

Sustainable forage-grain ratoon rice production: interactions between planting density and mowing time on forage and grain attributes

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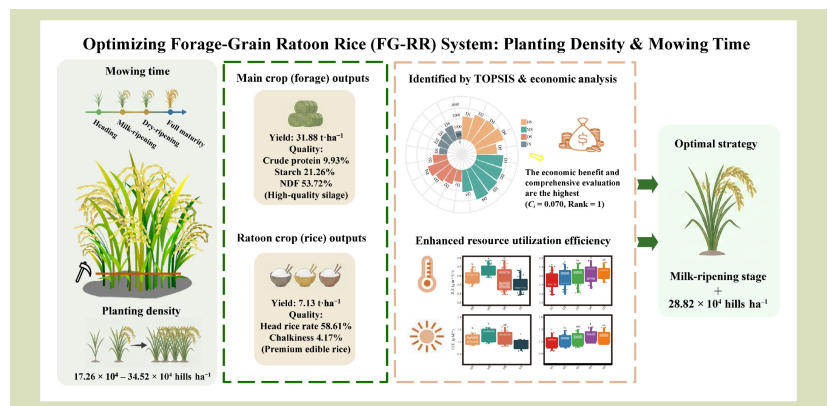
KEYWORDS

Forage-grain ratoon rice, planting density, quality, mowing time, yield, economic benefit

HIGHLIGHTS

- High planting density and milk-ripe mowing optimize dual-season productivity.
- High planting density balances main-crop forage and ratoon-crop grain yields.
- Higher ratoon rice yield is achieved by optimizing canopy structure and grain filling.
- EW-TOPSIS identifies optimal strategies for sustainable forage-ratoon rice systems.

GRAPHICAL ABSTRACT



ABSTRACT

Forage-grain ratoon rice (FG-RR) is a sustainable system designed to enhance ratoon rice yield and quality while simultaneously producing high-quality whole-plant rice forage through early harvesting of the immature main crop (MC) for silage. This study examined the effects of planting density and mowing time on forage and grain productivity and quality, to optimize ecological and economic benefits. Field experiments were conducted using two cultivars, Liangyou 6326 and Taoyouxiangzhan, across five planting densities (17.26×10^4 – 34.52×10^4 hills ha^{-1}) and four mowing stages (heading, milk-ripening, dry-ripening, and full maturity). Forage and ratoon crop (RC) yields, quality traits, resource utilization efficiency, and economic returns were assessed. Increasing planting density initially promoted but subsequently reduced both forage and RC yields. Delayed mowing increased forage yield but, after an initial rise, reduced RC yield. The optimal combination—mowing at the milk-ripening stage with a planting density of 28.82×10^4 hills ha^{-1} produced forage containing 53.72% neutral detergent fiber, 21.26% starch,

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and 9.93% crude protein, meeting standards for high-quality silage. In the RC season, the head rice rate reached up to 58.61% with a chalkiness level as low as 4.17%, meeting high-quality edible rice standards. TOPSIS analysis and economic evaluation indicated that this management strategy yielded the highest overall performance, generating 3086.08 USD·ha⁻¹. Integrating this optimal mowing time with optimal density produced 31.88 t·ha⁻¹ of high-quality forage and 7.13 t·ha⁻¹ of premium-grade rice. This integrated strategy enhances resource utilization efficiency, grain quality, and profitability, offering a practical approach for the sustainable development of FG-RR systems.

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1 Introduction

Rapid urbanization and rising living standards have led to substantial shifts in dietary preferences in China, with increasing consumption of animal-derived products, driving accelerated growth in the livestock industry^[1]. Consequently, the demand for high-quality forage has increased sharply, resulting in heavy dependence on imported feed resources^[2]. Concurrently, vast agricultural lands in southern rice-growing regions remain underutilized due to seasonal fallow periods, causing significant inefficiencies in the use of available solar radiation and thermal resources^[3]. To address the dual challenges of ensuring grain self-sufficiency and meeting the rising demand for livestock forage, Peng et al^[4] proposed the forage-grain ratoon rice (FG-RR) production system. Unlike conventional ratoon rice, FG-RR involves harvesting the main crop (MC) as whole-plant silage and the ratoon crop (RC) for grain, uniquely bridging the gap between food and feed production^[2].

Optimizing agronomic management practices is critical for balancing the conflicting demands for forage quality and grain yield in this dual-purpose system. Planting density significantly affects canopy architecture and light interception^[5]. In conventional ratoon systems, optimizing density ensures sufficient photosynthate accumulation for ratoon bud germination^[6]. However, in FG-RR systems, excessive density may impair light penetration into the lower canopy, increasing crude fiber content in MC forage while suppressing the ratoon of ratoon tillers^[5,7]. Conversely, insufficient density may limit total biomass production potential^[8,9]. Similarly, mowing time is a critical regulatory factor governing resource allocation^[4]. Early MC harvest (e.g., during flowering) enhances silage protein content and palatability, but it may result in excessive

moisture, which can hinder fermentation^[10]. Delayed harvest increases biomass but typically reduces digestibility and delays RC establishment, thereby increasing the risk of low-temperature stress during grain filling^[4,10]. Consequently, under condition of limited light and temperature resources, an optimized combination of planting density and harvest time is crucial for synergistically enhancing the yield and quality of both forage and rice in FG-RR cultivation.

Despite their importance, the interactive effects of planting density and harvest timing in FG-RR remain insufficiently studied. Most previous research focused on either grain-oriented high-yielding rice production or single-season forage rice, often overlooking the complex interplay between planting density and harvest timing on nutritional quality, economic returns, and profitability. Specifically, the combined influence of planting density and MC mowing stage on both MC forage performance and subsequent RC grain production is not well understood. To address this knowledge gap, we conducted a field experiment with varying planting densities and MC mowing times, aiming to: (1) clarify the impact of planting density on the yield and quality of the MC forage at different mowing times; (2) assess the effect of planting density on RC yield and grain quality across at different mowing times; (3) determine the optimal combination planting density and mowing time for FG-RR cultivation, providing practical agronomic recommendations to support its sustainable development.

