \text{Energy input} / \text{yield} \quad (8)$$

Calculation of net economic benefits of rice production. The costs involved in this study encompass the total agricultural input expenses. To calculate the unit cost of agricultural input ($\text{\$ ha}^{-1}$), we multiply the quantities of different agricultural inputs (including land leasing fees, fertilizers, pesticides, labor, machinery, seeds, etc.) by their respective market prices ($\text{\$ unit}^{-1}$). On the other hand, to determine the income ($\text{\$ ha}^{-1}$), we multiply the total GY of the rice system by the corresponding current market price. It is important to note that in this experiment, we assume that all cultivation management practices remain consistent across different years and sites. To analyze the economic performance of rice, we utilize the unit prices of various inputs and outputs (Supplementary Table 5). The calculation methods for net profit (NP) as follows:

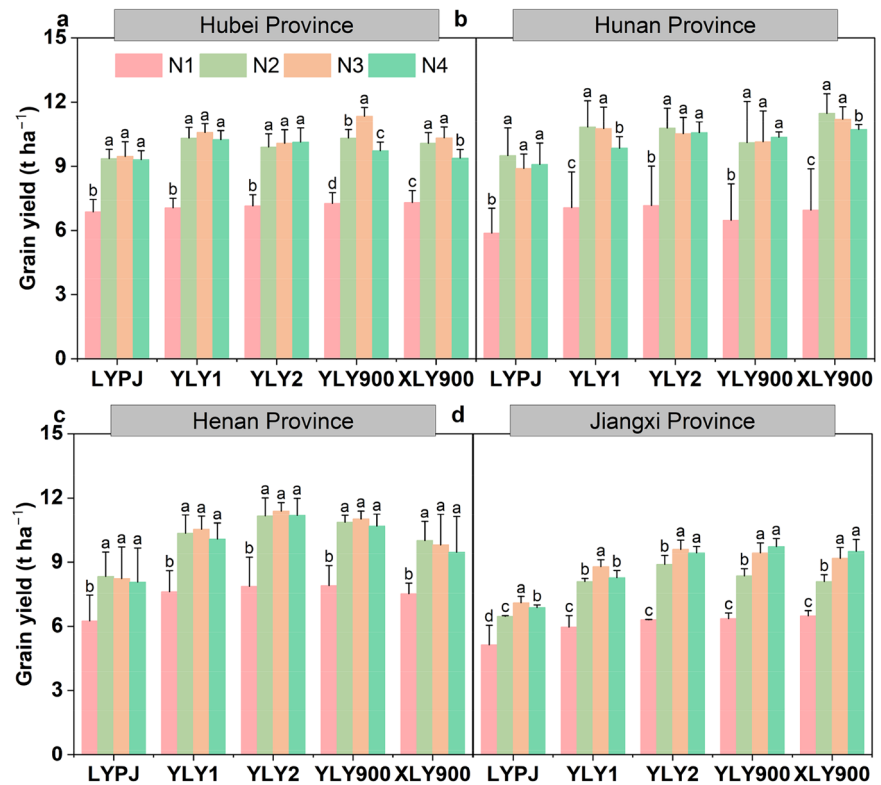
$$\text{Net profit} = \text{Income} - \text{Costs} \quad (9)$$

Rice production system sustainability assessment framework. To assess rice production's sustainability, we evaluated four key domains: CF, nitrogen footprint, EF, and NP. We developed a composite sustainability score using the FCNEP nexus framework from recent research^{14,38,39}. To ensure fair comparisons, we standardized the various metrics by transforming them into a uniform scale from 0 to 100. We aimed for smaller ecological footprints and higher profitability. The ecological footprint and NP were normalized using separate minimum-maximum scaling techniques. The sustainability score was then calculated as the average of these four standardized metrics, each assigned an equal weight. Additionally, we generated an evenness score (ES) using the same normalized indicators, as described in previous studies^{14,40,41}.

$$S_{\text{CNE}} = \frac{S_{\text{max}} - S_i}{S_{\text{max}} - S_{\text{min}}} \quad (10)$$

$$S_{\text{FP}} = \frac{S_i - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \quad (11)$$

Fig. 1 | Grain yield of five super rice varieties across four provinces in China. a Hubei Province, **b** Hunan Province, **c** Henan Province, and **d** Jiangxi Province. The data represent the average values over 3 years (2015–2017). Vertical bars indicate standard deviations ($n = 9$). Means within each variety that share the same letter are not significantly different according to the LSD test (0.05).



$$S_{FCNEP} = (S_F + S_C + S_N + S_E + S_P)/5 \quad (12)$$

$$ES = \frac{A_i}{\pi \times (L_i/2\pi)^2} \times 100 \quad (13)$$

$$L_i = 2|r_{\max} - r_{\min}| + \sum_{i=1}^n 2\pi w_i r_i \quad (14)$$

$$A_i = \sum_{i=1}^n \pi w_i r_i^2 \quad (15)$$

In this study, the normalized values for carbon, nitrogen, energy, food production, and NP are symbolized by S_{CNE} and S_{FP} , respectively. The upper and lower limits for each indicator are designated as S_{\max} and S_{\min} . The overall sustainability score, denoted as S_{FCNEP} , ranges from 0 to 100. The ES of the radar chart is calculated as the proportion of the total area encompassed by its five indicators to the area of a circle with a perimeter equivalent to L_i , which signifies the most uniform distribution of indicators. The ES scale, which spans from 0 to 100, diminishes as the disparities among the five indicators increase. The weight assigned to each indicator is represented by w_i , set at 1/5. The value for each indicator is expressed as $2\pi w_i r_i$.

Data analysis

Field experiment data were analyzed using Microsoft Excel 2020, Origin 2024 Pro for data processing and visualization, and ArcGIS Pro 10.5 for geographic information analysis. Statistical analyses were performed using SPSS Version 26.0, including analysis of variance (ANOVA) with a 0.05 significance level. Least significant difference (LSD) post-hoc tests were also applied.

Results

GY of super hybrid rice varieties

The GY of the super hybrid rice varieties was significantly influenced by environmental conditions, management practices, and their interaction (Fig. 1; Tables 1 and 2). Notably, the average GY in 2015 was substantially

higher than in 2016 and 2017. Significant differences in GY were observed across the experimental sites, with the lowest average yield recorded in Jiangxi Province (Fig. 1; Table 1). In contrast, GYs among the other sites did not differ significantly.

