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Synergistic effects of magnesium fertilisation and machine-transplanting density improve rice yield and grain quality

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Abstract: To clarify the regulatory mechanisms and optimal combinations of magnesium fertiliser application rates and machine-transplanting density on rice yield, quality, and magnesium uptake and utilisation in the hilly regions of Sichuan. This study utilised a two-factor split-plot design in field trials conducted from 2024 to 2025. The main plot was magnesium application rate, with four treatments: 0 kg/ha (Mg0), 30 kg/ha (Mg1), 45 kg/ha (Mg2), and 60 kg/ha (Mg3). With the secondary factor being machine-transplanting density, comprising three treatments: 14 cm × 30 cm (D1), 18 cm × 30 cm (D2), and 22 cm × 30 cm (D3). The study investigated the effects of interactions between magnesium fertiliser application rates and planting density on rice yield components, leaf physiological characteristics, dry matter transport, and magnesium fertiliser use efficiency. The results showed that, compared with the Mg0 treatment, the Mg3 treatment significantly increased rice yield, with the best results observed in combination with the D1 treatment, yielding a 14.52% increase over the Mg0 treatment. Dry matter transport in rice increased significantly with the application of magnesium fertiliser. Compared to the Mg0 treatment, the Mg3 treatment increased stem and leaf dry matter transport by 19.64%, and post-heading dry matter transport by 30.76%; the D1 treatment further optimised dry matter transport. Compared to the D3 treatment, the amount of stem and leaf dry matter transport, the transport rate, and the contribution rate to grain increased by 26.44, 34.28, and 40.32%, respectively. Magnesium uptake and utilisation efficiency were highest under the Mg3 treatment. Compared to the Mg0 treatment, magnesium uptake and utilisation efficiency increased by 31.25%, and the physiological utilisation rate of magnesium fertiliser increased by 24.71%; under the D1 treatment, the agronomic utilisation rate and uptake and utilisation efficiency of magnesium fertiliser increased by 38.22% and 20.20%, respectively, compared to the D3 treatment. Furthermore, the Mg3D1 treatment significantly increased the rice leaf area index and chlorophyll content, while simultaneously improving rice processing and appearance quality and reducing chalkiness and amylose content. This series of measures achieved synergistic optimisation of magnesium fertiliser application rates and machine-transplanting density.

Keywords: nutrient utilisation; population structure; photosynthetic characteristics; purple soil; source-sink balance

Rice is one of the world's staple foods and has long been widely used as a model crop in global research (Huang et al. 2018). However, with rapid economic development and ongoing population growth, food

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demand continues to rise, making food security a major global challenge. Therefore, adopting appropriate cultivation techniques to increase rice yields is crucial, as traditional methods fail to achieve expected yields. In rice production, yields are typically increased through the application of mineral fertilisers, higher machine-transplanting densities, and improved cultivation practices (Xu et al. 2017). However, over-fertilisation remains common among farmers, and excessive nitrogen fertiliser can lead to excessive nitrogen uptake by rice plants, resulting in increased nitrogen loss from the soil (Singh et al. 2025).

Magnesium (Mg) is the fourth most abundant nutrient after nitrogen (N), phosphorus (P), and potassium (K). It has an irreplaceable impact on crop physiology and plays a key role in plants' defence mechanisms against abiotic stress (Song et al. 2025). In agriculture, as the application of nitrogen, phosphorus, and potassium fertilisers increases, crops consume more and more magnesium from the soil. Furthermore, the reduced use of organic fertilisers, combined with a long-term lack of mineral magnesium supplements, has led to increasingly severe magnesium deficiency in soils (Li et al. 2025). Magnesium deficiency is most common in areas with highly weathered and acidic soils, as well as in regions with intensive farming practices (Liu et al. 2025). According to a national survey on magnesium nutrition, 45.3% of soils in China are severely magnesium-deficient (exchangeable magnesium content < 60 mg/kg), while 18.3% are relatively deficient (60–120 mg/kg). In northeastern China, the exchangeable magnesium content in soil ranges from 227 to 488 mg/kg, whereas in southern China, it ranges from only 32 to 89 mg/kg (Ishfaq et al. 2022).

Previous studies have reported that, at the same nitrogen fertiliser application rates, the application of magnesium fertiliser significantly promoted dry matter accumulation throughout the entire rice growth cycle, particularly from heading to maturity. This ensured that grains were well-filled and plump in the later stages of growth, thereby increasing yield (Chen et al. 2022). In rice fields with magnesium deficiency, applying magnesium fertiliser increased yield in proportion to the amount applied. Simultaneously, the application of magnesium effectively improves the brown-to-polished rice ratio and enhances the appearance and palatability of high-amylose rice varieties (Xiang et al. 2026). Within plants, magnesium ions (Mg^{2+}) constitute the largest proportion of divalent cations and serve as the central atom in chlorophyll molecules during photosynthesis (Cardoso et al. 2026).

In addition to magnesium content, machine-transplanting density is another critical factor influencing rice growth and yield. Machine-transplanting density is a key determinant of rice population structure and light energy utilisation efficiency. An appropriate machine-transplanting density optimises the spatial distribution of rice plants, enhances light capture and conversion efficiency, promotes the accumulation and distribution of photosynthetic products, and ultimately increases rice yield (Nasukawa and Tajima 2026).

Soils in the hilly regions of Sichuan are predominantly acidic and highly weathered, resulting in severe leaching losses of magnesium. The insufficient supply of available magnesium in the soil has become a major factor limiting improvements in rice yield and quality. At the same time, influenced by traditional cultivation practices, rice machine-transplanting density in this region is generally low, leading to low photosynthetic utilisation efficiency of the plant population; however, blindly increasing density can easily lead to issues such as canopy closure and intensified nutrient competition. Based on this, this study focuses on the synergistic regulation of magnesium fertiliser management and machine-transplanting density. It investigates the effects of interactions between different magnesium fertiliser application rates and planting densities on rice photosynthetic physiological characteristics, dry matter accumulation and transport, rice grain quality formation, and yield components. The study aims to identify the optimal coupling model between magnesium fertiliser and density, thereby providing a theoretical basis for green cultivation technologies that promote high-yield, high-quality rice production and efficient nutrient utilisation in the hilly regions of Sichuan.

Although there have been numerous reports on the effects of magnesium fertiliser application and machine-transplanting density on rice yield, most studies have focused on individual factors, and research on their interaction remains insufficient – particularly in the context of typical magnesium-deficient soils in the northwestern hilly region of Sichuan. Furthermore, while previous studies have primarily focused on yield effects, a comprehensive evaluation of rice physiological responses and economic benefits across different combinations of magnesium fertiliser application rates and machine-transplanting densities remains warranted. This

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study contributes to understanding the interaction between magnesium fertiliser application rates and mechanical transplanting density and their effects on rice production in the typical magnesium-deficient soils of the northwestern hilly region of Sichuan.

Currently, in magnesium-deficient areas of the Sichuan hilly region, the mechanism linking magnesium application rates and machine-transplanting density remains unclear, and there is a particular lack of evidence on appropriate magnesium fertiliser application rates. Therefore, this study aims to elucidate the underlying mechanisms governing the interaction between magnesium fertiliser application rates and machine-transplanting density. The specific objectives are: (1) to clarify the synergistic effects of magnesium fertiliser and machine-transplanting density on rice yield components and grain quality, and to identify the optimal application combinations; (2) to propose a high-yield, high-efficiency rice cultivation model suitable for the hilly regions of Sichuan, utilising magnesium supplementation to alleviate high-density stress, thereby achieving increased planting density without yield loss, while simultaneously improving quality and efficiency.

MATERIAL AND METHODS

Overview of the experimental site. The experiment was conducted from 2024 to 2025 at Guomei Family Farm in Zitong County, Mianyang City, Sichuan Province (31°32'N, 104°41'E). Data on temperature and precipitation during the local rice growing season were collected from a weather station near the experimental site, as shown in Figure 1. The topsoil (0–20 cm) contained 1.68 g/kg of total nitrogen, 0.53 g/kg of total phosphorus, 1.28 g/kg of total potassium, 182.76 mg/kg of alkali-hydrolysable nitrogen, magnesium content was 51.05 mg/kg, available phosphorus was 15.06 mg/kg, available potassium was 129.56 mg/kg, and the pH was 6.5. The test soil is paddy soil, classified as loam under the FAO soil texture and soil type classification system.

Experimental design. The experiment employed a two-factor split-plot design, with the main plot being the application rate of pure magnesium (Mg), set at 0 kg/ha (Mg0), 30 kg/ha (Mg1), 45 kg/ha (Mg2), and 60 kg/ha (Mg3); the sub-factor was machine-transplanting density, with treatments of 14 cm × 30 cm (D1), 18 cm × 30 cm (D2), and 22 cm × 30 cm (D3); the test rice cultivar was Shenyou Yuehe Simiao. The hybrid rice was sown on April 24 at a rate of 80 g of dry seed per tray (germination rate: 80%) and mechanically transplanted on May 18 using a Kubota rice transplanter from Japan. Each plot measured 40 m^2 and was set up with three replicates, for a total of 36 plots. The plots were separated by ridges, which were covered with black plastic sheeting to ensure independent irrigation and drainage for each plot. Protective rows were established around the perimeter, and field management practices followed local high-yield cultivation standards.