2 Materials and methods

2.1 Experimental site

This study was conducted from 2021 to 2022 at the

experimental production base of Henan Agricultural University located in Lilou village, Beixiangdian Township, Xinyang city, Henan Province, China (32°00'0"N, 114°54'0"E; 92 m asl.). The region has a humid subtropical monsoon climate, characterized by distinct seasons. Mean annual sunshine duration is 1990 hours, mean annual temperature is 15.4 °C, the frost-free period averages 226 days, and annual precipitation is approximately 1027.6 mm. The soil at this site is a paddy soil suitable for rice cultivation. The ratoon cropping (RC) growing period extends approximately from March to November each year. Soil analysis conducted in 2022 revealed the following baseline fertility parameters: a pH value of 6.73, organic matter content of 19.52 g·kg⁻¹, total nitrogen content of 1.08 g·kg⁻¹, available phosphorus content of 16.43 mg·kg⁻¹, and available potassium content of 167.43 mg·kg⁻¹.

2.2 Field experimental design and crop management practices

A split-split plot design was implemented with 3 replicates for each treatment. Main plots comprised two rice (*Oryza sativa*) varieties: Liangyou 6326 (LY6326) and Taoyouxiangzhan (TYXZ). Sub-plots were assigned to four mowing time treatments during the MC season: heading stage (HS, 0 days after flowering), milk-ripening stage (MS, 10 days after flowering), dry-ripening stage (DS, 20 days after flowering), and full maturity stage (FS, 30 days after flowering). Sub-sub plots were allocated to planting density treatments. Four densities were tested in 2021: D1 (17.2 × 10⁴ hills ha⁻¹), D2 (22.76 × 10⁴ hills ha⁻¹), D3 (25.34 × 10⁴ hills ha⁻¹), D4 (28.82 × 10⁴ hills ha⁻¹). In 2022, an additional density (D5: 34.52 × 10⁴ hills ha⁻¹) was implemented and examined to validate 2021 findings. Each subplot was 20 m².

Seeds were sown on 12 March 2021 and 15 March 2022. Seedlings were mechanically transplanted 30 days after sowing with 28 cm row spacing and 4 seedlings per hill. Total nitrogen (N) input during the MC season was 240 kg·ha⁻¹ N, with 40% used as the base fertilizer, another 40% applied in the early tillering stage (7 days after transplanting), and the remaining 20% during the panicle initiation stage. For the RC season, 150 kg·ha⁻¹ N was applied, with 75 kg·ha⁻¹ N applied as bud-promoting fertilizer 7 days before mowing and another 75 kg·ha⁻¹ N as nursery fertilizer one day after mowing. Urea (46% N) served as the nitrogen source. Phosphate fertilizer was applied at a rate of 112 kg·ha⁻¹ P as calcium superphosphate (P₂O₅; 12.0%) entirely as basal fertilizer. Potassium was applied

at a rate of 112 kg·ha⁻¹ K as potassium chloride (K₂O; 60.0%) during the base and panicle initiation stages in the MC season, and at 135 kg·ha⁻¹ K in the RC season along with the nitrogen fertilizer as nursery fertilizer. From transplantation to the mowing time, fields were drained during the peak tillering phase, while maintaining 3–5 cm water depth during other periods. Post-mowing, a 1–3 cm water layer was maintained until physiological maturity.

2.3 Measurements

2.3.1 Forage biomass yield and silage forage quality

During the MC season, rice was mowed at four growth stages: heading stage, milk-ripening stage, dry-ripening stage, and full maturity stage. A uniform stubble height of 25 cm was maintained in each 5-m² plots. Fresh biomass yield was determined by weighing the harvested straw. For each treatment, a representative 3 kg straw sample was immediately enzyme-deactivated at 105 °C for 30 min to halt metabolic activity, then oven-dried at 80 °C to constant weight. Fresh rice straw was then processed using a straw crusher to achieve a cut length of approximately 1–2 cm. Subsequently, 1 kg of the chopped straw was packed into polyethylene vacuum bags (dimensions: 20 cm × 30 cm; thickness: 0.16 mm), compressed, and vacuum-sealed. Samples were stored at room temperatures ranging from 17–28 °C. After 60 days of natural fermentation, approximately 100 g of the entailed forage sample was dried in an 80 °C oven to a constant weight, ground, and sieved through a 1 mm screen for testing. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined following the method^[11]. The crude protein content was measured according to Nelson & Sommers^[12], with the crude protein content calculated by multiplying the nitrogen content by a correction factor of 6.25^[13]. Starch content was quantified using the anthrone-H₂SO₄ method and a UV-Vis spectrophotometer (TU-1901, Beijing Purkinje Instruments Co., Beijing, China)^[14].

2.3.2 Growth duration and ratoon ability

For each treatment, the number of days from transplantation to mowing for each treatment during the MC season, as well as the number of days from mowing to the heading stage and from heading to maturity during the RC season, was recorded. At physiological maturity in both seasons, effective panicles were counted from 60 randomly selected plants per plot. Ratoon ability was calculated as the ratio of effective panicles in the RC season to those in the MC season.

2.3.3 Utilization of solar and thermal resources

Meteorological data were obtained from a weather station located approximately 1 km away from the experimental field. The records encompassed daily measurements from the time of transplanting, including average, maximum, and minimum temperatures, solar radiation levels, and precipitation. The formula for temperature utilization efficiency (TUE) was as follows,

$$TUE = PABA / (A - T) \tag{1}$$

PABA represents post-anthesis biomass accumulation in the RC season ($\text{g}\cdot\text{m}^{-2}$), and $A - T$ represents the effective accumulated temperature during post-anthesis in the RC season ($> 10\text{ }^\circ\text{C}$).

In the 2022 RC season, canopy light interception was measured at 7-day intervals from the heading stage to physiological maturity. Measurements were conducted between 11:00 and 13:00 on sunny days using a SunScan canopy analyzer (AccuPAR LP-80, Decagon Devices Inc., Pullman, WA, USA). In each plot, data were collected from three randomly selected locations. At each location, incident radiation (top of canopy) and transmitted radiation (5 cm above ground) were recorded to calculate the light interception ratio (F). The light utilization efficiency (LUE) was then calculated using the accumulated intercepted radiation and biomass accumulation as follows^[15]:

$$LUE = PABA / \sum I_{\text{light radiation}} \times F \tag{2}$$

$I_{\text{light radiation}}$ represents the daily incident light radiation ($\text{MJ}\cdot\text{m}^{-2}$). According to research by Lambers et al.^[16], photosynthetically effective radiation is approximately 50% of the total incident radiation. F represents the mean light interception ratio derived from the periodic measurements for each treatment^[15].