Compared to LYPJ, the average GYs of YLY1, YLY2, YLY900, and XLY900 were higher by 15.0%, 20.8%, 21.6%, and 21.7%, respectively. Nitrogen treatments had a marked impact on GY, with different varieties exhibiting varied responses (Table 2). The highest GYs for LYPJ, YLY1, YLY2, YLY900, and XLY900 were achieved under the N3 treatment, with yields of 8.6, 10.1, 10.5, 10.5, and 10.6 t ha⁻¹, respectively. For LYPJ, no significant yield differences were found among the N2, N3, and N4 treatments. Similarly, YLY1 exhibited no significant yield differences between the N2 and N4 treatments. For YLY2, YLY900, and XLY900, the average GYs under the N3 and N4 treatments were not significantly different.

GY components of super hybrid rice varieties

Tables 1 and 2 highlight significant variations in panicles number, spikelets per panicle, and grain filling across different years, sites, nitrogen and varieties. In contrast, the average 1000-grain weight remained consistent across various years and nitrogen treatments, showing no significant changes.

Under the N4 treatment, all varieties reached their peak panicles number. Compared to the N1 treatment, the average panicles number increased by 34.5%, 44.8%, and 51.6% under the N2, N3, and N4 treatments, respectively. The highest number of spikelets per panicle for LYPJ, YLY1, and YLY2 was observed under the N3 treatment, whereas YLY900 and XLY900 exhibited their maximum spikelets per panicle under the N2 treatment. The grain filling rate was significantly influenced by nitrogen application. All varieties, except YLY2, achieved their highest grain filling rates under the N2 treatment, while YLY2 reached its peak rate under the N1 treatment. In contrast, nitrogen application did not have a significant effect on the 1000-grain weight of any of the rice varieties.

In terms of overall performance, the highest average panicles number (212.8 panicles/m²) and grain filling rate (82.6%) were recorded in 2015, significantly exceeding those observed in 2016 and 2017. Conversely, the

Table 1 | The panicles number (P), spikelets per panicle (SP), grain filling (GF), and grain weight (GW) of five super rice varieties averaged in three years (2015–2017), four sites, five varieties, and four nitrogen treatments

Variety	Nitrogen	P (m ⁻²)	SP	GF (%)	GW (mg)
LYPJ	N1	173.4c	173.6b	75.5ab	25.5a
	N2	237.9b	185.3a	76.4a	26.0a
	N3	252.1ab	190.0a	74.6ab	25.9a
	N4	258.9a	186.5a	73.8b	25.5a
YLY1	N1	175.9c	173.4b	84.1ab	25.4a
	N2	225.9b	184.9a	85.0a	26.0a
	N3	242.2a	190.5a	83.6ab	25.8a
	N4	254.4a	187.5a	82.2b	25.1a
YLY2	N1	157.9c	223.9b	84.9a	24.0a
	N2	223.9b	222.5b	83.8a	23.8a
	N3	237.4a	237.5a	81.6b	23.9a
	N4	243.2a	228.4ab	80.6b	24.0a
YLY900	N1	139.6d	258.1b	79.5a	23.4a
	N2	186.9c	288.8a	78.1ab	23.7a
	N3	206.3b	283.4a	77.0ab	23.8a
	N4	222.4a	273.9ab	76.3b	23.7a
XLY900	N1	126.7c	277.8b	80.1a	24.2a
	N2	181.3b	293.2a	81.2a	24.4a
	N3	198.4a	288.7a	79.2a	24.2a
	N4	206.6a	287.4a	71.5b	24.0a
Year	2015	212.8A	231.1A	82.6A	24.9A
	2016	209.4A	224.8B	78.3B	24.9A
	2017	195.0B	239.8A	77.7B	24.4A
Site	Hubei	190.8C	245.2A	76.7C	23.1C
	Hunan	224.5A	221.8C	84.0A	25.8A
	Henan	225.5A	227.1BC	79.9B	24.4B
	Jiangxi	206.5B	233.3B	75.3D	25.4A
Variety	LYPJ	227.5A	184.4D	74.7D	25.8A
	YLY1	222.4A	184.1D	83.4A	26.1A
	YLY2	214.6A	227.9C	82.6A	23.5C
	YLY900	187.1B	276.4B	77.7C	23.7C
	XLY900	177.1C	286.7A	79.2B	24.3B
Nitrogen	N1	155.0D	222.0B	80.6A	24.6A
	N2	208.5C	234.5A	80.8A	24.6A
	N3	224.5B	238.3A	79.1B	25.0A
	N4	235.0A	232.7A	77.6C	24.8A

Means with the same letters in each column are not significantly different according to LSD (0.05).

peak average spikelets per panicle (239.8) occurred in 2017, while the 1000-grain weight remained consistent across the three years. Among the four experimental sites, Henan Province achieved the highest average panicle number (225.5 panicles/m²), significantly surpassing Hubei and Jiangxi Provinces, though it did not differ significantly from Hunan Province. Hubei Province displayed the highest average spikelets per panicle, while Hunan Province recorded the highest average grain filling rate and 1000-grain weight, highlighting notable regional variations.

LYPJ exhibited the highest average panicles number, while XLY900 had the lowest, reflecting a declining trend in panicle numbers with breeding progress. In contrast, spikelets per panicle showed an increasing trend with breeding progress. Compared to LYPJ, the average panicle numbers of

YLY1, YLY2, YLY900, and XLY900 decreased by 2.2%, 5.7%, 17.8%, and 22.2%, respectively, whereas their average spikelets per panicle increased by 0.2%, 23.8%, 50.1%, and 55.7%, respectively. Grain filling rate and 1000-grain weight initially increased but then declined with breeding progress, with YLY1 exhibiting the highest values for both traits. Additionally, higher nitrogen application significantly enhanced panicles number and spikelets per panicle but simultaneously reduced grain filling rate. Its effect on 1000-grain weight, however, remained negligible.