Fertiliser management. To ensure consistent background levels of nitrogen, phosphorus, and potassium across all treatments, a basal applica-

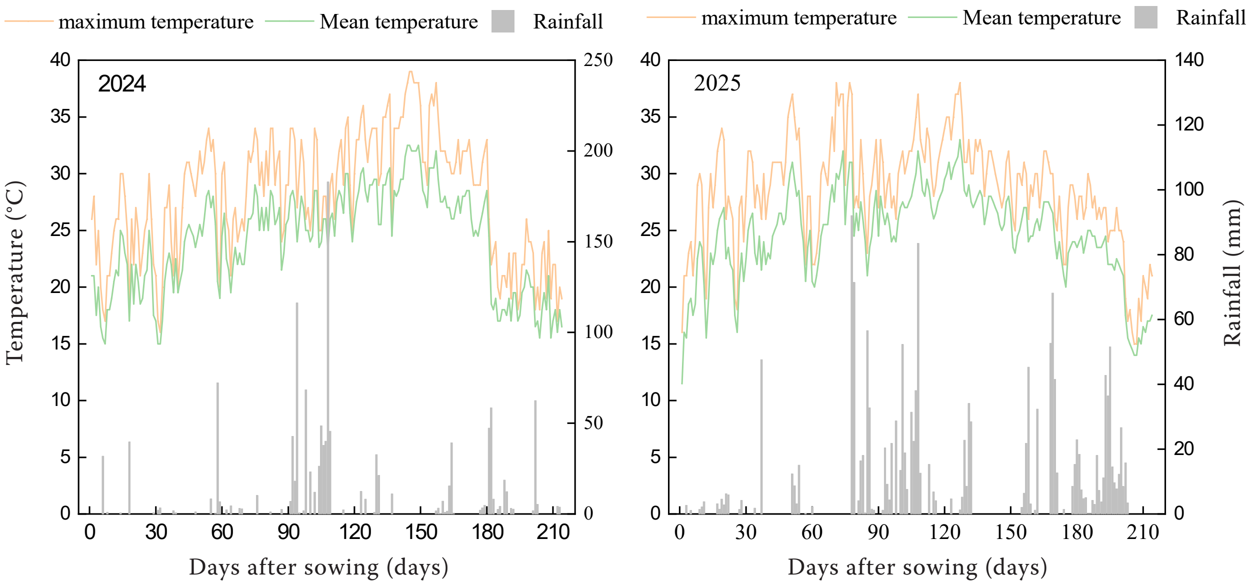

Figure 1. Meteorological data of the experimental area, including temperature and rainfall in 2024–2025

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tion of 150 kg/ha of compound fertiliser specifically formulated for rice was applied to all plots. The nutrient composition of this compound fertiliser was N-P_2O_5-K_2O = 25%-10%-15% (total nutrients ≥ 50%), with nitrogen in the form of amide nitrogen, phosphorus as water-soluble phosphorus, and potassium in the form of potassium sulfate. It contains no added magnesium or other trace elements and was broadcast in a single application one day before machine transplanting and tilled into the soil. The magnesium fertiliser used in this experiment was magnesium sulfate heptahydrate ($MgSO_4$•$7H_2O$). The application ratio of base fertiliser to topdressing was 5:5. The compound fertiliser and magnesium fertiliser for base fertilisation were applied in a single application one day before machine transplanting, while topdressing was applied at the four-leaf stage. Each magnesium application rate was quantified by the pure magnesium (Mg) content and labelled as Mg0 (no magnesium applied), Mg1, Mg2, and Mg3, respectively.

Measurements and methods

Variety evaluation and yield estimation. At the rice maturity stage, 15 plots were selected based on the average number of effective panicles for variety evaluation, and indicators such as grains per panicle, grain-setting rate, and thousand-grain weight were measured. At the same time, 30 plots were selected from each subplot to estimate yield on an actual-area basis.

Rice quality. The amylose content of milled rice was determined using a spectrophotometer. The determination of quality traits such as brown rice rate, milled rice rate, whole milled rice rate, chalky grain rate, chalkiness, and amylose content was conducted in accordance with the National Standard of the People's Republic of China, GB/T 1789-1999"High-Quality Rice".

Leaf area index. At the heading stage of rice, select three representative plants from each plot, cut off all leaves, measure the length and width of the rice leaves with a ruler, and calculate the leaf area index.

Chlorophyll content. After rice plants reach the heading stage, collect a labelled flag leaf from each plot every 7 days; the middle section of the leaf, with the midrib removed, is used as the test material. Procedure: take fresh rice flag leaves, remove the midrib, weigh 0.2 g of the chopped and mixed sample, place it in a 25 mL stoppered test tube, add 20 mL of 95% ethanol solution, seal the tube, and extract in the dark for 24 h until the leaves have completely lost their colour. Subsequently, shake to mix thoroughly, and measure the absorbance (OD) at 663 nm and 645 nm using a Shimadzu UV-4802 spectrophotometer (Kyoto, Japan), with the zero point adjusted using 95% ethanol. The calculation formula is as follows:

$$\text{Chlorophyll } a \text{ (mg/L)} = 13.95 \times \text{OD663} - 6.88 \times \times \text{OD645}$$

$$\text{Chlorophyll } b \text{ (mg/L)} = 24.96 \times \text{OD645} - 7.32 \times \times \text{OD663}$$

Nitrate reductase. Ten days after heading, the flag leaf from each plot was collected, and the mid-section of the leaf (with veins removed) was used as the test material. The assay was performed using a kit (micro-assay method) provided by Beijing Solarbio. The experimental procedure strictly followed the kit's operating instructions to ensure procedural standardisation and data reliability.

Dry matter accumulation. At the heading and maturity stages, three representative plants were selected from each plot. The coleoptiles, leaves, and panicles were blanched at 105 °C for 30 min, then dried at 75 °C to constant weight and weighed to calculate the dry matter content of the aboveground parts.

Total magnesium content in plants. Wash the samples with deionised water and blanch them in an oven at 105 °C for 30 min. Then dry them in an oven at 75 °C until constant weight is reached, weigh them, grind them, and pass them through a 100-mesh sieve. After acid digestion with $HClO_4$-HNO_3, determine the magnesium content using atomic absorption spectrophotometry.

The relevant calculation formula is as follows:

Magnesium accumulation (kg/ha) = (dry weight of aboveground biomass per plant × number of plants per hectare × total magnesium content) / 106

Agronomic utilisation rate of magnesium fertiliser (kg/kg) = (yield in magnesium-treated area − yield in non-magnesium-treated area)/magnesium fertiliser application rate

Absorption utilisation rate of magnesium fertiliser (%) = (magnesium accumulation per plant in magnesium-treated area − magnesium accumulation per plant in non-magnesium-treated area)/magnesium fertiliser application rate × 100%

Physiological utilisation rate of magnesium fertiliser (kg/kg) = (yield in magnesium-treated area − yield in non-magnesium-treated area)/(magnesium accumula-

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tion per plant in magnesium-treated area – magnesium accumulation per plant in non-magnesium-treated area)

Productivity contribution of magnesium fertiliser (kg/kg) = yield in magnesium-treated area/application rate of magnesium fertiliser

Data organisation and analysis. Data organisation and preliminary analysis were performed using Microsoft Excel 2016 (Microsoft, Redmond, USA). Subsequently, SPSS 2021 software (IBM, Chicago, USA) was used to perform a two-factor analysis of variance (ANOVA) with a split-plot design, with magnesium application rate as the main factor and machine-planting density as the secondary factor, to examine the main effects and their interactions on relevant rice indicators. Before conducting the ANOVA, the Shapiro-Wilk test was used to assess the normality of the data, and Levene's test was used to assess the homogeneity of variances, to verify the suitability of the ANOVA. In this study, a P-value of < 0.05 was used as the criterion for determining statistical significance. When treatment effects were significant, the least significant difference (*LSD*) test was used to perform multiple comparisons of the significance of differences among different treatments. This study focused on analysing pairwise differences between treatments; the *LSD* test offers high statistical sensitivity while reasonably controlling Type I errors, making it suitable for the characteristics of the experimental data and the analytical objectives of this study. Graphs and charts were generated using Origin 2021 software (OriginLab Corporation, Northampton, USA).

RESULTS

Effects of magnesium fertiliser application rates and mechanical transplanting density on rice yield and yield components. In a two-year field trial (Table 1), in 2024, under the same magnesium fertiliser treatments, the yield under the D1 treatment increased by 2.53% and 9.21% compared to the D2 and D3 treatments, respectively; under the same planting density conditions, as the amount of magnesium applied increased, rice yields followed a trend of Mg3 > Mg2 > Mg1 > Mg0, with yields under the Mg3 treatment being 1.56–8.12% higher than those of the other treatments. The yield trend in 2025 was consistent with that of 2024; under the same magnesium fertiliser conditions, the yield in the D1 treatment was 4.91–8.67% higher than in the other treatments; under the same planting density conditions, the yield in the Mg3 treatment was 3.65–10.10% higher than in the other treatments. In both 2024 and 2025, under all magnesium fertiliser treatments, the number of grains per panicle and the number of effective panicles in rice followed the pattern D1 > D2 > D3, with the D1 treatment exceeding the others by 6.94–9.73%, 5.13–9.61%, 3.18–3.57%, and 2.11–4.33%, respectively. In 2024, the grain-setting rate showed a trend of D2 > D3 > D1, with the D2 treatment increasing by 0.71–2.98% compared to other treatments; in 2025, under the Mg3 treatment, it increased by 2.26–4.97% compared to other treatments. Under the same density treatments, the number of effective panicles increased with increasing magnesium application rates; under the Mg3 treatment, the increase over other treatments was 3.45–10.22% and 1.56–13.93%, respectively. Overall, the yield in 2024 was 1.05% higher than in 2025, and the highest yield was achieved under the Mg3D1 treatment in both years.

Effects of magnesium fertiliser application rates and mechanical transplanting density on rice quality. Processing quality is typically expressed as brown rice yield, milled rice yield, and whole-milled rice yield (Table 2). A two-year field trial demonstrated that magnesium fertiliser application rates and machine-transplanting density had a significant impact on rice quality. Compared with the control (no magnesium fertiliser), the brown rice yield, milled rice yield, and whole milled rice yield all showed a significant upward trend as magnesium application rates increased over the two years. With the largest increases observed under the Mg3 treatment. Compared to other treatments, the increases were 1.19–3.7%, 2.03–6.94%, 1.20–4.25%, 0.47–2.81%, 1.29–6.52%, and 0.32–3.52%, respectively. Under the density treatments, the brown rice rate, milled rice rate, and whole milled rice rate in both years showed a trend of D1 > D2 > D3, with D1 exhibiting increases of 0.89–1.12%, 0.50–2.17%, 1.20–8.00%, 0.72–0.76%, and 1.34–1.67%, respectively, compared to the other treatment groups; however, for the whole-polished rice rate in 2025, the order was D3 > D1 > D2, with D3 showing an increase of 1.12–2.03% compared to the other treatment groups. Under the same density conditions, both the chalky grain rate and chalkiness decreased with increasing magnesium application over the two years, and the amount of magnesium fertiliser had a significant effect on the chalky grain rate and chalkiness. With the reduction in Mg3 compared to other treatment groups, ranging from 11.70–23.32%, 6.87–22.64%, 9.95–24.26%, and

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20.90–22.26%, respectively. Under the same magnesium fertiliser conditions, all density treatments showed increases as density increased. Compared with other treatments, the D3 treatment exhibited increases of 2.77% to 12.61%, 3.81% to 9.80%, 0.39% to 8.56%, and 8.95% to 13.39%, respectively. Under magnesium fertiliser treatments, the amylose content showed a trend of Mg3 < Mg2 < Mg1 < Mg0, with reductions in Mg3 compared to the other treatment groups ranging from 5.27% to 18.44% and from 5.22% to 15.56%, respectively.