2.3.4 Ratoon rice yield and quality

At RC maturity, five representative plants per plot were selected based on median effective panicle counts to determine yield components. Grain yield was determined from a 5 m² harvest area per plot, then adjusted to reflect actual rice production at a standard moisture content of 13.5% using a standardized calculation method.

After threshing and natural air-drying, the brown rice rate, milled rice rate, head rice rate, chalkiness, chalkiness degree, amylose content, and protein content were determined according to the national standard “High-Quality Paddy” (GB/T 17891-2017).

2.3.5 Economic benefit assessment

Economic benefits involve agricultural input costs and income^[17]. Economic benefit analysis focuses on maximizing income, which corresponds to maximizing total output across both cropping seasons while accounting for the average cost of local input factors. The economic benefits were calculated as follows:

$$\text{Economic benefit} = \text{Income} - \text{Costs} \tag{3}$$

Agricultural input costs were divided into seed costs and production-related expenses. The latter included fuel, machinery, electricity, fertilizer, pesticides, labor, and groundwater ($\text{USD}\cdot\text{ha}^{-1}$, Table S1). Total cost ($\text{USD}\cdot\text{ha}^{-1}$) was estimated by multiplying the sum of unit agricultural inputs by the corresponding market price (USD per unit, Table S2), and the income ($\text{USD}\cdot\text{ha}^{-1}$) was calculated by multiplying the yields of fresh forage and ratoon rice by the corresponding current market price. Except for seed costs, all other input costs were assumed to be uniform across treatments.

2.3.6 EW-TOPSIS model

The Entropy Weight-Technique for Order Preference by Similarity to Ideal Solution (EW-TOPSIS) method was applied to comprehensively evaluate the effects of mowing time and planting density treatments on yield and quality in the FG-RR system. Initially, the entropy weight method (EW) was used to assign objective weights to each evaluation indicator based on their information entropy variability, thereby minimizing subjective bias. Subsequently, a normalized decision matrix was constructed, and the weighted Euclidean distances to the positive ideal solution (denoted as D^+) and negative ideal solution (denoted as D^-) were calculated. The relative proximity coefficient (C_i) was defined as:

$$C_i = \frac{D^-}{D^+ + D^-} \tag{4}$$

The above formula was used to quantify the proximity of each treatment to the optimal solution. Additional methodological details are provided in Yuan et al^[18].

2.4 Statistical analysis

All statistical analyses were performed in R Studio (version 4.1.2) software. Analysis of variance and multiple comparisons among mowing time and planting density treatments were conducted using the aov function from the base package and the LSD.test function from the agricolae package, with FDR

correction applied for *P*-value adjustment. Distance matrices for forage and rice yield and quality traits were generated using the *vegdist* function in the *vegan* package, and dimensionality reduction was performed using the *cmdscale* function in the *stats* package. Permutational multivariate analysis of variance analysis was conducted on yield and quality parameters under different mowing time treatments and planting densities using the *adonis2* function in the *vegan* package. All visualizations were created utilizing the *ggplot2* v3.3.5 and Adobe Illustrator CC 2018.

3 Results

3.1 Forage biomass yield

Planting density significantly influenced fresh forage biomass yield across mowing times in both 2021 and 2022 (Fig. 1;

Table S3, Table S4), accounting for 14.88% and 17.05% of yield variation ($P < 0.001$). Both varieties exhibited a unimodal response to increasing density: yields increased from D1 to D4 but declined at D5, with maximum yields at D4 density (LY6326: 35.51 t·ha⁻¹; TYXZ: 37.76 t·ha⁻¹). During the MS stage in 2021, the D4 density produced 9.70%, 7.43%, and 5.74% higher yields than D1, D2, and D3, respectively. Similarly, during the MS stage in 2022, D4 exceeded D1–D3 by 6.52%, 3.06%, and 3.77%, and exceeded D5 by 6.03%. Regarding varieties, across all mowing treatments in 2022, D4 in LY6326 outperformed D1–D3 and D5 by 14.12%, 8.96%, 5.50%, and 9.64%, respectively; TYXZ showed similar outperformance by 13.35%, 8.23%, 3.64%, and 7.33%, respectively. Furthermore, delaying mowing to FS maximized yields, boosting LY6326 and TYXZ yields by 19.69% and 22.98%, respectively, compared with earlier mowing stages. Dry forage yield followed the same pattern, reaching peak values at D4 density during FS in 2022 (Fig. S1; LY6326: 20.86 t·ha⁻¹; TYXZ: 19.15 t·ha⁻¹).