Photosynthetic characteristics of super hybrid rice varieties

Significant variations in net Pn, Ci, Gs, and Tr were observed across genotypes, environment and management (Table 2 and Supplementary Table 6). Despite these differences, physiological responses generally followed consistent trends across Hubei and Hunan Provinces. Nitrogen supplementation notably enhanced Pn, Ci, Gs, and Tr across varieties, although the extent of enhancement varied significantly.

In Hubei Province, YLY1 exhibited its highest Ci under the N2 treatment, while other varieties achieved peak Pn and Ci under N3 treatment. Compared to the N1 treatment, average Pn increased by 10.9%, 19.7%, and 16.8% under the N2, N3, and N4 treatments, respectively. Similarly, average Gs increased by 9.7%, 21.3%, and 25.8%, and average Ci by 14.1%, 19.2%, and 6.4%, respectively. Except for YLY2, which showed its highest Tr under the N4 treatment, LYPJ, YLY1, YLY900, and XLY900 all exhibited peak Tr under the N3 treatment. Across varieties, the average Pn and Ci of the five-phase super rice displayed minimal variation. However, there was an increasing trend in maximum Pn values with breeding progress and across different nitrogen treatments. Compared to LYPJ, Pn of YLY1, YLY2, YLY900, and XLY900 increased by 0.7%, −2.4%, 2.4%, and 3.1%, respectively.

The CF of super hybrid rice varieties

Increasing nitrogen fertilizer significantly enhanced the CF and GHGI of super hybrid rice (Fig. 2). The most notable increases were observed under the N4 treatment, consistently across both Hubei Province and Henan Province regions. In Hubei Province, average CF increased by 38.0%, 52.5%, and 61.2% under the N2, N3, and N4 treatments, respectively, compared with N1 treatment. Similarly, in Henan Province, average CF showed increases of 38.5%, 53.8%, and 63.9% under the N2, N3, and N4 treatments, respectively. GHGI of the five-phase super rice ranged from 0.93 to 3.27 t CO₂-eq t⁻¹ in Hubei Province and from 1.03 to 3.18 t CO₂-eq t⁻¹ in Henan Province. Across both regions, average GHGI increased by 7.7%, 29.3%, and 46.3% under the N2, N3, and N4 treatments, respectively, compared with N1 treatment.

Significant differences in CF and GHGI were observed among the rice varieties, with both metrics generally increasing along the breeding timeline, showing consistent trends in Hubei and Henan provinces. In Hubei Province, compared to LYPJ, the CF of YLY1, YLY2, YLY900, and XLY900 increased by 44.1%, 35.7%, 63.1%, and 82.3%, respectively, while their GHGI rose by 31.5%, 27.9%, 49.6%, and 67.0%. Similarly, in Henan Province, the CF of YLY1, YLY2, YLY900, and XLY900 were 19.3%, 17.6%, 56.3%, and 71.4% higher than that of LYPJ, with corresponding GHGI increases of 4.9%, 1.5%, 42.0%, and 45.0%. Notably, YLY2 demonstrated a substantial reduction in both CF and CEL, bringing its levels comparable to those of LYPJ.

The nitrogen footprint of super hybrid rice varieties

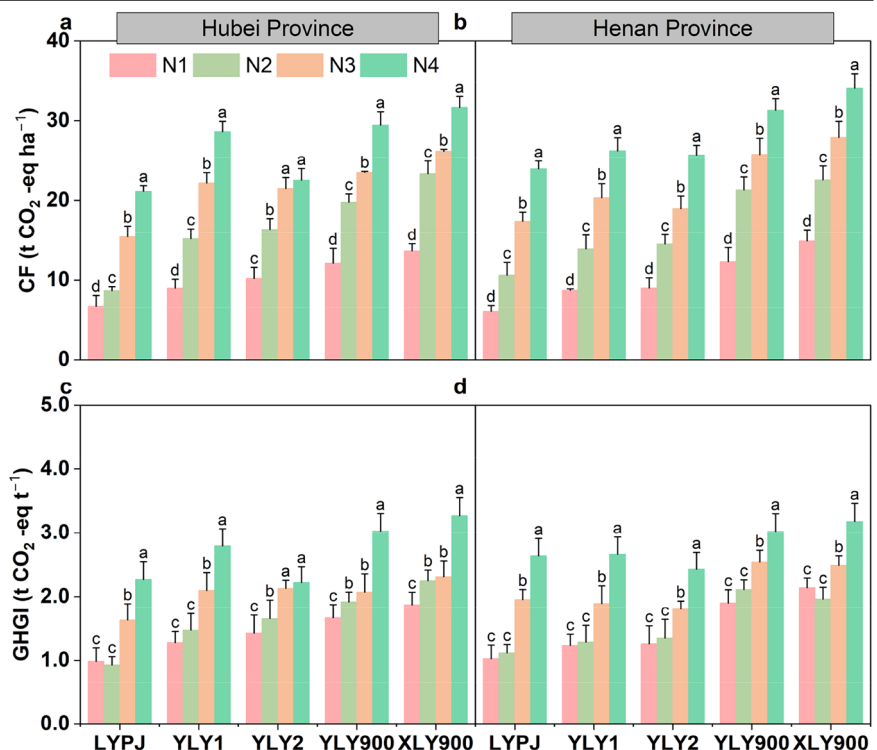
The NF of super hybrid rice varieties showed an increasing trend over different phases (Fig. 3). The nitrogen had significantly increased the nitrogen footprint and NFI of different varieties (Fig. 3). Compared with N2 treatment, the average NF increased by 42.9%, and 85.7% under the N3, and N4 treatments, respectively. The average NFI under the N2, N3, and N4 treatments had increased by 48.9%, 50.8%, and 44.1% than that under N1 treatment. Furthermore, the NF was the lowest in YLY2, Hubei Province, but in LYPJ, Henan Province. Specifically, compared to LYPJ, the average NF of YLY1, YLY2, YLY900 and XLY900 increased by 11.0%, 8.0%, 22.0%

Table 2 | Analysis of variance (ANOVA) of the *F*-values for grain yield (GY), panicles number (P), spikelets per panicle (SP), grain filling (GF), grain weight (GW), net photosynthetic rate (Pn), intercellular CO₂ concentration (Ci), stomatal conductance (Gs), and transpiration rate (Tr) of five super rice varieties