Effects of the interaction between magnesium fertiliser application rate and mechanical transplanting density on the RVA spectral character-

Table 1. Effects of magnesium (Mg) fertiliser application rates and machine-transplanting density (D) on rice yield and yield components

Year (Y)	Treatment		Effective panicles ($\times 10^4$/ha)	Spikelets per panicle	Seed setting rate (%)	1 000-grain weight (g)	Yield (kg/ha)
2024	Mg0	D1	234.92^{bc}	209.98^{ab}	86.25^{b}	22.06^{c}	9 332.78^{ab}
		D2	230.86^{bc}	198.24^{ab}	89.75^{a}	22.56^{bc}	9 262.57^{ab}
		D3	203.03^{d}	193.81^{ab}	85.6^{b}	22.9^{ab}	8 590.67^{c}
	Mg1	D1	239.68^{bc}	216.26^{ab}	83.17^{c}	22.46^{c}	9 668.58^{ab}
		D2	235.8^{bc}	198.69^{ab}	89.48^{a}	23^{ab}	9 640.42^{ab}
		D3	221.21^{cd}	195.24^{ab}	84.89^{bc}	22.74^{bc}	9 044.22^{bc}
	Mg2	D1	255.56^{ab}	224.02^{ab}	86.46^{b}	23.12^{ab}	10 098.1^{ab}
		D2	233.33^{bc}	212.14^{ab}	84.26^{b}	23.63^{ab}	9 778.17^{ab}
		D3	230.3^{bc}	198.52^{ab}	88.47^{a}	22.86^{ab}	9 250.58^{ab}
	Mg3	D1	258.73^{a}	227.92^{a}	86.12^{b}	22.9^{ab}	10 535.59^{a}
		D2	251.85^{ab}	201.19^{ab}	85.73^{b}	23.13^{ab}	9 953.09^{ab}
		D3	234.34^{bc}	191.77^{b}	84.89^{bc}	23.89^{a}	9 099.32^{bc}
2025	Mg0	D1	217.46^{b}	205.59^{bc}	87.37^{bc}	23.58^{b}	9 205.01^{ab}
		D2	197.53^{c}	214.67^{ab}	90.3^{a}	23.27^{b}	8 904.65^{b}
		D3	196.97^{c}	202.87^{bc}	89.65^{ab}	23.99^{b}	8 622.2^{b}
	Mg1	D1	238.1^{a}	204.04^{bc}	83^{cd}	24.14^{b}	9 719.2^{ab}
		D2	230.86^{a}	199.24^{c}	85.29^{bc}	23.71^{b}	9 285.5^{ab}
		D3	229.29^{a}	192.01^{c}	85.3^{bc}	23.76^{b}	8 931.73^{b}
	Mg2	D1	239.68^{a}	214.76^{ab}	81.23^{cd}	23.97^{b}	10 005.67^{ab}
		D2	235.8^{a}	190.8^{c}	81.11^{d}	26.36^{a}	9 568.33^{ab}
		D3	224.24^{ab}	202.19^{bc}	87.66^{bc}	22.81^{b}	9 076.72^{ab}
	Mg3	D1	241.27^{a}	224.46^{a}	83.32^{bc}	23.4^{b}	10 544.46^{a}
		D2	239.51^{a}	192.24^{c}	87.76^{bc}	24.31^{b}	9 773.72^{ab}
		D3	230.3^{a}	186.28^{c}	89.83^{ab}	24.52^{b}	9 417.51^{ab}
F-value		Y	*	ns	ns	**	ns
		Mg	**	ns	**	*	**
		D	**	**	**	*	**
		Y × Mg	ns	ns	**	ns	ns
		Y × D	ns	ns	*	ns	ns
		Mg × D	ns	ns	ns	**	ns
		Y × Mg × D	ns	ns	ns	ns	ns

Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

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istics of rice starch. Two-year trials indicated that the effects of magnesium fertiliser application rate and mechanical transplanting density on the RVA spectral characteristics of rice starch were significant or highly significant (Table 3). Under the same magnesium fertiliser treatment conditions, the disintegration and reduction values of rice exhibited a trend of D1 > D2 > D3, with the D1 treatment showing increases of 2.70–5.42%, 4.67–13.87%, 5.29–13.62%, and 30.15–30.26% compared to the other treatment groups, respectively. Peak viscosity was highest in the D1 treatment in 2025, increasing by 8.70% compared to the D3 treatment, whereas the opposite was true in 2024, with the D3 treatment showing a 0.35% increase over the D1 treatment. Under identical density-treatment conditions, peak

Table 2. Effects of magnesium (Mg) fertiliser application rates and mechanical transplanting density (D) on rice quality

Year (Y)	Treatment		Brown rice rate (%)	Milled rice rate (%)	Head rice rate (%)	Chalky rice rate (%)	Chalkiness degree (%)	Amylose (%)
2024	Mg0	D1	75.22[bc]	64.97[d]	57.38[ab]	22.31[ab]	5.89[ab]	20.96[a]
		D2	74.79[c]	65.81[d]	56.73[ab]	24.97[a]	6.16[a]	21.08[a]
		D3	74.77[c]	65.14[d]	55.12[ab]	23.51[ab]	5.85[ab]	19.02[ab]
	Mg1	D1	77.42[c]	67.22[d]	57.76[ab]	19.54[b]	5.27[bc]	19.94[b]
		D2	76.60[c]	66.68[d]	57.58[ab]	20.65[ab]	5.46[bc]	19.08[ab]
		D3	76.78[c]	66.21[d]	50.53[b]	22.31[ab]	5.94[ab]	18.82[ab]
	Mg2	D1	78.35[ab]	69.52[ab]	58.32[a]	18.86[bc]	4.82[cd]	18.73[ab]
		D2	77.90[c]	68.40[bc]	57.82[ab]	19.41[b]	4.61[cd]	17.59[ab]
		D3	77.54[c]	68.35[bc]	55.01[ab]	20.58[ab]	5.25[bc]	16.88[c]
	Mg3	D1	78.76[a]	70.45[a]	60.21[a]	14.96[c]	3.89[d]	15.49[c]
		D2	77.68[c]	69.91[ab]	58.73[a]	19.13[bc]	4.96[cd]	16.94[c]
		D3	77.16[c]	69.79[ab]	54.29[ab]	20.18[b]	4.99[cd]	17.37[c]
2025	Mg0	D1	76.67[cd]	64.73[d]	55.48[cd]	24.68[ab]	7.34[bc]	21.75[a]
		D2	76.36[cd]	64.42[d]	54.90[cd]	25.97[a]	8.20[a]	20.75[ab]
		D3	75.88[d]	64.73[d]	54.85[d]	23.18[bc]	7.86[ab]	20.20[ab]
	Mg1	D1	78.38[a]	66.78[c]	56.29[cd]	21.60[bc]	6.78[bc]	20.20[ab]
		D2	78.17[ab]	66.27[c]	56.71[cd]	22.13[bc]	5.07[cd]	19.65[ab]
		D3	77.88[ab]	65.59[c]	59.87[ab]	22.75[bc]	6.34[cd]	19.57[ab]
	Mg2	D1	78.41[a]	69.29[ab]	54.17[cd]	19.21[c]	5.76[cd]	19.69[ab]
		D2	77.65[bc]	67.64[c]	58.14[bc]	20.00[bc]	5.31[cd]	18.98[bc]
		D3	77.88[ab]	67.84[c]	58.42[bc]	21.65[bc]	6.09[cd]	17.88[c]
	Mg3	D1	79.03[a]	70.17[a]	61.43[a]	15.28[d]	4.21[d]	16.27[c]
		D2	78.05[ab]	68.11[b]	53.02[cd]	19.89[c]	6.76[bc]	17.73[c]
		D3	78.46[a]	69.16[ab]	56.82[cd]	20.75[bc]	7.54[bc]	18.94[bc]
F-value	Y		*	ns	ns	ns	**	*
	Mg		**	**	ns	**	**	**
	D		ns	ns	*	**	*	ns
	Y × Mg		ns	ns	ns	ns	ns	ns
	Y × D		ns	ns	**	ns	ns	ns
	Mg × D		ns	ns	ns	*	*	*
	Y × Mg × D		ns	ns	ns	ns	ns	ns

Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

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viscosity, disintegration values, and reduction values reached their maximum in the Mg3D1 treatment, increasing by 21.43, 17.82, 80.71, 15.46, 13.07, and 48.16%, respectively, compared to the Mg0D1 treatment. The hot pulp viscosity under magnesium fertiliser treatments showed a trend of Mg2 > Mg3 > Mg1 > Mg0, with Mg2 showing increases of 3.21–7.60% and 2.90–8.74% compared to the other treatments.

Effects of magnesium fertiliser and mechanical transplanting density on the photosynthetic characteristics of rice. As shown in Figure 1, there were significant differences in the leaf area index of rice at the heading stage among the different treatments (Figure 2). In 2024, with the same magnesium fertiliser treatment, the leaf area index across different density treatments showed the trend D1 > D2 > D3.