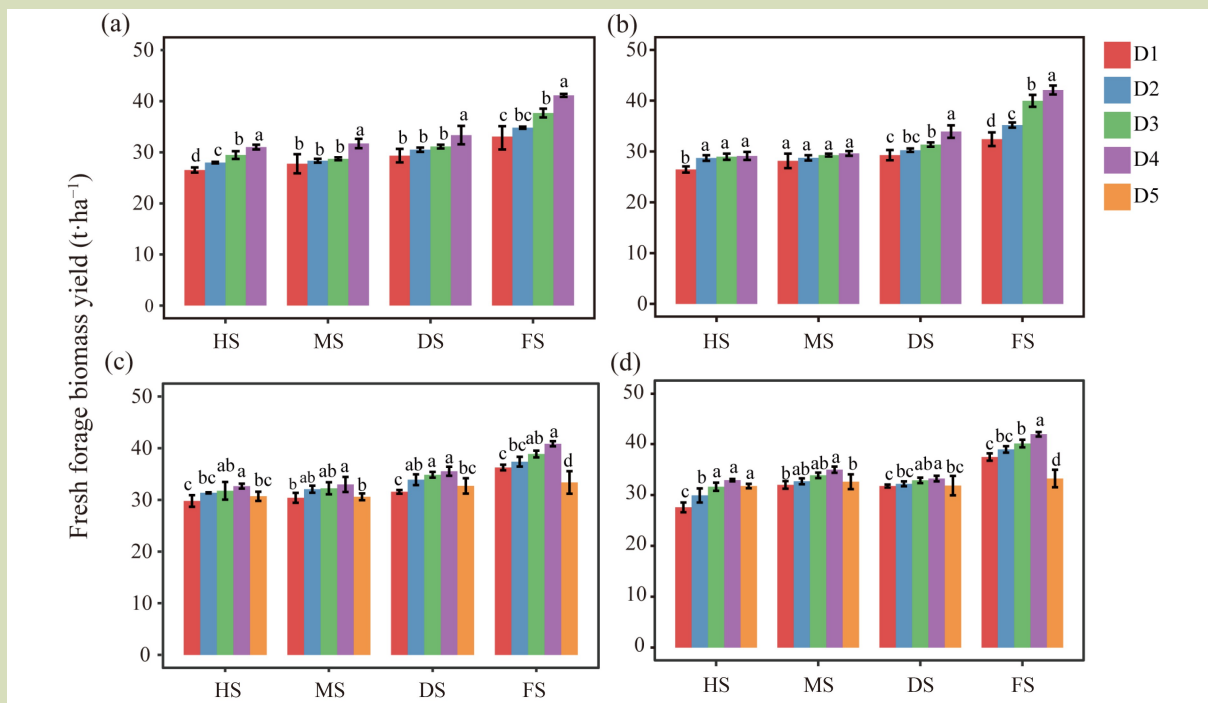


Fig. 1 Fresh forage biomass yield of LY6326 and TYXZ under different planting density and mowing time treatments in 2021 and 2022. (a) LY6326 in 2021; (b) TYXZ in 2021; (c) LY6326 in 2022; (d) TYXZ in 2022. HS, Heading stage; MS, Milk-ripening stage; DS, Dry-ripening stage; FS, Full maturity stage. D1, Planting density set to 17.2×10^4 hills ha⁻¹; D2, Planting density set to 22.76×10^4 hills ha⁻¹; D3, Planting density set to 25.34×10^4 hills ha⁻¹; D4, Planting density set to 28.82×10^4 hills ha⁻¹; D5, Planting density set to 34.52×10^4 hills ha⁻¹. Data are presented as mean \pm standard error (SE). Different lowercase letters above the bars indicate significant differences between treatments at the $P < 0.05$ level.

3.2 RC grain yield and yield components

Planting density significantly affected RC grain yield for both LY6326 and TYXZ across mowing time treatments in 2021–2022 (Fig. 2; Table S4). Yields exhibited a unimodal response to increasing density, peaking at D4 under MS treatment (5.80 t·ha⁻¹ in 2021; 8.46 t·ha⁻¹ in 2022) before declining at D5. In 2021, D4 density yielded 24.69%, 16.20%, and 9.27% more than D1, D2, and D3, respectively. Similarly, in 2022, D4 surpassed D1–D3 by 21.11%, 11.53%, and 7.29%, and exceeded D5 by 20.89%. Under D4 density during MS in 2022, varietal yield maxima reached 9.56 t·ha⁻¹ (LY6326) and 7.36 t·ha⁻¹ (TYXZ). Advancing mowing to MS further enhanced yields, with density and mowing interactions explaining 36.87% of yield variance, while environmental factors accounted for 6.77% (Table S5).

Planting density also significantly influenced RC yield components across all mowing time treatments, particularly

seed-setting rate, panicle number, and spikelets per panicle (Table S6, Table S7). Under MS treatment, increased density correspondingly increased panicle density. On average, the highest planting densities (D4 in 2021; D5 in 2022) increased panicles by 15.5% in LY6326 and 12.1% in TYXZ compared to D1. At D4 density during MS in 2022, the average panicle density across both varieties reached $509.63 \times 10^4 \text{ ha}^{-1}$. Conversely, seed-setting rate followed a unimodal response, peaking at D4 density in 2022 (MS: 84.06% for LY6326, 78.06% for TYXZ). Spikelets per panicle inversely correlated with density, exhibiting consistent declines under MS as density increased. Advancing mowing to MS consistently optimized yield components in 2021, increasing 1000-grain weight (MS averages: 29.04 g for LY6326 and 29.05 g for TYXZ) and seed-setting rate (MS average peak for LY6326: 88.86%).

3.3 Silage forage quality

Planting density significantly influenced silage forage quality in

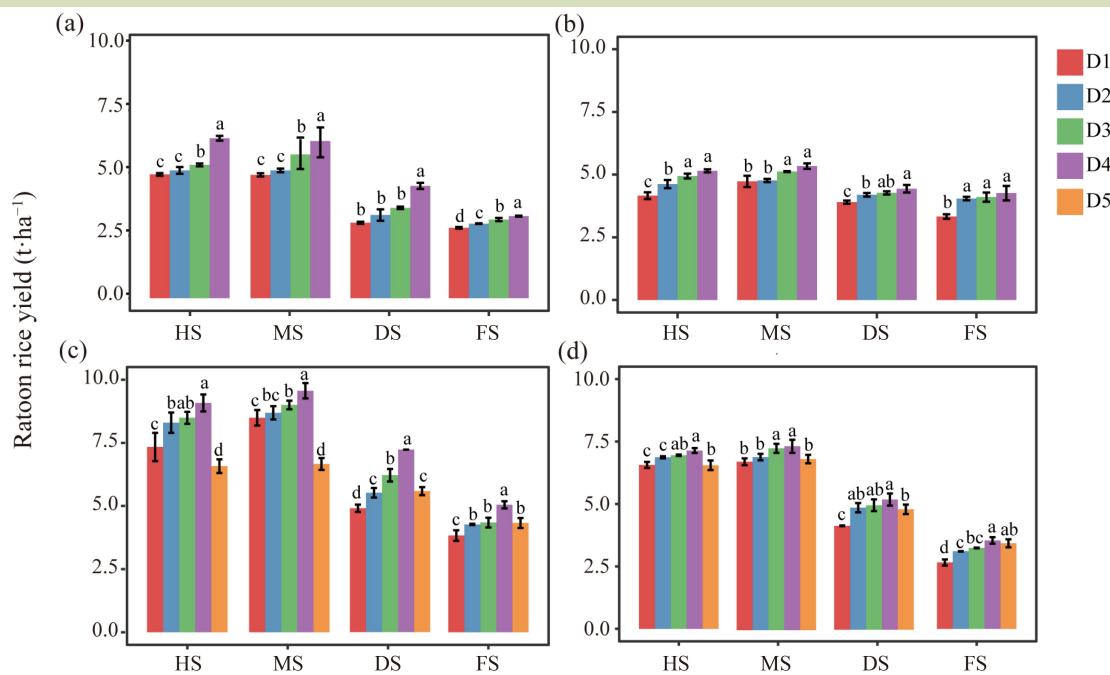


Fig. 2 Ratoon rice yield of LY6326 and TYXZ under different planting density and mowing time treatments in 2021 and 2022. (a) LY6326 in 2021; (b) TYXZ in 2021; (c) LY6326 in 2022; (d) TYXZ in 2022. HS, Heading stage; MS, Milk-ripening stage; DS, Dry-ripening stage; FS, Full maturity stage. D1, Planting density set to 17.2×10^4 hills ha^{-1} ; D2, Planting density set to 22.76×10^4 hills ha^{-1} ; D3, Planting density set to 25.34×10^4 hills ha^{-1} ; D4, Planting density set to 28.82×10^4 hills ha^{-1} ; D5, Planting density set to 34.52×10^4 hills ha^{-1} . Data are presented as mean \pm standard error (SE). Different lowercase letters above the bars indicate significant differences between treatments at the $P < 0.05$ level.