ANOVA	GY	P	SP	GF	GW	Pn	Ci	Gs	Tr
Year (Y)	54.39**	59.24**	25.17**	104.26**	5.78	/	/	/	/
Site (S)	110.06**	155.65**	20.24**	113.85**	45.9**	85.88**	5.86*	220.69**	25.96**
Variety (V)	154.47**	198.61**	635.62**	116.35**	64.08**	6.56**	8.62**	3.49*	2.99
Nitrogen(N)	809.9**	629.27**	16.39**	25.04**	2.03	99.38**	720.01**	47.85**	9.43**
Y × S	22.29**	24.51**	46.95**	28.95**	13.73**	/	/	/	/
Y × V	1.28	1.92	2.83**	11.65**	1.77	/	/	/	/
Y × N	3.37*	3.07*	3.08**	2.24*	1.7	/	/	/	/
S × V	9.9**	7.43**	4.72**	15.96**	4.15**	1.33	2.06	0.01	0.28
S × N	7.92**	11.92**	2.74**	2.66**	2.84**	4.1*	2.38	6.25**	3.95*
V × N	2.2*	1.49	1.4	1.35	3.97**	6.29**	4.04*	3.58*	3.98*
Y × S × V	2.96**	1.49	3.55**	5.11**	1.21	/	/	/	/
Y × S × N	5.76**	3.64**	5.84**	2.85**	1.19	/	/	/	/
Y × V × N	0.81	1.38	1.02	1.05	1.03	/	/	/	/
S × V × N	1.14	1.29	1.42	1.74*	2.77**	85.88**	5.86*	220.69**	25.96**
Y × S × V × N	1.37	1.85	3.6	0.5	0.71	/	/	/	/

**Significant at $p < 0.01$; *Significant at $p < 0.05$.

Fig. 2 | Carbon footprint (CF) and greenhouse gas emission intensity (GHGI) of five super rice varieties in central China. a CF in Hubei Province, **b** CF in Henan Province, **c** GHGI in Hubei Province, and **d** GHGI in Henan Province. The data represent the average values over 3 years (2015–2017). Vertical bars indicate standard deviations ($n = 45$). Means within each variety that share the same letter are not significantly different according to the LSD test (0.05).



and 34.5%, respectively, while the average NFI of YLY1, YLY2, YLY900 and XLY900 increased by −7.1%, −12.1%, −2.1%, and 14.2% respectively.

The EF of super hybrid rice varieties

Five super hybrid rice varieties showed a decreasing trend in EF, and the trend was consistent across the five regions (Fig. 4). Among the varieties, LYPJ had the highest EF and the EF of XLY900 was the lowest. The average energy footprint of LYPJ was 16.3%, 21.5%, 20.1%, and 22.7% higher than YLY1, YLY2, YLY900, and XLY900, respectively. The increased nitrogen fertilizer application greatly

raised the energy footprint for different varieties, and the performance trend was consistent across the five regions. Compared to N1 treatment, the average EF had increased by 48.9%, 76.4%, and 115.9%, respectively.

The NPs of super hybrid rice varieties

There was an upward trend in the NP of super rice across all five locations (Fig. 5), although NP varied significantly across sites and nitrogen treatments. In Hunan and Henan Province, NP remained relatively stable across different nitrogen treatments. Conversely, in

Fig. 3 | Nitrogen footprint (NF) and nitrogen footprint intensity (NFI) of five super rice varieties in central China. a NF in Hubei Province, **b** NF in Henan Province, **c** NFI in Hubei Province, and **d** NFI in Henan Province. The data represent the average values over 3 years (2015–2017). Vertical bars indicate standard deviation ($n = 9$). Means within each variety that share the same letter are not significantly different according to the LSD test (0.05).

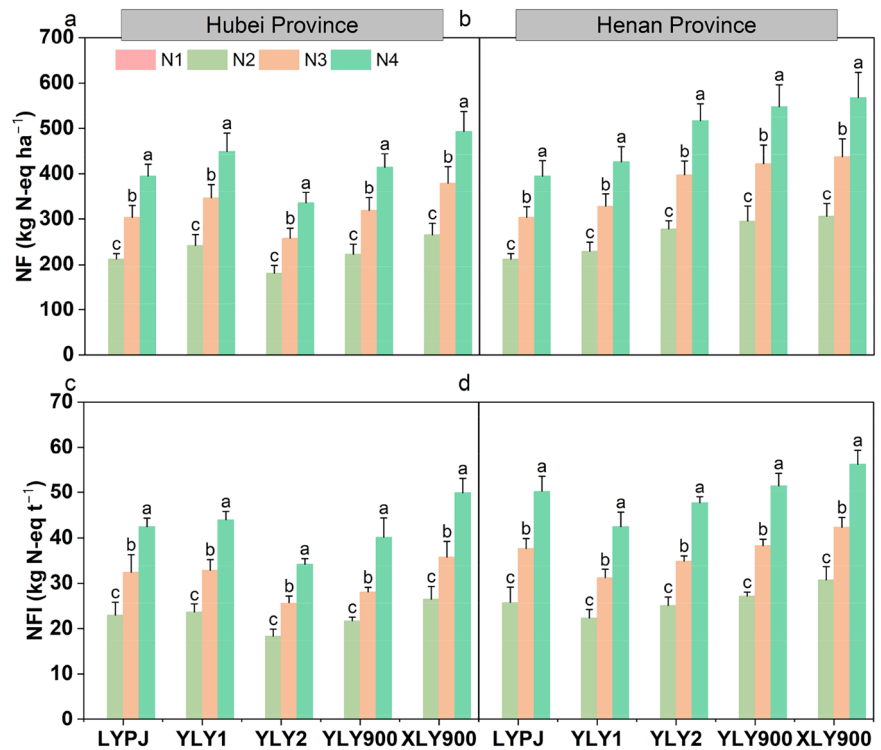
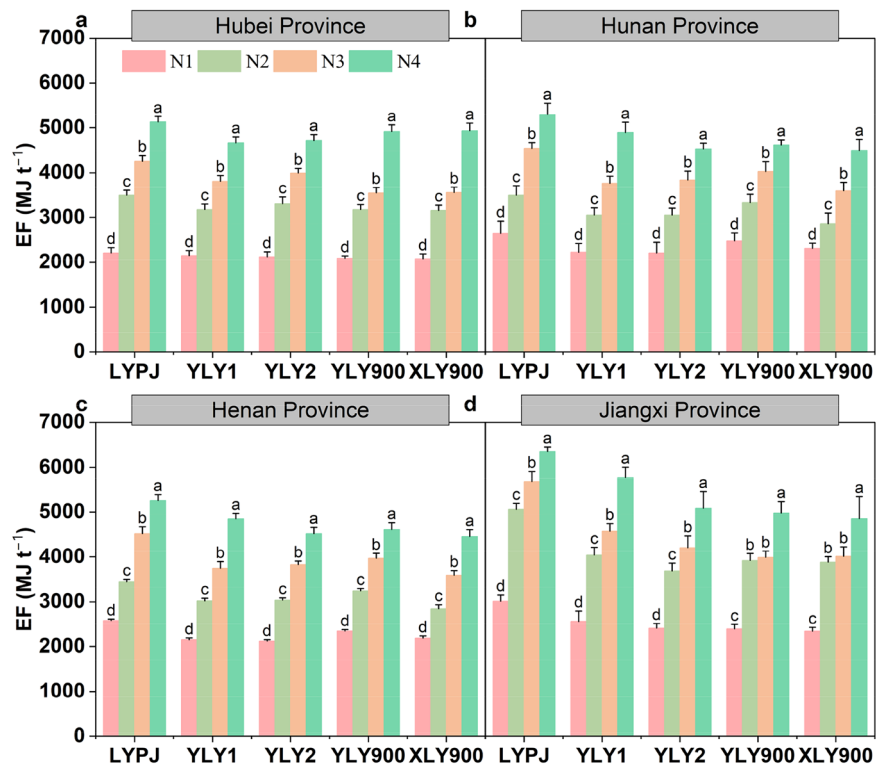