Table 3. Effects of the interaction between magnesium (Mg) fertiliser application rate and machine-planting density (D) on the rapid visco-analyser (RVA) spectral characteristics of rice starch

Year (Y)	Treatment		Peak viscosity	Trough viscosity	Breakdown	Final viscosity	Setback
2024	Mg0	D1	3 022.00^{d}	1 919.67^{a}	1 435.67^{b}	2 875.33^{c}	–146.67^{a}
		D2	3 172.33^{cd}	2 061.67^{a}	1 510.67^{ab}	3 003.00^{bc}	–169.33^{ab}
		D3	3 340.33^{c}	2 058.67^{a}	1 548.33^{ab}	3 031.00^{bc}	–309.33^{bc}
	Mg1	D1	3 627.67^{ab}	2 132.67^{a}	1 628.33^{ab}	3 046.33^{bc}	–581.33^{cd}
		D2	3 610.00^{ab}	2 106.00^{a}	1 544.00^{ab}	3 115.67^{ab}	–494.33^{bc}
		D3	3 575.33^{b}	2 045.67^{a}	1 563.00^{ab}	3 095.33^{bc}	–480.00^{bc}
	Mg2	D1	3 782.67^{ab}	2 146.00^{a}	1 703.33^{ab}	3 154.67^{ab}	–628.00^{cd}
		D2	3 699.33^{ab}	2 211.00^{a}	1 655.00^{ab}	3 279.67^{a}	–419.67^{bc}
		D3	3 641.33^{ab}	2 180.33^{a}	1 527.67^{ab}	3 090.00^{bc}	–551.33^{cd}
	Mg3	D1	3 846.67^{a}	2 133.00^{a}	1 747.00^{a}	3 086.33^{bc}	–760.33^{d}
		D2	3 828.67^{ab}	2 100.00^{a}	1 628.67^{ab}	3 089.33^{bc}	–739.33^{d}
		D3	3 772.67^{ab}	2094.33^{a}	1521.67^{ab}	3096.00^{bc}	–676.67^{d}
2025	Mg0	D1	3 070.67^{c}	1 587.67^{bc}	1 183.00^{bc}	2 572.00^{a}	–498.67^{ab}
		D2	3 015.67^{bc}	1 466.67^{c}	1 315.67^{ab}	2 662.67^{a}	–353.00^{ab}
		D3	2 766.67^{bc}	1 505.67^{bc}	1 161.00^{bc}	2 594.00^{a}	–172.67^{a}
	Mg1	D1	3 467.67^{ab}	1 647.67^{ab}	1 153.33^{bc}	2 620.33^{a}	–847.33^{c}
		D2	3 304.00^{bc}	1 624.00^{bc}	1 080.00^{bc}	2 605.33^{a}	–698.67^{bc}
		D3	3 295.00^{bc}	1 600.33^{bc}	994.67^{c}	2 571.67^{a}	–723.33^{bc}
	Mg2	D1	3 513.00^{ab}	1 661.67^{ab}	1 284.67^{ab}	2 630.67^{a}	–882.33^{c}
		D2	3 440.67^{ab}	1 691.33^{a}	1 216.00^{bc}	2 697.00^{a}	–743.67^{bc}
		D3	3 331.67^{bc}	1 644.00^{ab}	1 087.67^{bc}	2 642.33^{a}	–689.33^{bc}
	Mg3	D1	3 632.33^{a}	1 671.33^{ab}	1 361.00^{a}	2 670.33^{a}	–962.00^{c}
		D2	3 174.67^{bc}	1 608.33^{bc}	1 106.33^{bc}	2 741.67^{a}	–433.00^{ab}
		D3	3 099.33^{bc}	1 572.33^{bc}	960.33^{c}	2 619.33^{a}	–480.00^{ab}
F-value		Y	**	**	**	**	*
		Mg	**	**	ns	**	**
		D	ns	ns	**	**	*
		Y × Mg	ns	ns	ns	ns	ns
		Y × D	**	ns	ns	ns	ns
		Mg × D	ns	ns	ns	ns	ns
		Y × Mg × D	ns	ns	ns	ns	ns

Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

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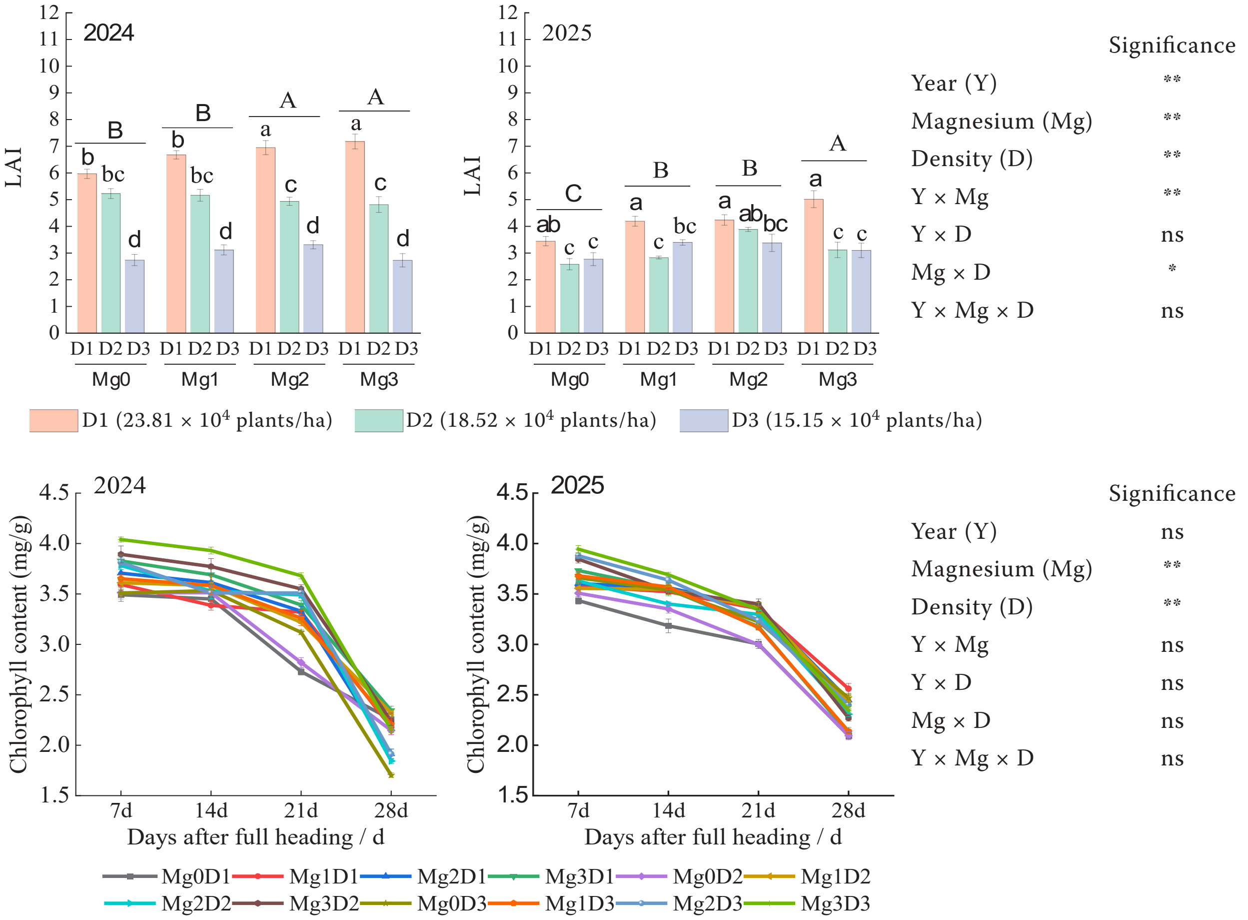

Figure 2. Effects of magnesium fertiliser application rates and mechanical transplanting density on rice leaf-related indices. Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

Compared to 2025, the trend in leaf area changes under density treatments was more pronounced in 2024, with the D1 treatment showing an increase of 24.75–55.58% compared to other treatment groups. In 2025, the leaf area index was higher under the D1 density treatment, increasing by 25.10–26.51% compared to other treatments. Under the same density treatments, the leaf area index in both years showed an upward trend with increasing magnesium application, reaching a maximum in the Mg3D1 treatment, which was 16.85% and 31.35% higher than the Mg0D1 treatment, respectively. Chlorophyll content peaked on the 7th day after heading and subsequently began to decline. In 2024, under magnesium fertilisation treatments, chlorophyll content showed an upward trend with increasing magnesium application rates, with the Mg3 treatment exhibiting a 3.92–10.61% increase compared to other treatment groups; under density treatments, chlorophyll content followed the pattern D3 > D2 > D1, with D3 showing a 1.42–2.61% increase compared to other treatment groups. Changes in rice chlorophyll content in 2025 were consistent with those in 2024. Under magnesium fertiliser treatments, the Mg3 treatment showed an increase of 3.55–7.95% compared to other treatments; under density treatments, the D3 treatment showed an increase of 5.05–6.31% compared to other treatments.

Effects of magnesium fertiliser and mechanical transplanting density on nitrate reductase activity in rice. In a two-year field experiment, nitrate reductase (NR) activity in rice peaked 14 days after heading (Figure 3). After day 14, NR activity across all treatment groups declined significantly. Both magnesium

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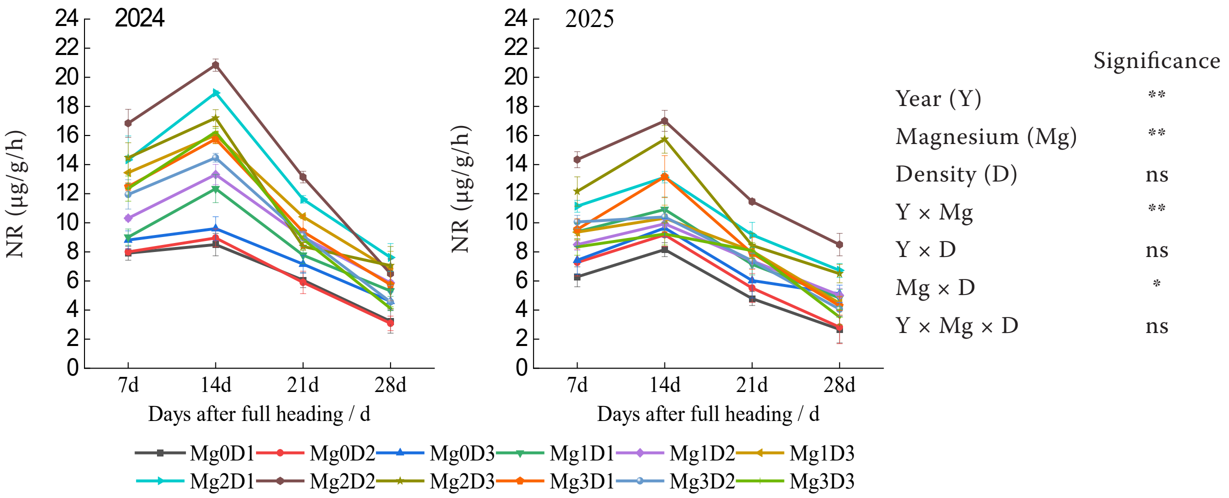

Figure 3. Effects of magnesium fertiliser application rates and mechanical transplanting density on rice leaf-related indices. Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); $^*P < 0.05$ (significant); $^{**}P < 0.01$ (highly significant); ns – not significant; NR – nitrate reductase

fertiliser application rate and machine-transplanting density had significant effects on rice NR activity after heading. At the same planting density, the application of magnesium fertiliser significantly increased NR activity after heading. Over both years, a trend of Mg2 > Mg3 > Mg1 > Mg0 was observed. Compared with Mg0, NR activity under the Mg1, Mg2, and Mg3 treatments increased NR enzyme activity by 35.10, 52.50, 41.79, 13.44, 41.21, and 17.79%, respectively, compared to Mg0. Under the same magnesium fertiliser treatments, NR enzyme activity in 2024 showed a trend of D3 > D2 > D1 as planting density increased, with D3 increasing by 5.97% and 2.48% over D1 and D2, respectively. In 2025, NR enzyme activity was highest under the D2 treatment, following a pattern of D2 > D1 > D3, with the D2 treatment showing increases of 2.45% and 3.41% compared to the D1 and D3 treatments, respectively. The results from both years indicate that the Mg2D2 treatment exhibited the highest NR enzyme activity at all stages after heading, exceeding that of the Mg0D1 treatment by 59.22% and 52.06%, respectively. NR enzyme activity showed significant inter-annual variation, with a 17.18% increase in 2024 compared to 2025.