both LY6326 and TYXZ across mowing time treatments during 2021–2022 (Table S4). Increasing density consistently reduced major nutritional attributes, with NDF, ADF, crude protein, and starch content all exhibiting declining trends (Fig. 3, Table S8). In 2022, NDF for LY6326 was reduced by 5.67% under D4 density compared to D1, by 3.85% compared to D2, and by 2.10% compared to D3, but was 2.36% higher than in D5. Similarly, ADF decreased by 7.72% (D1), 4.72% (D2), and 2.88% (D3), while rising 2.76% relative to D5. Notably, D4 at the milk-ripening stage (MS) maintained crude protein content > 9.75% for both varieties in 2022. Delayed mowing reduced NDF and ADF but also lowered crude protein content. Across two years, from the heading stage (HS) to the full-ripening stage (FS), NDF decreased by 10.56% in LY6326 and 12.56% in TYXZ, while ADF declined by 11.33% and 12.42%, respectively. Advancing mowing to HS maximized crude protein, peaking at 10.99% (LY6326) and 10.85% (TYXZ), surpassing MS values by 1.11% and 0.71%, respectively. Conversely, delayed mowing resulted in significantly increased starch accumulation. Across two years, starch content in LY6326 increased to 23.10%, 32.00%, and 37.99%, while TYXZ exhibited corresponding increases of 25.94%, 32.60%, and 38.92%. TYXZ demonstrated superior forage quality to LY

6326 in the RC season. Multifactorial analysis revealed that planting density and mowing time collectively accounted for 1.88% and 6.92% of the variance in silage quality in 2021, decreasing to 1.27% and 3.85% in 2022 (Table S9).

3.4 RC grain quality

Planting density significantly affected ratoon rice quality traits across mowing time treatments (Fig. 3; Table S10, Table S11). Regarding processing quality, increasing planting density reduced brown rice, milled rice, and head rice rates in both varieties, with the highest values consistently observed at the D1 density across all mowing times. Advancing mowing time enhanced processing quality for both LY6326 and TYXZ, with peak quality attributes occurring under the MS treatment. At D4 density during MS, two-year mean brown rice, milled rice, and head rice rates were 79.14%, 69.40%, and 55.86%, respectively. Higher density impaired appearance quality, whereas advancing mowing time reduced chalkiness and chalkiness degree. After MS treatment in both years, the mean chalkiness at D4 was 4.17% (LY6326) and 1.15% (TYXZ), with chalkiness degrees of 1.02 and 0.25, respectively. Higher

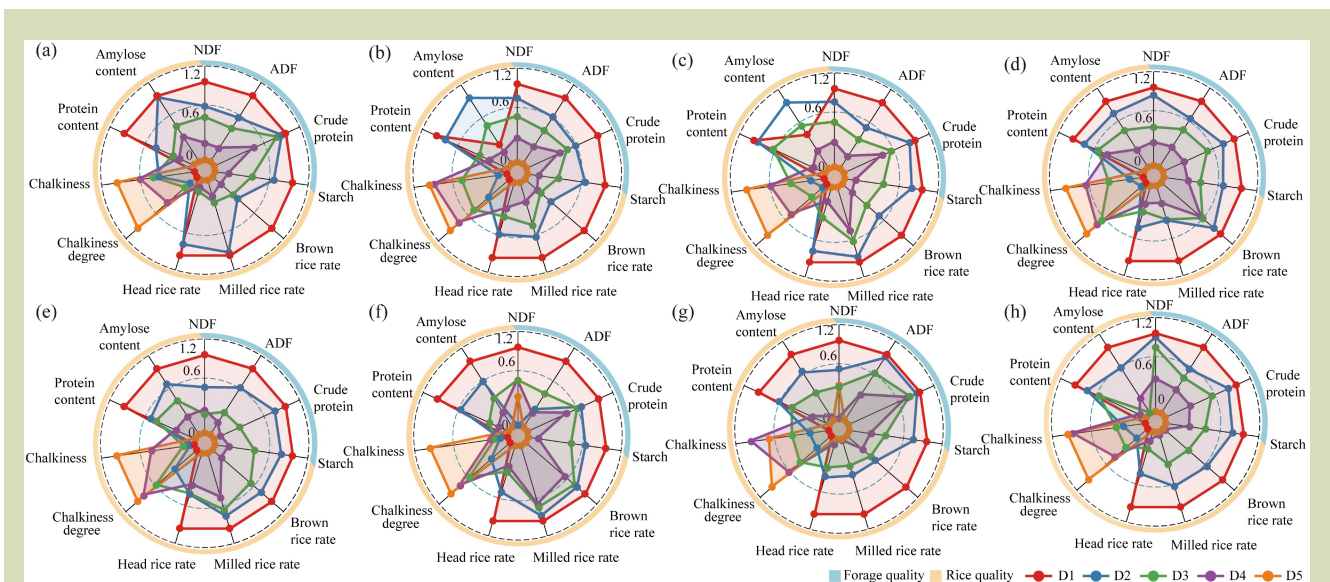


Fig. 3 Effects of planting density and mowing time on the silage forage quality of the MC season and grain quality of the RC season. (a) LY6326 in Heading stage; (b) LY6326 in Milk-ripening stage; (c) LY6326 in Dry-ripening stage; (d) LY6326 in Full maturity stage; (e) TYXZ in Heading stage; (f) TYXZ in Milk-ripening stage; (g) TYXZ in Dry-ripening stage; (h) TYXZ in Full maturity stage. D1, Planting density set to 17.2×10^4 hills ha^{-1} ; D2, Planting density set to 22.76×10^4 hills ha^{-1} ; D3, Planting density set to 25.34×10^4 hills ha^{-1} ; D4, Planting density set to 28.82×10^4 hills ha^{-1} ; D5, Planting density set to 34.52×10^4 hills ha^{-1} . NDF, neutral detergent fiber; ADF, acid detergent fiber. Data are presented as mean \pm standard error (SE). Different lowercase letters indicate significant differences among treatments at the $P < 0.05$ level.