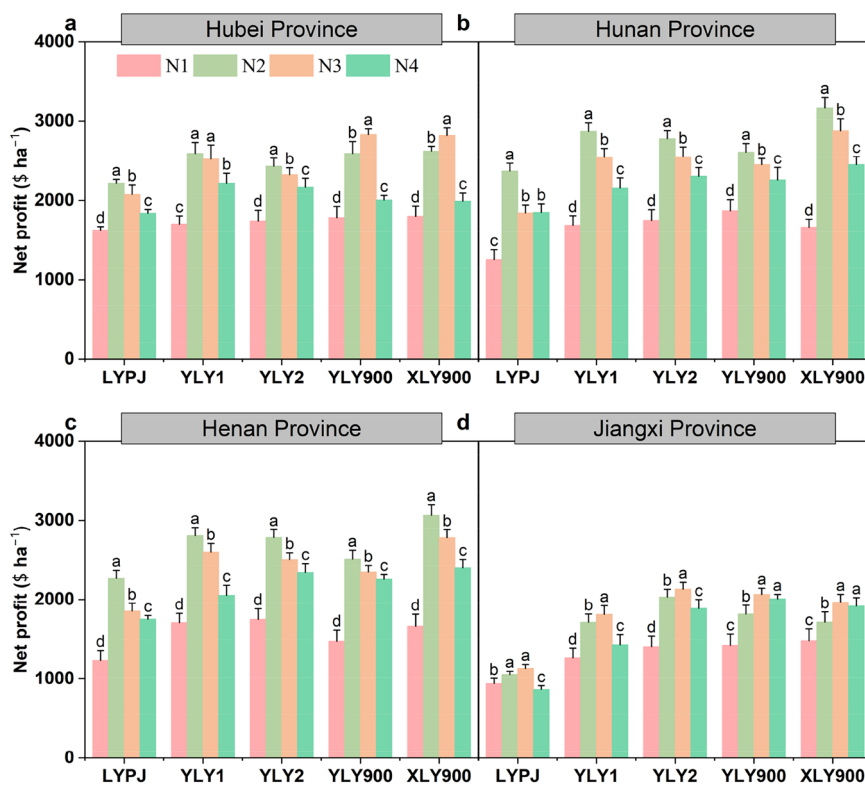
Fig. 4 | Energy footprint (EF) of five super rice varieties across four provinces in China. a EF in Hubei Province, **b** EF in Hunan Province, **c** EF in Henan Province, and **d** EF in Jiangxi Province. The data represent the average values over 3 years (2015–2017). Vertical bars indicate standard deviation ($n = 9$). Means within each variety that share the same letter are not significantly different according to the LSD test (0.05).



Jiangxi Province, the highest NP was observed under N2 or N3 treatments. Specifically, in Henan Province, XLY900 yielded the highest NP under N2 treatment, surpassing LYPJ, YLY1, YLY2, and YLY900 by 35.1%, 9.4%, 10.2%, and 22.2%, respectively. In Hubei Province, LYPJ, YLY1, and YLY2 achieved the highest NP under N2 treatment, while YLY900 and XLY900 performed best under N3 treatment. The NP of YLY900 and XLY900 was not significantly different, but it was considerably higher than LYPJ, YLY1, and YLY2.

Except for Jiangxi Province, XLY900 consistently demonstrated the highest NP across the other four sites. Overall, N2 treatment resulted in the highest average NP, reaching $2358.4 \text{ kg N ha}^{-1}$, representing a 32.6%, 2.1%, and 13.0% increase compared to N1, N3, and N4 treatments, respectively. Among the varieties, XLY900 exhibited the highest average NP of $2296.0 \text{ kg N ha}^{-1}$, surpassing LYPJ, YLY1, YLY2, and YLY900 by 28.7%, 10.3%, 3.8%, and 5.5%, respectively.

Fig. 5 | Net profits (NP) of five super rice varieties across four provinces in China. **a** NP in Hubei Province, **b** NP in Hunan Province, **c** NP in Henan Province, and **d** NP in Jiangxi Province. The data represent the average values over 3 years (2015–2017). Vertical bars indicate standard deviation ($n = 9$). Means within each variety that share the same letter are not significantly different according to the LSD test (0.05).