Effects of magnesium fertiliser application rates and mechanical transplanting density on dry matter accumulation and transport in rice. A two-year field experiment demonstrated that different magnesium fertiliser application rates and machine-transplanting densities had highly significant effects on rice dry matter accumulation and transport at various growth stages (Table 4). During the heading and maturity stages, under all magnesium fertiliser treatments, the cumulative dry matter accumulation over the two years showed a clear upward trend with increasing magnesium application rates. With increases relative to the Mg0 and Mg1 treatments of 25.11–27.28%, 2.72–11.96%, 3.02–24.55%, and 3.17–27.35%, respectively, under the Mg3 treatment. Under the density treatments, dry matter accumulation consistently followed a D1 > D2 > D3 trend, with the D1 treatment exceeding the other treatment groups by 20.63–36.77%, 18.17–30.69%, 10.16–19.33%, and 10.32–19.71%, respectively. Dry matter accumulation over both years was highest under the Mg3D1 treatment, with accumulation at maturity significantly higher than at the heading stage, representing an average increase of 24.63%. Under magnesium fertilisation treatments, the dry matter transport volume, dry matter transport rate, and post-heading dry matter transport volume of rice stems and leaves over both years all followed the pattern Mg3 > Mg2 > Mg1 > Mg0. With the Mg3 treatment exceeding the Mg0 treatment by 16.49, 9.12, 22.75, 33.98, 12.48, and 27.54%, respectively. In 2024, the grain contribution rate was highest under the Mg3 treatment compared to Mg2, increasing by 12.59% relative to the Mg2 treatment; however, in 2025, the trend was reversed, with an increase of 9.15% relative to the Mg3 treatment. Under the density treatments,

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Table 4. Dry matter accumulation and transport in rice under different treatments

Year	Treatment		Dry matter accumulation (kg/ha)		Dry matter translocation amount from stems and leaves (kg/ha)	Dry matter translocation rate from stems and leaves (%)	Dry matter accumulation after heading (kg/ha)	Contribution rate to grain (%)
			full heading stage	maturity stage				
2024	Mg0	D1	11 365.87^{c}	14 817.46^{c}	2 111.90^{cd}	57.02^{ab}	3 451.58^{bc}	61.92^{b}
		D2	9 768.51^{d}	12 800.61^{d}	2 285.18^{cd}	55.56^{ab}	3 032.09^{c}	56.55^{bc}
		D3	8 004.54^{e}	10 917.67^{d}	1 879.79^{d}	44.86^{bc}	2 913.13^{c}	43.93^{cd}
	Mg1	D1	13 493.65^{b}	17 487.30^{b}	2 613.49^{bc}	62.85^{a}	3 993.65^{ab}	61.07^{b}
		D2	11 216.66^{c}	15 072.83^{c}	3 024.07^{ab}	60.40^{a}	3 856.17^{ab}	63.23^{b}
		D3	9 544.94^{d}	13 232.82^{d}	2 178.28^{cd}	44.98^{bc}	3 687.87^{bc}	40.85^{d}
	Mg2	D1	15 760.31^{b}	19 827.77^{b}	2 895.23^{ab}	54.64^{ab}	4 067.46^{ab}	67.94^{ab}
		D2	12 441.35^{b}	16 057.40^{b}	3 178.39^{b}	60.67^{a}	3 616.04^{bc}	62.25^{b}
		D3	9 752.52^{d}	13 648.48^{d}	1 744.44^{d}	37.23^{c}	3 895.95^{ab}	31.94^{de}
	Mg3	D1	17 198.41^{a}	21 511.11^{a}	3 673.80^{a}	62.75^{a}	4 312.69^{a}	77.73^{a}
		D2	12 458.02^{b}	16 325.30^{b}	2 830.24^{bc}	54.15^{ab}	3 867.28^{ab}	55.19^{bc}
		D3	9 254.04^{d}	13 239.39^{d}	1 012.62^{e}	23.72^{d}	3 985.35^{ab}	19.42^{e}
2025	Mg0	D1	8 103.96^{d}	10 852.38^{d}	1 665.07^{c}	64.52^{bcd}	2 748.41^{bc}	62.71^{bc}
		D2	8 664.81^{d}	11 076.54^{d}	2 187.03^{bc}	58.51^{cd}	2 411.72^{c}	64.01^{bc}
		D3	7 206.06^{e}	10 259.59^{d}	1 721.21^{c}	45.38^{d}	3 053.53^{bc}	41.46^{c}
	Mg1	D1	11 580.95^{b}	15 180.15^{b}	2 538.09^{ab}	69.05^{bc}	3 599.20^{bc}	66.12^{bc}
		D2	10 674.69^{c}	14 645.67^{b}	2 480.24^{ab}	54.90^{cd}	3 970.98^{ab}	52.04^{bc}
		D3	9 816.16^{d}	13 075.25^{cd}	2 538.88^{ab}	52.52^{cd}	3 259.09^{bc}	46.43^{bc}
	Mg2	D1	12 207.93^{b}	16 270.63^{b}	3 096.82^{ab}	77.52^{ab}	4 062.69^{ab}	74.73^{a}
		D2	11 522.22^{b}	15 422.83^{b}	2 605.55^{ab}	53.88^{cd}	3 900.61^{ab}	53.11^{bc}
		D3	10 351.01^{c}	13 419.69^{c}	2 599.49^{ab}	51.21^{cd}	3 068.68^{bc}	47.09^{bc}
	Mg3	D1	13 614.28^{a}	18 635.71^{a}	3 446.03^{a}	83.00^{a}	5 021.42^{a}	67.89^{ab}
		D2	10 021.60^{c}	13 503.08^{c}	2 531.48^{ab}	59.50^{cd}	3 481.48^{bc}	57.04^{bc}
		D3	9 334.84^{d}	12 168.18^{d}	2 464.64^{ab}	49.93^{cd}	2 833.33^{bc}	51.47^{bc}
F-value		Y	**	**	ns	**	*	ns
		Mg	**	**	**	ns	**	ns
		D	**	**	**	**	**	**
		Y × Mg	**	**	ns	ns	ns	ns
		Y × D	**	**	**	*	ns	*
		Mg × D	**	**	**	ns	ns	ns
		Y × Mg × D	*	ns	ns	ns	ns	ns

Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

the effects on stem and leaf dry matter transport volume, stem and leaf dry matter transport rate, and contribution rate to grain were all highly significant, showing a pattern of D1 > D2 > D3, with D1 showing increases of 0.21–39.65%, 2.73–36.44%, 11.71–49.32%, 8.76–13.23%, 22.88–32.31%, and 16.68–31.31% compared to the other treatment groups, respectively.

Effects of magnesium fertiliser application rates and mechanical transplanting density on magnesium accumulation. Two-year field trials indicated

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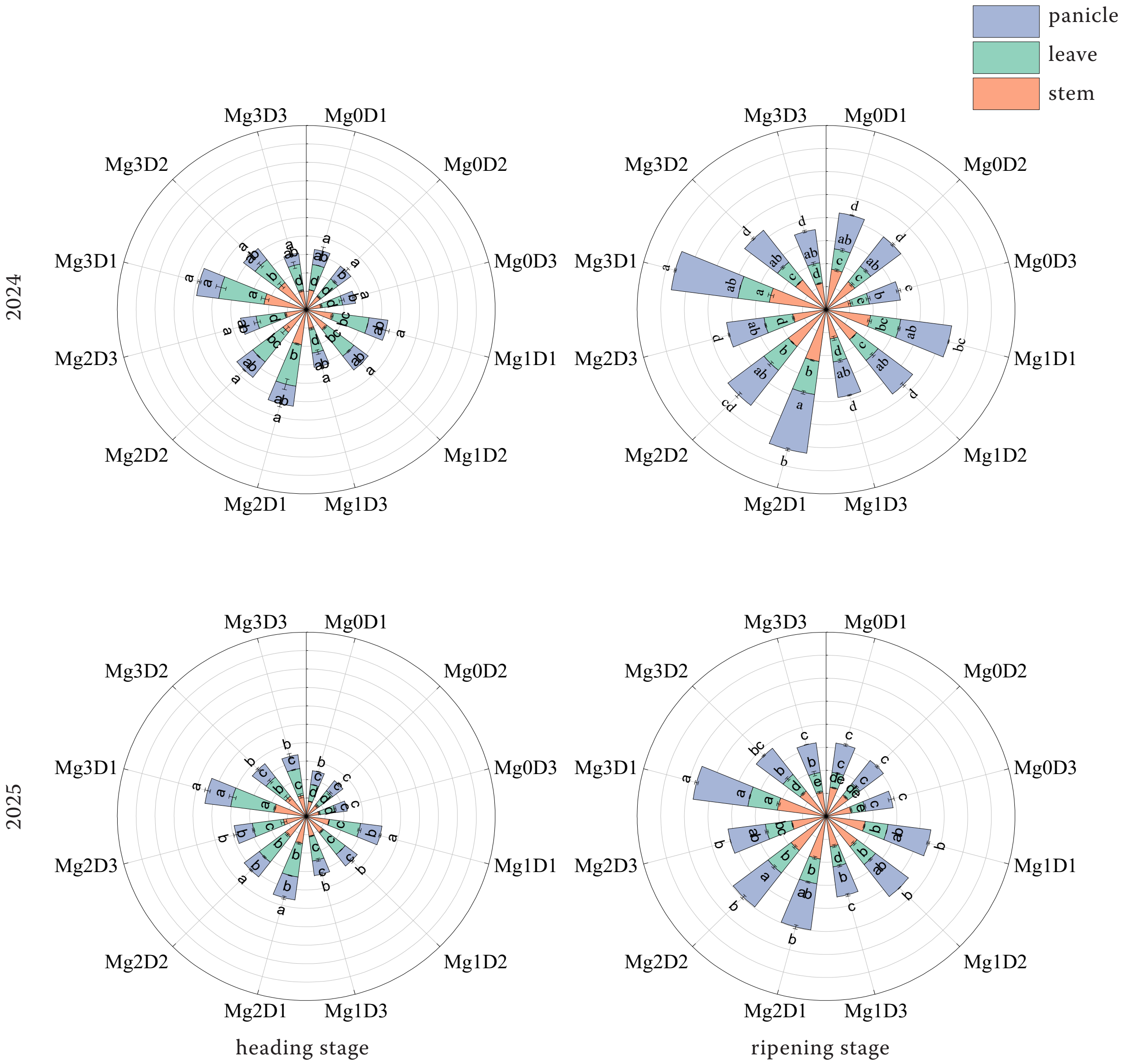