planting density reduced protein content in both varieties, with average declines of 0.81% and 1.14% in 2022 across mowing treatments. Under D4 density during MS, protein content ranged from 6.82% to 7.28% across two years. Amylose content exhibited a trend similar to that of protein content. At D4 density during MS, averaged amylose content values for LY6326 and TYXZ across both years were 9.0% and 10.35%, respectively. LY6326 exhibited superior processing quality to TYXZ, while TYXZ demonstrated better appearance quality. Notably, planting density and mowing time collectively accounted for 4.41% of the variance in ratoon rice quality in 2022 (Table S12).

3.5 Utilization of temperature and light resources during the RC season

Increasing planting density significantly shortened the RC season duration for both varieties, concurrently reducing the required effective accumulated temperature and accumulated light radiation (Fig. S2; Table S13). During the two-year trial, RC season duration ranged from 67–89 days at D1, 66–88 days at D2, 65–88 days at D3, 64–88 days at D4, and 64–87 days (only in 2022) at D5 planting densities. Based on two-year averages across all mowing treatments, effective accumulated temperature at D4 density decreased by 1.63% compared to D1, while accumulated light radiation correspondingly declined by 2.20%. Mowing time adversely impacted the RC season duration. Compared to delayed mowing, earlier mowing greatly enhanced thermal and radiative resource utilization, increasing the mean effective accumulated temperature by 47.78% and accumulated light radiation by 19.08%.

Figure 4 illustrates the impacts of mowing time and planting density on LUE and TUE. Moderate increases in density improved both indices for LY6326 and TYXZ. At D4, TUE increased by 10.71%, 7.08%, and 4.74% relative to D1, D2, and D3 treatments across 2021–2022, whereas D5 reduced TUE by 3.09% compared with D4 in 2022. Similarly, at D4, LUE increased by 7.45%, 4.20%, 2.91%, and 1.48% compared to D1, D2, D3, and D5 densities in 2022. Mowing at the MS further enhanced resource-utilization efficiency: TUE increased by 11.69%, 2.10%, and 18.81% relative to HS, DS, and FS treatments over both years, while LUE increased by 7.49%, 5.20%, and 20.33% under the same comparisons in 2022. Regarding ratoon ability in 2022, both varieties exhibited substantial gains as planting density increased, peaking at D4. On average, producing 26.16%, 18.58%, 10.71%, and 6.85%

higher ratoon ability at D4 during MS than D1, D2, D3, and D5, respectively (Table S14).

3.6 TOPSIS and economic benefit evaluation

A comprehensive evaluation was performed using the TOPSIS method, incorporating 4 key parameters: forage yield, forage quality, RC grain yield, and RC grain quality (Table 1, Table S15). The analysis revealed that the MS treatment consistently produced the highest TOPSIS scores across mowing times (HS, DS, FS). Notably, under the optimal MS treatment, the D4 planting density achieved the highest ranking in 2022, with the density performance order within this stage being D5 > D3 > D2 > D1. These results demonstrate that combining MS with D4 density treatment provides the most favorable balance relationship between forage production and ratoon rice performance.

Economic benefit analysis further demonstrated that coordinated optimization of mowing time and planting density treatments maximized profitability across both seasons. As shown in Fig. 5 and Table S16, HS and MS treatments generated relatively high economic benefits, consistently exceeding 2000 USD·ha⁻¹. As shown in Supplementary Tables S16, the D4 density under HS treatment produced 2894.88 USD·ha⁻¹, while D4 under MS treatment reached 3086.08 USD·ha⁻¹ for both varieties—a 6.60% increase and the highest overall benefit. Under MS treatment, economic benefits increased sequentially by 5.43%, 5.27%, and 5.76% as planting density increased from D1 to D2, D2 to D3, and D3 to D4, respectively. Conversely, D5 resulted in a 31.72% reduction relative to D4. DS and FS treatments exhibited lower average monetary benefits across density treatments, likely due to reduced RC grain yields.

4 Discussion

4.1 Moderate increases in planting density enhance forage and ratoon rice yield

The forage-ratoon rice (FG-RR) system represents a promising yet underexploited strategy for improving dual-season productivity and strengthening China's food security in regions already suitable for conventional ratoon rice cultivation^[18,19]. This study has demonstrated that, within an optimal planting density range, while delaying mowing to later stages can