FCNEP composite sustainability and evenness of super hybrid rice varieties

Figure 6 illustrates distinct patterns in sustainability scores across five-phase super hybrid rice varieties under varying nitrogen (N) treatments, as assessed by the FCNEP index. Notably, the highest composite sustainability scores were consistently observed under N2 treatment in both Hubei Province and Henan Province. Furthermore, YLY2 and YLY1 cultivated under N2 treatment demonstrated superior composite sustainability and evenness, exceeding 60 points across all Hubei and Henan Province. Although all varieties exhibited higher food production and NP under N3 treatment, they were compromised by poorer performances in CF, NF, and EF. In contrast, under N2 treatment, the varieties showed relatively high and balanced performances in food production, CF, NFF, EF, and NP, even if they did not achieve the highest scores in each individual category.

Discussion

Super hybrid rice breeding has significantly advanced, yielding high-productivity varieties that bolster global food security. However, the environmental costs of these intensive production systems are a growing concern. We evaluate the sustainability of super rice production by assessing its impact on food security, greenhouse gas emissions, nitrogen losses, energy consumption, and economic profit. Using an FCNEP framework, we aim to provide a comprehensive analysis of the breeding process's dual roles in food security and environmental sustainability. Our findings will aid policymakers in balancing these critical aspects when shaping future food production strategies.

In recent decades, China has made significant progress in rice yield with the development of super hybrid rice^{7,42}. This study investigated the yield and yield components of five generations of super hybrid rice varieties released between 1999 and 2017 under four nitrogen levels. Results showed that the yield of all five generations of super hybrid rice varieties continuously increased, but the experimental yield was lower than the yield achieved during the high-yield campaign period. This could be attributed to the climatic conditions and soil factors (Supplementary Table 1) of the experimental site^{28,43}. The study confirmed that applying high levels of

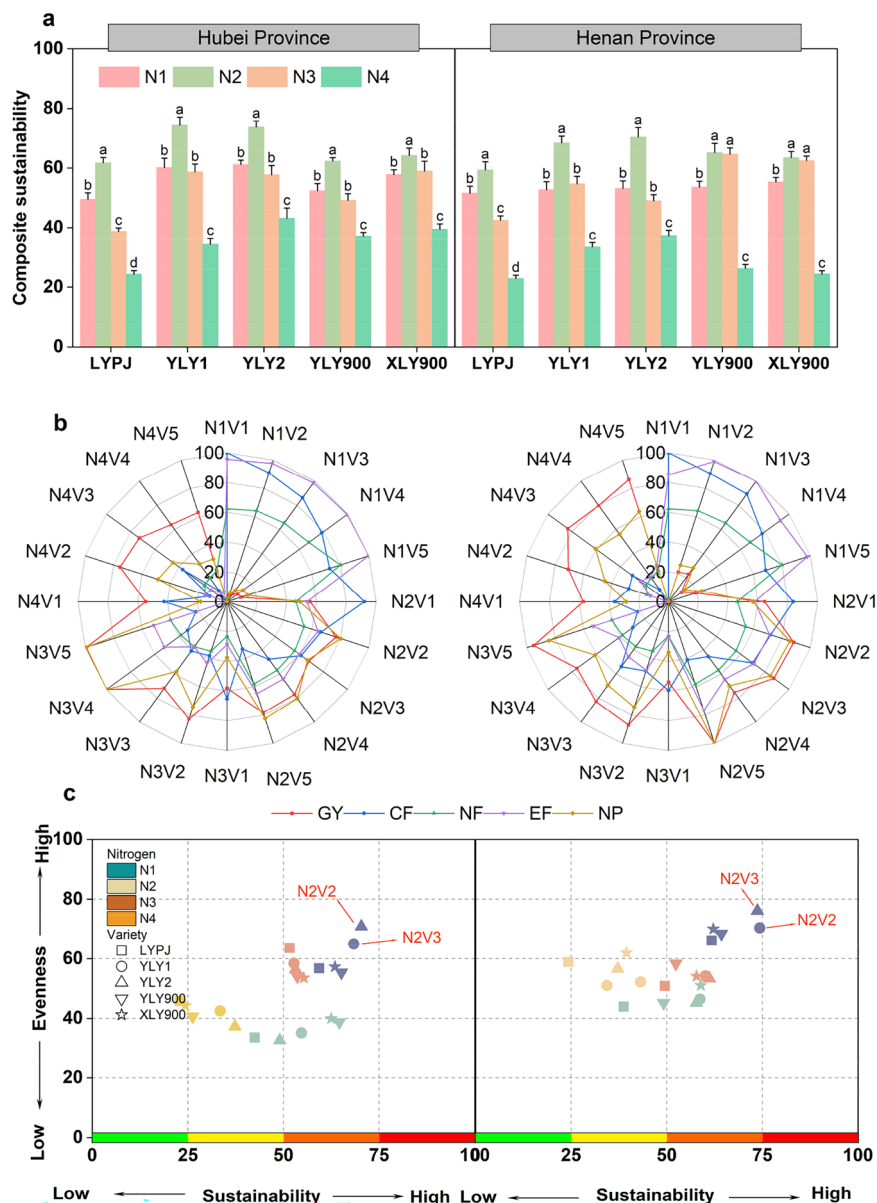
nitrogen fertilizer can significantly improve the yield of superhybrid rice⁸. For instance, under the N3 treatment, the yield of the second to fifth generations of super rice exceeded 10 t ha⁻¹, with the latest generation XLY900, showing the highest yield of 10.6 t ha⁻¹ (Fig. 1).

The yield of the five super hybrid rice varieties exhibited a trend of increasing and then decreasing with increasing nitrogen levels, but different varieties showed varying sensitivities to nitrogen fertilizer. For example, in this study, the yield of LYPJ did not significantly differ under N2, N3, and N4 treatments, suggesting that the optimal nitrogen application rate for LYPJ is approximately 210 kg ha⁻¹. While the yield of YLY1, YLY2, YLY900, and XLY900 reached the highest under N3 treatment, YLY1 showed no significant difference between N2 and N4 treatments, while the other three varieties showed no significant difference between N3 and N4 treatments. This indicates that as the yield potential of super hybrid rice increases, its tolerance to fertilizer also enhances^{43,44}. Moreover, the yield of YLY2, YLY900, and XLY900 did not significantly differ under N3 and N4 treatments, suggesting that nitrogen fertilizer is not a limiting factor for further yield improvement of super hybrid rice.