Figure 4. Effects of different treatments on magnesium accumulation in rice. Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant

that magnesium fertiliser treatments and mechanical transplanting density had significant effects on magnesium accumulation in various parts of rice at different growth stages (Figure 4). Magnesium accumulation at maturity was significantly higher than that at the heading stage. Under the same planting density, magnesium accumulation at the heading stage increased with increasing magnesium application rates; specifically, the Mg3 treatment group showed increases of 11.34–32.30% and 13.65–42.39% compared to the other treatment groups. Magnesium accumulation at maturity followed the order Mg3 > Mg0 > Mg1, with the Mg3 treatment showing increases of 4.45–21.19% and 8.26–19.69% compared to the other treatments. Under the same magnesium fertilisation conditions, magnesium accumulation across all planting densities followed the trend D1 > D2 > D3. The magnesium accumulation at the heading and maturity stages was 15.17–33.39%, 19.10–34.28%, 17.71–23.43%, and 10.27–23.38% higher than that of the D2 and D3 treatments, respectively. Regarding magnesium accumulation in different parts of the

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rice plant, at the heading stage, the order was leaves > stems > panicles. The difference in magnesium accumulation between stems and leaves was relatively small, while magnesium accumulation in leaves was 17.34, 47.11, 18.51, and 36.76% higher than that in stems and panicles, respectively. In contrast, at the maturity stage, the trend was reversed, with magnesium accumulation following the pattern of panicle > leaf > stem. Specifically, magnesium accumulation in the panicle was 9.24, 39.26, 5.85, and 43.38% higher than that in the stem and leaf, respectively.

Effects of magnesium fertiliser application rate and mechanical transplanting density on magnesium uptake and utilisation. Magnesium fertiliser application rate and mechanical transplanting density significantly affected the agronomic utilisation rate,

Table 5. Magnesium (Mg) uptake and utilisation in rice under different treatments

Year (Y)	Treatment		AE-Mg (kg/kg)	RE-Mg (%)	PE-Mg (%)	PFP-Mg (kg/kg)
2024	Mg0	D1	–	–	–	–
		D2	–	–	–	–
		D3	–	–	–	–
	Mg1	D1	12.68^{a}	20.39^{b}	71.08^{a}	323.78^{a}
		D2	10.24^{a}	19.35^{b}	66.86^{a}	318.99^{a}
		D3	9.18^{a}	19.17^{b}	64.86^{a}	294.51^{a}
	Mg2	D1	15.63^{a}	27.64^{b}	74.4^{a}	223.02^{b}
		D2	11.61^{a}	24.4^{b}	70.69^{a}	217.45^{b}
		D3	13.33^{a}	30.88^{ab}	66.89^{a}	203.54^{bc}
	Mg3	D1	19.97^{a}	41.38^{a}	82.46^{a}	175.51^{cd}
		D2	10.68^{a}	26.74^{b}	78.75^{a}	165.06^{c}
		D3	7.69^{a}	24.44^{b}	74.01^{a}	150.35^{c}
2025	Mg0	D1	–	–	–	–
		D2	–	–	–	–
		D3	–	–	–	–
	Mg1	D1	14.37^{a}	28.92^{bc}	59.06^{a}	321.2^{a}
		D2	11.06^{a}	27.83^{bc}	52.46^{a}	307.88^{a}
		D3	10.02^{a}	25.38^{c}	54.06^{a}	297.42^{a}
	Mg2	D1	18.37^{a}	36.08^{ab}	80.71^{a}	222.93^{b}
		D2	14.03^{a}	32.34^{bc}	76.16^{a}	211.91^{bc}
		D3	10.34^{a}	27.79^{bc}	74.69^{a}	201.95^{bc}
	Mg3	D1	20.8^{a}	44.24^{a}	92.17^{a}	174.22^{cd}
		D2	15.1^{a}	36.77^{ab}	87.4^{a}	163.51^{cd}
		D3	12.03^{a}	30.17^{bc}	77.69^{a}	155.73^{d}
F-value	Y		ns	**	**	ns
	Mg		ns	**	*	**
	D		*	**	*	**
	Y × Mg		*	ns	ns	ns
	Y × D		*	ns	ns	ns
	Mg × D		ns	*	ns	ns
	Y × Mg × D		ns	ns	ns	ns

Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively. Different lowercase letters to the right of the values indicate significant differences among treatments ($P < 0.05$); *$P < 0.05$ (significant); **$P < 0.01$ (highly significant); ns – not significant. AE-Mg – agronomic utilisation rate; RE-Mg – absorption utilisation rate; PE-Mg – physiological utilisation rate; PFP-Mg – partial productivity of magnesium fertiliser; D – density

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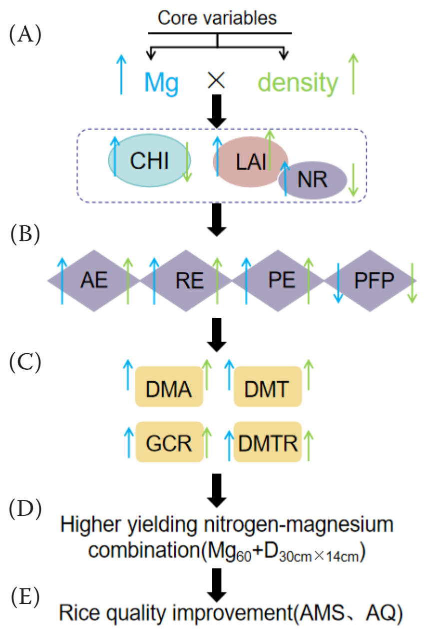
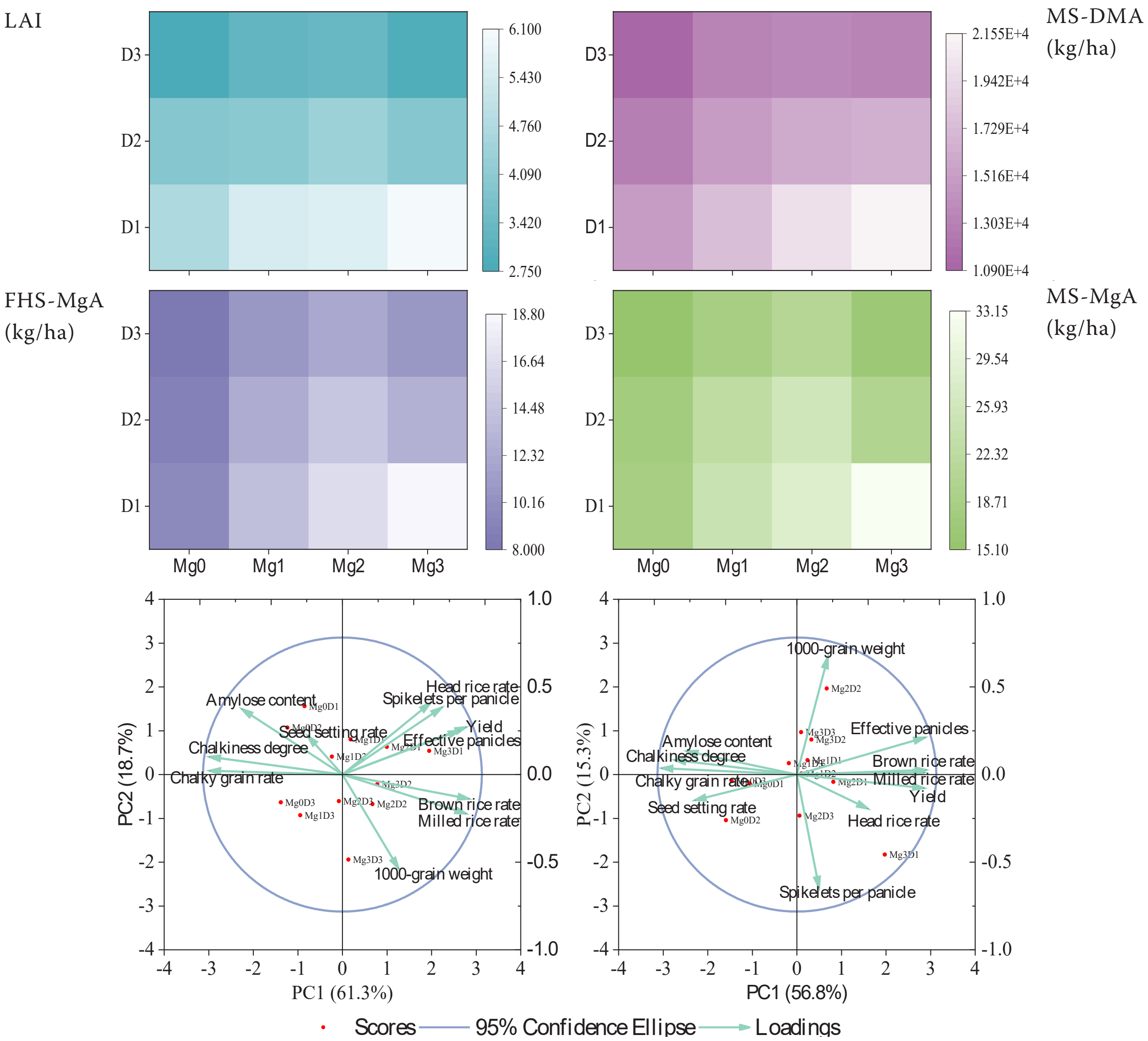