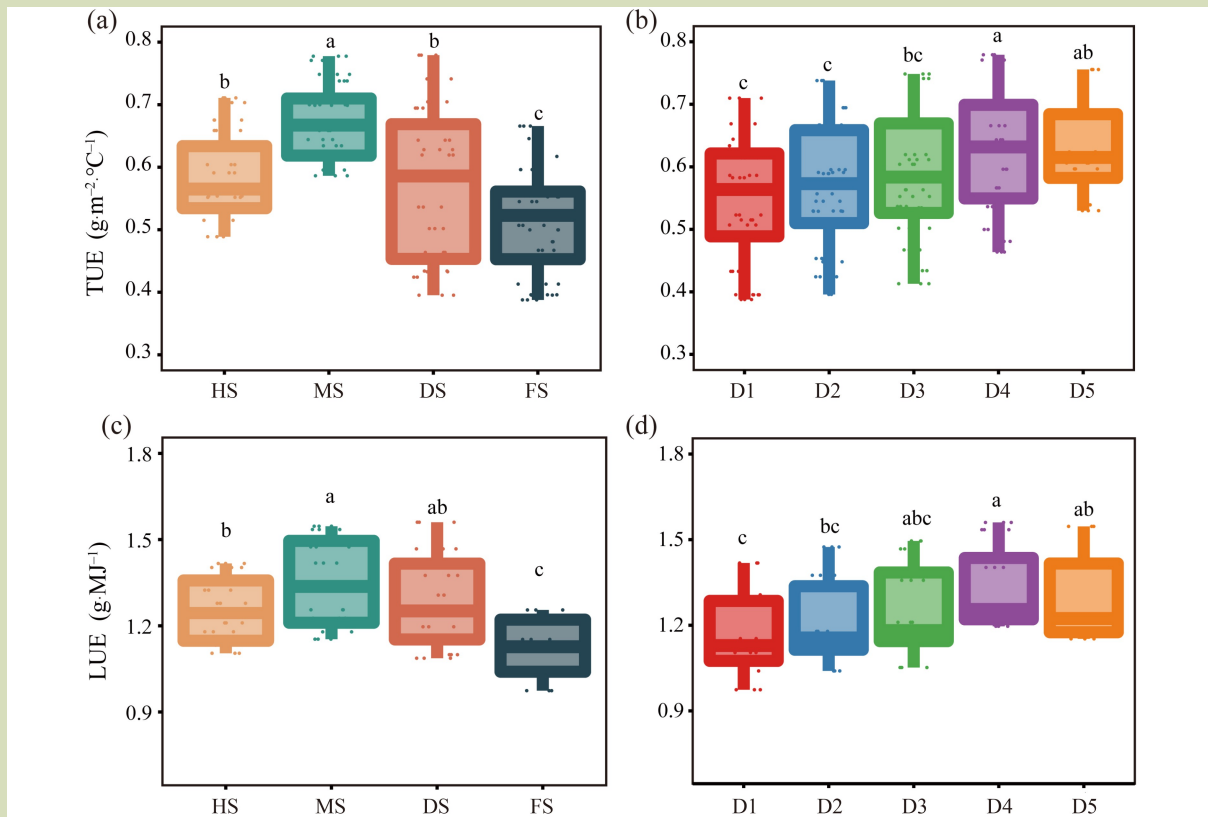


Fig. 4 Post-anthesis resource utilization efficiency of RC for different planting density and mowing time treatments. (a, b) Temperature utilization efficiency in 2021 and 2022 (TUE); (c, d) light utilization efficiency after heading in 2022 (LUE). HS, Heading stage; MS, Milk-ripening stage; DS, Dry-ripening stage; FS, Full maturity stage. D1, Planting density set to 17.2×10^4 hills ha^{-1} ; D2, Planting density set to 22.76×10^4 hills ha^{-1} ; D3, Planting density set to 25.34×10^4 hills ha^{-1} ; D4, Planting density set to 28.82×10^4 hills ha^{-1} ; D5, Planting density set to 34.52×10^4 hills ha^{-1} . Different lowercase letters in the box within each panel indicate significant differences between treatments at the $P < 0.05$ level.

maximize biomass (e.g., up to a 30.21% increase), the milk-ripening stage (MS) provides the optimal balance. This increase is physiologically attributable to the extended vegetative growth phase, which allows for greater interception of solar radiation and accumulation of biomass^[4,9]. While Cao et al.^[20] identified 22.4×10^4 hills ha^{-1} as the optimal MC planting density for conventional ratoon rice, this FG-RR system supports higher planting densities without compromising performance. This distinction reflects the system’s emphasis on maximizing high-quality forage biomass during the MC season, where strategic density increases optimize population structure and maximize resource capture capacity per unit area before severe inter-plant competition limits individual plant growth.

Mechanistically, the interaction between planting density and

mowing timing regulates RC yield through the coordination of source-sink dynamics. Before mowing, the stem sheath functions as a temporary “sink” for photosynthates; after mowing, it becomes the principal source supporting axillary bud regrowth^[21]. Our results suggest that mowing at the MS strikes a crucial physiological balance: it allows sufficient accumulation of non-structural carbohydrates in the stubble to fuel bud germination, while preventing the excessive translocation of assimilates to the MC panicles, occurring during the full maturity stage. Consequently, the D4 density under MS treatment achieved peak RC yields ($7.13 \text{ t}\cdot\text{ha}^{-1}$) and increased ratoon ability by 15.21% relative to the average of other density treatments. Furthermore, optimal density (D4) also improved canopy architecture. Unlike the highest density (D5), which intensified competition and mutual

Table 1 Comprehensive scores of TOPSIS in 2022

Mowing time	Planting density	D^+	D^-	C_i	Rank
HS	D1	3.163	0.186	0.056	15
	D2	3.160	0.185	0.055	16
	D3	3.155	0.188	0.056	14
	D4	3.139	0.206	0.062	4
	D5	3.149	0.192	0.057	11
MS	D1	3.135	0.200	0.060	7
	D2	3.130	0.203	0.061	5
	D3	3.127	0.208	0.062	3
	D4	3.108	0.233	0.070	1
	D5	3.127	0.208	0.062	2
DS	D1	3.156	0.188	0.056	13
	D2	3.167	0.172	0.051	18
	D3	3.160	0.169	0.051	19
	D4	3.146	0.179	0.054	17
	D5	3.168	0.157	0.047	20
FS	D1	3.222	0.199	0.058	9
	D2	3.213	0.197	0.058	10
	D3	3.210	0.192	0.057	12
	D4	3.185	0.204	0.060	6
	D5	3.187	0.199	0.059	8

Note: D^+ and D^- means the distance between the evaluation object and the positive and negative ideal solution, respectively; C_i means relative closeness ($C_i = D^- / (D^+ + D^-)$). HS, Heading stage; MS, Milk-ripening stage; DS, Dry-ripening stage; FS, Full maturity stage. D1, Planting density set to 17.2×10^4 hills ha^{-1} ; D2, Planting density set to 22.76×10^4 hills ha^{-1} ; D3, Planting density set to 25.34×10^4 hills ha^{-1} ; D4, Planting density set to 28.82×10^4 hills ha^{-1} ; D5, Planting density set to 34.52×10^4 hills ha^{-1} .

shading—resulting in excessive but weaker panicles and a reduced survival rate of lower axillary buds—D4 maintained an optimal population of robust tillers. By striking this balance, D4 prevented the dense-canopy penalty on grain filling, significantly improving the seed-setting rate (by up to 4.88% compared to D5) while sustaining a high effective panicle density. This trade-off reflects photosynthate allocation constraints: while higher densities maximize panicle number per unit area, they reduce assimilate availability for individual panicle development, resulting in fewer spikelets per panicle^[6,21].