Previous studies have suggested that newer super hybrid rice varieties can achieve higher yields with increased nitrogen inputs^{6,7}. However, these high-yield trials were typically conducted in specific ecological zones characterized by optimal climate conditions, fertile soils, and advanced agricultural practices. These ideal conditions, which include favorable temperature ranges, sufficient and well-distributed rainfall, and nutrient-rich soils, play a critical role in maximizing the potential of superhybrid rice varieties. Furthermore, these regions often employ high levels of input, such as precision irrigation, optimal fertilizer management, and pest control practices^{14,24,28}, all of which contribute to higher yields. The success of these trials is, therefore, not solely due to the variety itself but also a result of a combination of favorable factors. These factors include access to high-quality seeds, cutting-edge agricultural technologies, and well-established farming practices. In contrast, the variability in yield responses observed in our study reflects the reality that yield outcomes are highly dependent on site-specific conditions. For example, soil type, soil fertility, and its ability to retain nutrients can significantly affect nitrogen uptake efficiency^{14,42}.

Fig. 6 | Composite sustainability and performance under five nitrogen treatments in Hubei and Henan Province, China from 2015 to 2017.

a Variation in composite sustainability across nitrogen treatments and rice varieties. Error bars represent the standard deviation across different years. Means within each variety that share the same letter are not significantly different according to the LSD test (0.05). **b** Multi-dimensional assessment of sustainability performance across nitrogen treatments. **c** Relationship between sustainability and evenness among nitrogen treatments and rice varieties. Super hybrid rice varieties: V1 (LYPJ), V2 (YLY1), V3 (YLY2), V4 (YLY900) and V5 (XLY900).



Similarly, climate factors, including temperature, rainfall patterns, and the timing of these factors during critical crop growth stages, can either enhance or limit the expression of yield potential. These variables can significantly influence how rice varieties respond to nitrogen application, and they are not easily replicated in regions with different environmental conditions or management practices. For instance, in some of the experimental sites in our study, soil conditions may have been suboptimal for nitrogen uptake, or the climate may not have aligned with the ideal conditions for nitrogen utilization by the crop.

Therefore, while increased nitrogen application can lead to higher yields under certain conditions, our findings emphasize the importance of considering the broader environmental and management context when evaluating the potential for superhybrid rice to deliver high yields across diverse regions. The complexity of these interactions highlights the need for site-specific nitrogen management practices that are tailored to local conditions to achieve optimal productivity without compromising sustainability.

In this study, YLY1 and LYPJ exhibited comparable panicle numbers and spikelets per panicle, but YLY1 showed significantly higher grain filling rate and slightly increased grain weight compared to LYPJ (Table 1). Consequently, the yield improvement in YLY1 is mainly attributed to the

significant increase in grain filling rate and a moderate increase in 1000-grain weight. Compared with YLY1, YLY2 showed a significant reduction in panicle number and grain weight, with a slight decrease in grain filling rate but a dramatic increase in spikelets per panicle. This suggests that the yield potential improvement in YLY2 was primarily driven by the substantial increase in spikelets per panicle. YLY900 exhibited comparable grain weight to YLY2, but significantly reduced panicle number and grain filling rate while displaying a considerable increase in spikelets per panicle. This indicates that the yield increase in YLY900 was also primarily attributed to the significant increase in a number of spikelets per panicle. Compared to YLY900, XLY900 showed a significant decrease in panicle number but a significant increase in spikelets per panicle, grain filling rate, and grain weight. This suggests that increasing the spikelets per panicle significantly while maintaining a certain level of grain filling rate and grain weight, can enhance the yield potential of super rice^{45,46}. Furthermore, our results revealed a general decreasing trend in panicles number, grain filling rate, and grain weight across the five generations of super rice, while a significant increase was observed in spikelets per panicle. This indicates that the breeding direction of super rice has shifted from the multi-panicle type to the large-panicle type^{47,48}.

Improving harvest index and biomass can increase rice yield⁴⁹. However, studies suggest that there is little room for further improvement in the current rice harvest index^{50,51}, and further increasing the upper limit of rice yield depends on increasing biomass⁵². Photosynthesis is the foundation for rice biomass production, with 90% of rice yield attributed to leaf photosynthesis⁵³. Therefore, breeders continuously improve the photosynthetic characteristics of rice^{53,54}. Previous studies have shown that as rice varieties have been improved, their Pn, Gs, and Tr have all significantly increased⁵⁵. In this study, increased nitrogen application led to a certain degree of improvement in Pn, Ci, Gs, and Tr in five-phase super hybrid rice varieties. Among them, the average Pn of YLY900 or XLY900 was highest in Hubei Province and Henan Province regions. Previous studies have shown that higher leaf chlorophyll content, greater leaf thickness, larger leaf area, and higher Pn, leading to higher yield^{54,56}.

Furthermore, at the canopy scale, photosynthesis is referred to as radiation use efficiency (RUE). The RUE of super hybrid rice varieties was not significantly different from that of conventional indica rice, but it was 10%–12% higher than that of hybrid rice⁵⁷. The yield increase in super rice mainly depends on the coordinated increase in RUE and intercepted photosynthetically active radiation^{57–59}. Huang et al.²⁹ found that the RUE of super hybrid rice Yliangyou087 is 14% higher than that of hybrid rice Teyou838, with no significant difference in the intercepted solar radiation between the two rice varieties²⁹. Liu et al.⁵⁹ suggested that RUE contributes more to the increase in yield of super hybrid rice than the harvest index improving the RUE of rice may effectively increase yield.

Rice plants fix carbon through photosynthesis and transport these carbon molecules to the roots, stems, and grains⁶⁰. The carbon in the roots not only promotes root growth but also releases organic acids and sugars, etc. into the soil through secretion, providing nutrition for microorganisms and influencing the microbial community^{61,62}. The anaerobic environment of the paddy field promotes the growth of methanogenic archaea, which use this secreted organic matter to produce methane through biochemical reactions⁶³, and then release it into the atmosphere through the roots or soil surface. In this study, the CF of five-phase superhybrid rice increased (Fig. 2) due to the significant increase in CH₄ emissions (Supplementary Figs. 4 and 5). Our study found that there are differences in methane emissions among different rice varieties, which is consistent with the previous studies^{51,62}.