Figure 5. Comprehensive analysis of physiological indicators, yield, and quality under different magnesium fertiliser rates and mechanical transplanting densities. Mg0, Mg1, Mg2, and Mg3 – magnesium application rates of 0, 30, 45, and 60 kg/ha, respectively; D1, D2, and D3 – machine-transplanting densities of 238 100, 185 200, and 151 500 plants/ha, respectively; CHI – chlorophyll content; NR – nitrate reductase activity; AE – agronomic efficiency of magnesium fertiliser; RE – absorption efficiency of magnesium fertiliser; PE – physiological efficiency of magnesium fertiliser; PFP – net productivity of magnesium fertiliser; DMA – dry matter accumulation in stems and leaves; DMT – dry matter transport in stems and leaves; GCR – contribution rate to grain; DMTR – dry matter transport rate after heading; LAI – two-year average of leaf area index; MS-DMA – dry matter accumulation at maturity; FHS-MgA – magnesium accumulation at the heading stage; MS-MgA – magnesium accumulation at maturity



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uptake rate, physiological utilisation rate, and net productivity of magnesium in rice (Table 5). In 2024 and 2025, under the same magnesium fertiliser treatment conditions, the agronomic utilisation rate, absorption and utilisation rate, physiological utilisation rate, and magnesium fertiliser net productivity were all highest in the D1 density treatment, showing a trend of D1 > D2 > D3. With increases relative to other treatments ranging from 32.61% to 37.44%, 16.68% to 21.15%, 5.10% to 9.73%, 31.28–47.62%, 24.94–39.50%, 11.26–23.71%, 6.86–10.99%, and 31.26–46.73%, respectively. Compared with the D2 and D3 treatments, the D1 treatment significantly improved the magnesium fertiliser absorption efficiency of rice. Under the same density treatment, both absorption efficiency and physiological utilisation increased with increasing magnesium application rates, following the pattern Mg3 > Mg2 > Mg1. With increases in Mg3 compared to other treatment groups ranging from 10.42–36.37%, 9.88–13.78%, 13.47–26.13%, and 9.99–35.63%. Magnesium fertiliser productivity reached its maximum under the Mg1 treatment, increasing by 31.28, 47.62, 31.26, and 46.73% compared to the Mg2 and Mg3 treatments, respectively. In 2025, the agronomic utilisation rate of magnesium fertiliser was highest under the Mg3 treatment, increasing by 10.81% compared to Mg2. However, in 2024, it decreased slightly under the Mg3 treatment compared to Mg2, with a 5.49% decrease.

Comprehensive analysis of physiological indices, yield, and quality under different magnesium fertiliser rates and mechanical transplanting densities. The comprehensive analysis is presented below (Figure 5). The regulatory mechanisms of magnesium fertiliser application rates and machine-transplanting densities on various indicators were significant. By increasing magnesium fertiliser input and machine-transplanting density, these factors influenced rice chlorophyll content and leaf area index, thereby regulating magnesium fertiliser use efficiency, providing energy for rice dry matter accumulation, and ultimately supporting the increase in total dry matter and yield formation. Heatmaps and PCA were used to further identify the patterns and high-yield combinations under these regulatory conditions. Significant interaction effects were observed between different magnesium fertiliser levels and machine-transplanting densities on rice leaf area index (LAI), dry matter accumulation at maturity, magnesium accumulation at heading, and magnesium accumulation at maturity. As machine-transplanting density increased, LAI, MS-DMA, FHS-MgA, and MS-MgA all showed a marked upward trend and were significantly higher under the D1 treatment; simultaneously, as magnesium fertiliser application rates increased, these indicators also exhibited a clear upward trend, with the interaction between the two being most pronounced under the Mg3D1 treatment. Principal component analysis (PCA) identified yield and quality as the two core principal components. The results indicated that PC1 and PC2 accounted for 80% of the cumulative contribution in 2024 and 72.1% in 2025, effectively reflecting the characteristics of yield and quality traits over the two years. Furthermore, the 95% confidence ellipses for both years largely overlapped, indicating good stability of the experimental results. Significant differences

Table 6. Correlation analysis of rice yield and influencing factors

Indicator	GY	EP	SP	SSR	TGW	CHL	NR	DMA	MgA	AEMg
GY	1									
EP	0.921**	1								
SP	0.701*	0.458	1							
SSR	–0.740**	–0.756**	–0.550	1						
TGW	0.161	0.208	–0.304	–0.361	1					
CHL	0.334	0.476	–0.265	–0.128	0.491	1				
NR	0.452	0.513	0.129	–0.621*	0.545	0.459	1			
DMA	0.958**	0.880**	0.748**	–0.833**	0.125	0.226	0.544	1		
MgA	0.864**	0.794**	0.730**	–0.863**	0.179	0.074	0.644*	0.946**	1	
AEMg	0.935**	0.851**	0.954**	–0.654	–0.174	–0.069	0.267	0.963**	0.838**	1

GY – grain yiled; EP – effective panicles; SP – spikelets per panicle; SSR – seed-setting rate; TGW – 1 000-grain weight; CHL – chlorophyll; NR – nitrate reductase; DMA – dry-matter accumulation at maturity; MgA – magnesium accumulation at maturity; AEMg – agronomic efficiency of magnesium fertiliser; *P < 0.05; **P < 0.01

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Table 7. Correlation analysis of rice quality characteristics

Indicator	BRR	MRR	HRR	AC	CGR	CD
BRR	1					
MRR	0.898**	1				
HRR	0.576	0.520	1			
AC	–0.730**	–0.830**	–0.544	1		
CGR	–0.893**	–0.899**	–0.745**	0.818**	1	
CD	–0.839**	–0.748**	–0.831**	0.732**	0.903**	1

BRR – brown rice rate; MRR – milled rice rate; HRR – head rice rate; AC – amylose content; CGR – chalky grain rate; CD – chalkiness degree; *$P < 0.05$; **$P < 0.01$

were observed in various indicators across different treatments. Among them, chalkiness, chalky grain rate, grain-setting rate, and amylose content were all significantly negatively correlated with yield, while the number of fertile spikes, grains per spike, brown rice rate, milled rice rate, and whole milled rice rate were significantly positively correlated with yield. Under the Mg3D1 treatment, the number of fertile spikes, brown rice rate, and milled rice rate contributed most significantly to both yield and quality.

Correlation reflects the linear relationship between rice yield and its influencing factors and can be used to predict the impact of various trait indicators on yield. As shown in Table 6, the degree of correlation between yield and other trait indicators is as follows: dry matter accumulation at maturity > agronomic utilisation efficiency of magnesium fertiliser > number of fertile panicles > magnesium accumulation > number of grains per panicle > NR enzyme activity > chlorophyll > thousand-grain weight > grain-setting rate. Among these, dry matter accumulation at maturity, agronomic utilisation efficiency of magnesium fertiliser, number of fertile panicles, and magnesium accumulation showed a significant positive correlation with yield, while grain-setting rate showed a significant negative correlation with yield. These results indicate that dry matter accumulation at maturity, the agronomic utilisation efficiency of magnesium fertiliser, the number of fertile panicles, and magnesium accumulation have a significant impact on yield; improving any of these traits will increase yield.

To further clarify the intrinsic relationships among rice quality indicators, a correlation analysis was conducted on each quality indicator (Table 7). The results showed that the brown rice rate was strongly and highly significantly positively correlated with the polished rice rate, with a correlation coefficient of 0.898; meanwhile, the chalky grain rate and chalkiness were both strongly and highly significantly negatively correlated with processing quality indicators and extremely significantly positively correlated with amylose content. The amylose content showed a highly significant negative correlation with the polished rice yield, indicating that appearance and nutritional quality indicators exert a significant constraining effect on processing quality.

Effects of magnesium fertiliser application rates and mechanical transplanting density on the eco-

Table 8. Effects of magnesium fertiliser application rates and machine-planting density on the economic benefits of rice

Magnesium fertiliser treatment	Magnesium fertiliser level (kg/ha)	Magnesium fertiliser cost (yuan/ha)	Fixed cost (yuan/ha)	Total cost (yuan/ha)	Average grain yield (kg/ha)	Average output value (yuan/ha)	Average net profit (yuan/ha)
Mg0	0	0	10 720	10 720	8 986.31^{c}	25 161.67^{c}	16 175.36^{d}
Mg1	30	54	10 720	10 774	9 381.60^{b}	26 268.50^{b}	16 886.89^{c}
Mg2	45	81	10 720	10 801	9 629.59^{b}	26 962.86^{b}	17 333.26^{b}
Mg3	60	108	10 720	10 828	9 887.28^{a}	27 684.38^{a}	17 797.10^{a}

Fixed costs (seeds, pesticides, labor, etc.); magnesium sulfate heptahydrate ($MgSO_4·7H_2O$) was priced at 1.8 yuan/kg, and rice was priced at 2.8 yuan/kg; different lowercase letters following data in the same column indicate significant differences at the $P < 0.05$ level

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nomic benefits of rice. Economic benefits are a key constraint on whether a fertilisation regimen can be adopted on a large scale; input costs, yield returns, and fertiliser use efficiency must be considered comprehensively (Su et al. 2024). As shown by the average economic benefits of rice yields over the two years of this study (Table 8), as the application rate of magnesium fertiliser increased, rice yield, output value, and net profit all exhibited a significant upward trend. In terms of net profit, the economic performance of rice followed the order Mg3 > Mg2 > Mg1 > Mg0, with the Mg3 treatment yielding the highest net profit at 17 797.10 yuan/ha, representing increases of 10.03, 5.39, and 2.68% compared to the Mg0, Mg1, and Mg2 treatments, respectively. Although the cost of magnesium fertiliser increased, both production value and net profit under the Mg3 treatment were significantly higher than those of the other treatments. Based on a comprehensive analysis, 60 kg/ha is the optimal magnesium fertiliser application rate that balances high yields with high efficiency, and it holds practical value for real-world application.