4.2 Moderate increase in planting density Improves forage and grain quality in the FG-RR system

Because the FG-RR system aims to produce high-quality forage

while maintaining robust RC grain production, forage nutritional value is a critical indicator of the system’s performance alongside MC forage and RC grain yield enhancement. The variation in forage quality observed in this study is closely linked to canopy architecture and light penetration. High planting density intensifies inter-plant competition for light^[5]. This physiological response promotes stem elongation and secondary cell wall lignification to support taller plants, which explains our finding that excessive density (D5) increased NDF and ADF contents. These observations align with reports on maize and canola^[7,17,22], indicating a common trade-off between population density and forage quality. However, strategic management can mitigate these effects. The combination of D4 density and MS mowing produced high-quality forage (averaging 53.72% NDF and 9.93% protein content across both varieties). By harvesting at the milk-ripening stage, we effectively intercepted the crop

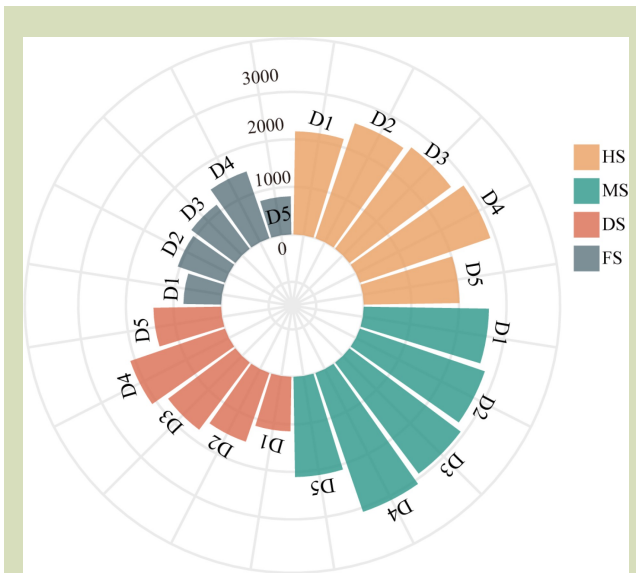


Fig. 5 Comparison of economic benefits under different planting density and mowing time treatments in 2022. The unit of economic benefit in the figure is USD-ha⁻¹. HS, Heading stage; MS, Milk-ripening stage; DS, Dry-ripening stage; FS, Full maturity stage. D1, Planting density set to 17.2×10^4 hills-ha⁻¹; D2, Planting density set to 22.76×10^4 hills-ha⁻¹; D3, Planting density set to 25.34×10^4 hills-ha⁻¹; D4, Planting density set to 28.82×10^4 hills-ha⁻¹; D5, Planting density set to 34.52×10^4 hills-ha⁻¹.

before the lignification process fully peaked (as seen in FS) while ensuring sufficient starch accumulation (averaging 21.26%) that had not yet been fully translocated to the grain. These findings align with previous reports^[4,21], suggesting that controlling the harvest window is critical for balancing carbohydrate retention and translocation in ratoon rice.

Regarding RC grain quality, high planting density typically reduced appearance quality due to diminished light availability and ventilation^[23]. However, our study demonstrated that optimizing mowing time can offset these density-related limitations. Early mowing of the MC enhanced RC grain filling by enabling the ratoon crop to exploit higher light intensity and temperature, thereby enhancing assimilate production and translocation. This optimization of thermal and light resources enhanced the photosynthetic rate and the efficient translocation of assimilates to the grains, thereby significantly reducing chalkiness and increasing the head rice rate compared to late-mowing treatments (FS), in which lower temperatures

disrupted starch-protein partitioning^[24]. Consequently, the D4-MS combination achieved exceptional milling quality, exemplified by the LY6326 variety, which maintained a head rice rate of 58.61% and low chalkiness (4.17%), meeting China’s high-quality edible rice standard (NY/T-593-2002).

4.3 Comprehensive evaluation of planting density under optimized mowing management

While previous studies have primarily focused on the impact of harvest timing on yield and quality^[4,10,25], the optimization of planting density to balance these attributes within the FG-RR system remains insufficiently explored. To address this gap, this study employed a multi-criteria evaluation framework combining the EW-TOPSIS model with economic benefit analysis. The adoption of the EW-TOPSIS model offers distinct advantages for optimizing the complex FG-RR system, which involves inherently conflicting objectives: maximizing forage biomass, grain yield, and quality traits. Unlike subjective weighting methods (e.g., analytic hierarchy process), the entropy weight method derives weights strictly from the information entropy of the dataset, effectively mitigating subjective bias and more accurately reflecting the informational contribution of each indicator^[26,27]. Nevertheless, the method is sensitive to data distribution: indicators with greater statistical dispersion receive higher weights, which may not perfectly align with biological stability or economic priorities^[28-30]. Despite this constraint, EW-TOPSIS provides a robust and mathematically rigorous framework for identifying optimal trade-offs within the scope of this study. Based on this evaluation, mowing at the milk-ripening stage (MS) combined with a planting density of D4 (28.82×10^4 hills-ha⁻¹) achieved the highest comprehensive score in 2022. Economic analysis corroborated this result, showing that the D4-MS treatment generated the highest profitability (3086.08 USD-ha⁻¹), largely due to the superior RC grain output. Although conventional ratoon rice may achieve higher net profits in specific high-yield regions^[2], the FG-RR system requires region-specific consideration of natural resources, labor availability, and production goals to maximize its ecological and economic benefits.

5 Conclusions

Under the agro-ecological conditions and management practices of this study, the D4 planting density ($28.82 \times$

10⁴ hills ha⁻¹) consistently outperformed other densities for both MC forage production and RC grain yield across two years. Moderately increasing planting density combined with mowing at the milk-ripening stage (approximately 10 days after flowering) not only improved forage quality but also

optimized RC yield by balancing panicle number and Spikelets per panicle. Consequently, this integrated strategy synergistically enhances both yield, quality, and economic benefits, thereby supporting the sustainable development and broader adoption of the FG-RR system.

Supplementary materials

The online version of this article at <https://doi.org/10.15302/J-FASE-2027718> contains supplementary materials (Figs. S1–S2; Tables S1–S16).

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Compliance with ethics guidelines

Qiuyuan Chen, Yan Hou, Guangyi Jia, Yajun Sun, Yafan Zhao, Jing Zhang, Quanzhi Zhao, Ting Peng, and Ye Liu 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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