Previous studies have highlighted the importance of rice roots in methane emissions, as they provide both substrates and environments for methanogenic archaea⁶⁴. Varieties with larger root systems tend to have higher methane emissions⁶⁵. As the yield of super hybrid rice increases, root growth also increases^{66–68}, potentially contributing to a higher CF. Furthermore, the carbon emission intensity of different superhybrid rice varieties varies depending on the amount of nitrogen fertilizer applied. Among the varieties studied, YLY2 consistently emitted the least methane across all nitrogen treatments.

Super rice has made a huge contribution to global food security, but it also has drawbacks, such as high nitrogen requirements and excessive nitrogen application leading to low nitrogen use efficiency, greenhouse gas emissions, and environmental problems caused by nitrogen loss^{17,45}. To reduce methane emissions from rice paddies, researchers are seeking and breeding low-methane-emitting rice varieties. Zhang⁶⁹ proposed the development of “green super rice” to reduce nitrogen inputs. Currently, some low-methane-emitting rice varieties have been identified, such as Heijing 5⁶². The future goals of super rice breeding include high yields, disease resistance, and low methane emissions. Strategies to reduce nitrogen fertilizer application and improve rice cultivation practices, such as intensive planting^{49,70} and alternate wetting and drying⁷¹, as well as developing new types of fertilizers⁷² and soil amendments⁷³, are all effective measures to reduce methane emissions. These measures are of great significance for mitigating climate change and achieving sustainable agricultural development.

Our study reveals a notable decline in EFs, but an increase in nitrogen footprint across five-phase of super rice development (Fig. 4). The reduction

in nitrogen footprint for YLY2 may largely be attributed to enhanced nitrogen use efficiency (Supplementary Fig. 6). Advancements in super hybrid rice breeding and the augmented capacity of rice varieties to harness nitrogen have necessitated higher nitrogen inputs to unlock their full yield potential. Except for XLY900, the average NFI of YLY1, YLY2, and YLY900 was 7.1%, 12.1%, and 2.1% lower than LYPJ. Following nitrogen fertilizer application, super rice plants exhibit elevated nitrogen uptake, leading to diminished nitrogen losses to the environment and thus reduced environmental impact. Furthermore, the improved root morphology of super rice facilitates enhanced nitrogen absorption and utilization^{66,67}, effectively curtailing nitrogen runoff and shrinking the nitrogen footprint.

Nitrogen fertilizers bear the heaviest energy consumption among all agricultural inputs⁷⁴, thereby exerting a dominant influence over the overall EF of rice production. Given its indispensable role in crop growth promotion⁷⁵, the synthesis of nitrogen fertilizers entails substantial energy expenditures⁷⁶, contributing to significant energy consumption and environmental burdens within the agricultural sector. In our study, we meticulously designed experiments to standardize all cultivation practices except for nitrogen fertilizer application levels, encompassing aspects like seed quality, machinery usage, and irrigation protocols, to precisely gauge the specific impact of nitrogen fertilization on the EF of rice production. Our findings underscore that escalating nitrogen input precipitates a marked increase in the EF across diverse rice cultivars and geographical locations, culminating at the N4 treatment threshold. This observation corroborates the direct positive correlation between nitrogen fertilizer application and EF⁷⁷, underscoring the pivotal role of nitrogen management in shaping the environmental sustainability of rice farming.

Remarkably, our analysis across Hunan, Henan, and Jiangxi provinces reveals a pronounced downtrend in the EF of super rice varieties as breeding progresses. This trend can be largely ascribed to yield enhancements stemming from varietal advancements, where heightened per-unit-area yields equate to reduced energy consumption per unit of production. However, the data from Hubei province diverges slightly, hinting at the influence of eco-adaptability on super rice performance. The eco-adaptability of super rice is indeed a cornerstone of its success, yet it manifests varied responses under distinct environmental conditions. The contrasting observations in Hubei relative to the provinces highlight that the EF of super rice is contingent upon a multitude of site-specific factors, encompassing soil properties, and climatic conditions. Consequently, a judicious selection of super rice cultivars that are optimally aligned with local ecological contexts becomes paramount for attaining desired yield benchmarks while simultaneously minimizing the EF.

This study employed a framework of FCNEP to systematically examine the relationship between the progress of super rice yields and the sustainability of ecological environments. The results showed that while the breeding progress of super rice leads to increased yields, it also reduces environmental sustainability, particularly greenhouse gas emissions. However, optimized management practices can effectively reduce ecological footprints and enhance environmental sustainability³⁴. Previous research has demonstrated that optimizing nitrogen fertilizer management can decrease greenhouse gas emissions in rice fields^{49,70}, while alternate wetting and drying irrigation can reduce methane emissions from rice paddies⁷¹. Therefore, integrating optimized management practices with the high-yield characteristics of super rice can ensure food security and reduce ecological footprints, thereby enhancing environmental sustainability.

However, this study has limitations. Our nitrogen footprint and EF calculations rely on theoretical models and assumptions, potentially introducing inaccuracies in assessing actual nitrogen emissions and energy consumption. While we referenced actual N₂O emissions data for different varieties, we did not measure specific data on nitrogen digestion, volatilization, and loss. This gap means our calculations may not fully capture the contributions of these processes to the nitrogen footprint, limiting the accuracy of our environmental impact assessments in agriculture. Additionally, the lack of specificity in EF calculations could lead to overestimations or underestimations of the true energy impact of each variety.

To enhance accuracy and reliability, future research should focus on precise measurements of these parameters and integrate them into nitrogen footprint assessments. Empirical field trials should be comprehensive, multi-dimensional, and long-term, encompassing yield, resource use efficiency, environmental impact, and economic viability. Such research should explore how different super hybrid rice varieties respond to various management practices and evaluate their performance under climate change scenarios, supported by thorough LCAs.

Data availability

Data are provided within the manuscript or supplementary information files.

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Author contributions

Y.Z. and K.L. designed the experiments and revised the paper; J.D., N.T., and X.F. investigated the traits, J.D. analyzed the data, J.D. wrote the main manuscript text, Z.W., Q.Z., J.Z., T.P., M.T.H., L.H., and X.T. aided with conceptualization, scientific rigor, and manuscript editing. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests. As Editorial Board Members, Matthew Tom Harrison and Ke Liu were not involved in the peer review of this article and had no access to any information related to its peer-review process or decision-making.

Additional information

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