DISCUSSION

The synergistic effects of magnesium fertiliser and planting density on rice yield and quality. As an essential macronutrient in photosynthesis, magnesium plays a key role in maintaining carbohydrate synthesis and facilitating transport between "sources and sinks," thereby enhancing crop yield and quality. In the hilly regions of northwestern Sichuan, where purple soils predominate, magnesium ions are primarily retained through adsorption by clay minerals and organic matter. The exchangeable magnesium content in these purple soils is only about 2.4 cmol (1/2 mg_+)/kg – far below the national average for Chinese soils. This inherent deficiency in magnesium retention capacity causes available magnesium to be easily leached with water, resulting in a naturally magnesium-deficient soil.

This study indicates that, compared with no magnesium application, the application of magnesium fertiliser significantly increases rice yield while simultaneously improving rice quality. Among the treatments, the Mg3 treatment showed the most significant yield increase; its mechanism of action does not simply depend on an increase in the number of effective panicles but is achieved through synergistic regulation with machine-transplanting density. Previous studies have shown that basal application of magnesium fertiliser can increase the number of effective tillers and the number of grains per panicle in rice, but has little effect on thousand-grain weight (He et al. 2024). At the same time, increased machine-transplanting density typically boosts yield by increasing the number of panicles per unit area; however, excessively high density can lead to a decline in stand quality, an increase in ineffective tillers, and a heightened risk of lodging due to an overly dense stand (Wang et al. 2020, Ouyang et al. 2025). This differs from the findings of the present study: under high-density conditions combined with high-magnesium treatment, not only did the yield reduction commonly associated with high density fail to occur, but a significant increase in yield was also achieved. This discrepancy may stem from the compensatory regulatory effect of magnesium fertilisation on the physiological functions of high-density stands, which effectively improved the photosynthetic performance and stem quality of the high-density stands, thereby increasing yield. Considering interannual environmental conditions, variations in temperature and precipitation primarily affect yield by altering photosynthetic efficiency, respiratory consumption, and grain filling status. In 2025, compared with 2024, the climate was milder, and moisture conditions were more balanced, resulting in higher photosynthetic accumulation efficiency and more complete grain filling, leading to a slight overall increase in yield. Even though there were marked climatic differences between the two years, the Mg3D1 treatment still yielded the highest output in both years. High magnesium supply effectively enhances the plants' ability to synthesise and transport biomass, complementing the high-density stand structure well and achieving stable yield increases under varying environmental conditions.

The application of magnesium fertiliser can significantly increase the maximum starch viscosity, hot paste viscosity, and disintegration value, while significantly reducing the final viscosity, recovery value, and reduction value, thereby improving rice quality (Anago et al. 2023). The findings of this study are consistent with those results. As an activator of key enzymes involved in starch synthesis, magnesium promotes the uniform transport of assimilates to the grain and the orderly accumulation of starch by regulating the activity of key enzymes such as amylosynthetase in the grain, thereby reducing the likelihood of chalkiness formation, and this process is also regulated by interannual climatic conditions;

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suitable temperature and humidity ensure stable grain filling, which further facilitates magnesium fertilisation's role in optimising the distribution of starch chain lengths and improving cooking quality. The application of magnesium fertiliser can effectively alleviate stress or amplify favourable conditions under various climatic backgrounds, thereby maintaining stable rice quality performance. Research findings on the effects of machine-transplanting density on cooking and sensory quality have been inconsistent. Some studies indicate that increasing planting density can improve the high-yield palatability of conventional japonica rice (Ge et al. 2022), while others suggest that increasing machine-transplanting density may worsen rice texture and reduce its sensory quality (Dong et al. 2022). This experiment indicates that rice quality improves significantly under high-density conditions; however, the effect of increased magnesium fertiliser on rice quality is far greater than that of machine-transplanting density. Therefore, an appropriate combination of machine-transplanting density and magnesium fertiliser can optimise ventilation and light penetration within the plant population, balance nutrient distribution, and simultaneously enhance the physiological process of starch synthesis. This leads to more thorough grain filling and a superior starch structure, thereby simultaneously improving both the appearance and processing quality of the rice.

The optimal structure of a rice stand directly determines the accumulation and distribution of photosynthetic products, and machine-planting density is a key means of regulating this structure. To increase yield, measures to increase machine-planting density are used to regulate the flow and distribution of dry matter among various organs at different growth stages of rice, thereby improving the efficiency of dry matter conversion. Adequate magnesium not only ensures the continuous synthesis of photosynthetic products but also maintains plant physiological activity, delays leaf senescence, and promotes the transport and accumulation of assimilates within the plant; these multiple effects collectively drive an increase in rice dry matter accumulation. In this study, dry matter accumulation was significantly higher under the high-density treatment.

Effects of magnesium fertiliser application rates and machine-transplanting density on selected physiological parameters and magnesium utilisation efficiency in rice. Rice flag leaves are the primary source of photosynthetic products transported to the panicle, and more than 90% of rice biomass comes from photosynthetic products, of which more than 90% are produced by photosynthesis in the leaves (Zhou et al. 2024).

Previous studies have shown that magnesium application can significantly increase chlorophyll content and net photosynthetic rate in rice flag leaves after heading, while also enhancing antioxidant enzyme activity, promoting the accumulation of osmoregulatory substances, and mitigating oxidative damage to photosynthetic tissues caused by reactive oxygen species, thereby maintaining normal physiological and biochemical activities in the leaves (Zhong et al. 2026). A study by Cao et al. (2024) also confirmed that an appropriate increase in plant density did not reduce stand productivity; in fact, increasing plant density not only raised rice SPAD values and leaf area index but also increased net photosynthetic rate. This is consistent with the findings of the present study. Building on this, the present study further elucidated the synergistic regulatory mechanism between magnesium fertilisation and machine-transplanted planting density: high-density cultivation tends to exacerbate premature leaf senescence and photosynthetic limitation due to canopy closure, whereas the enhancing effects of magnesium fertilisation on chlorophyll content and leaf area index are more pronounced in high-density stands. On the one hand, it compensates for the individual photosynthetic disadvantage caused by high density by strengthening the light energy capture and carbon assimilation capabilities of individual leaves; on the other hand, by enhancing the antioxidant defence system, it effectively alleviates the problem of premature leaf senescence under high-density stress, demonstrating the synergistic effect of magnesium fertilisation and planting density in maintaining the photosynthetic function of the stand. During rice growth, the uptake of various mineral elements is crucial for maintaining normal physiological and biochemical activities, as these elements play a vital role in enzyme activity and metabolism (Lamichhane et al. 2023). The activity of rice nitrate reductase is closely related to metabolic processes within the plant. In this study, appropriately increasing planting density was found to enhance nitrate reductase activity in rice leaves. This may be because dense planting optimises the canopy microenvironment, providing an ample supply of photosynthetic products. Combined with the auxiliary role of magnesium in enzymatic reactions, this further stabilises and enhances the enzyme's activity, thereby promoting nitrogen metabolism.

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Previous studies have shown that nitrogen uptake and assimilation by plant roots are energy-dependent processes that require the consumption of large amounts of Mg-ATP; at the same time, the activity of key enzymes involved in nitrogen assimilation is directly regulated by the plant's magnesium nutritional status (Chao et al. 2012). Magnesium application can enhance nitrogen absorption and utilisation efficiency by increasing Mg-ATP levels and the activity of nitrogen assimilation enzymes, thereby laying a physiological foundation for improving magnesium fertiliser utilisation efficiency. In this study, the high magnesium fertiliser utilisation efficiency in rice was the result of coupled regulation by magnesium fertiliser and mechanical transplanting density: the two factors synergistically enhanced the rice root system's ability to uptake magnesium, reduced soil magnesium fixation and leaching, ensured a continuous supply of magnesium to the plants, and, by increasing the activity of nitrogen assimilation-related enzymes, maintained the stability of cellular physiological structures, thereby further ensuring the normal functioning of root physiology. At the same time, the simultaneous increase in magnesium-to-productivity ratio clearly reflects the overall optimisation of magnesium absorption, transport, and metabolism, ultimately converting the nutrient advantage into yield gains. The regulatory effects on magnesium fertiliser utilisation were significantly influenced by interannual climate conditions: in 2025, favourable temperature and light conditions were more conducive to maintaining root vitality and magnesium absorption and transport, resulting in a higher overall magnesium fertiliser utilisation rate; in 2024, high temperatures during the grain-filling stage inhibited root function and reduced the efficiency of magnesium allocation to the leaves, resulting in a decline in utilisation rates. While magnesium fertilisation enhances magnesium uptake by the plant, it may also alter the distribution of magnesium among various organs during the maturity stage, which is consistent with the findings of Ye et al. (2025). Therefore, from the perspective of nutrient accumulation and distribution, magnesium fertilisation enhances the stability of nutrient supply during the later stages of rice growth by increasing magnesium absorption and its allocation to grains, thereby contributing to stable and increased yields.

This study indicates that in the hilly region of northwestern Sichuan, the coupled effect of magnesium fertilisation and machine-transplanting density further modulates the interaction between the two, and this synergistic effect is particularly pronounced in high-density stands. In this study, under the high-density treatment combined with high magnesium application, both magnesium accumulation in the rice aboveground parts and magnesium absorption and utilisation rates were significantly higher than in other treatment combinations. This suggests that by optimising the combination of magnesium fertilisation and machine-transplanting density, the synergistic effect between the two can be fully leveraged to achieve efficient utilisation of magnesium nutrients.

In conclusion, through field experiments, this study investigated the effects of magnesium fertiliser application rates and machine-transplanting density on rice yield, rice grain quality, and magnesium fertiliser use efficiency. The results indicate that the interaction between magnesium fertiliser application rate and machine-transplanting density significantly increases rice dry matter accumulation and yield, promotes leaf area index and chlorophyll content, and enhances NR enzyme activity to improve magnesium fertiliser absorption and utilisation efficiency. Correlation analysis clarified the intrinsic regulatory mechanisms among these indicators, leading to the core conclusion that: Mg3D1 is the optimal cultivation model for magnesium fertiliser application rate and machine-transplanting density in the hilly regions of Sichuan, providing a scientific theoretical basis for the sustainable development of rice production.

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