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The Use of Magnesium Fertilizer Can Improve the Nutrient Uptake, Yield, and Quality of Rice in Liaoning Province

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Abstract: In this study, the effects of the soil application and foliar spraying with magnesium fertilizers on rice yield and quality in Liaoning Province were investigated. Field experiments were conducted at Kaiyuan, Xinmin, and Dawa in 2022 and 2023. Magnesium fertilizers were used in the soil as magnesium sulfate monohydrate and silicon–magnesium fertilizer and on leaves was magnesium sulfate heptahydrate. The results showed that the application of 12 kg magnesium hm^{-2} in the soil at the Kaiyuan site can significantly increase rice yield by 14.8% compared with sites without magnesium fertilizer. The use of silicon–magnesium fertilizer showed a more obvious yield increase of 22.2%. The application of 3 kg magnesium hm^{-2} or 6 kg magnesium hm^{-2} on the leaf surface increased the rice yield at Kaiyuan by 19.4% and 21.6% and at Xinmin by 17.8% and 5.4%, respectively. The yield increase was more significant under the optimal fertilization treatment compared with the conventional fertilization treatment. The application of magnesium fertilizer increased the magnesium, nitrogen, and phosphorus contents in rice shoots and the potassium and crude protein contents in rice grains. The effect of foliar spraying with magnesium fertilizers was more obvious than soil application. Therefore, the magnesium fertilizer used on the leaf surface plays an important role in improving rice yield and quality in rice-growing areas with relatively rich soil magnesium content. Magnesium fertilizer can compensate for the yield decrease caused by the reduced use of nitrogen and phosphorus fertilizers by promoting nitrogen and phosphorus absorption in rice. Conclusively, the application of magnesium fertilizer is a promising measure to improve rice production in Liaoning province under a reduced nitrogen and phosphate fertilizer background.

Keywords: magnesium fertilizer; rice; rice yield and quality; foliar spraying; Liaoning province

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1. Introduction

Magnesium (Mg) is an essential nutrient for plant growth and plays diverse physiological functions in plant systems [1,2], mainly involved in chlorophyll synthesis, photosynthesis, and enzyme activation [3]. Magnesium deficiency can inhibit chlorophyll metabolism and plant photosynthesis, resulting in leaf chlorosis, stunted growth, and ultimately, a decline in crop yield and quality [4–8]. When the human body does not gain sufficient magnesium, various diseases, including high blood pressure, migraines, and other cardiovascular and cerebrovascular diseases can be induced [9]. In agriculture, with the increase in nitrogen, phosphorus, and potassium fertilizers used in soil, the crops take more and more magnesium out of the soil. In addition, the reduction in organic fertilizer use, coupled with a long-term lack of mineral magnesium fertilizer supplements results in increasingly serious magnesium deficiency in soil [10]. Magnesium deficiency most commonly occurs in regions where soils are highly weathered and acidic [11] and where intensive cropping systems are experienced [12]. According to the National Magnesium Nutrition Research Survey, 45.3% of soils in China are severely deficient in magnesium (60 mg kg^{-1}) and 18.3% are relatively deficient in magnesium (60–120 mg kg^{-1}) [13]. There is an obvious spatially declining trend in soil exchangeable magnesium (Mg_{ex}) from 227 to 488 mg kg^{-1} in Northeast China toward 32–89 mg kg^{-1} soil in South China [14]. Magnesium deficiency can be primarily traced back to a higher depletion of soil Mg_{ex} by fruits, vegetables, sugarcane, tubers, tea, and tobacco in tropical and subtropical climate zones.

At present, magnesium deficiency in crops is a widespread and urgent problem all over the world, and using magnesium fertilizers can significantly improve the productivity and quality of crops. Previous researchers reported that magnesium fertilizer increased the yield and quality of sugarbeet [15], oregano [16], potato [17,18], tomato [19,20], soybean and pomelo [21–23], rapeseed crops [24], and hazelnuts [25]. The foliar application of magnesium promoted the synthesis of chlorophyll and an increase in the yield of tomatoes, especially in the years characterized by unfavorable weather conditions [17]. The magnesium application on foliar depressed the content of nitrates (V) in tubers, which considerably increased during potato storage [18]. Magnesium-fortified phosphate fertilizers improve nutrient uptake and growth in soybeans [23]. The application of appropriate magnesium fertilizer could increase the seed yield of rapeseed plants [24] and increase the yield of hazelnuts by 51% and total oil content by 4.8% [25]. At present, the positive effect of magnesium fertilizers has gradually developed from cash crops to field crops, and the research related to the impact of magnesium fertilizer on rice is becoming more and more important [26].

Rice is one of the main food crops in the world, and it has an imperious demand for magnesium [27,28]. Soil Mg_{ex} for rice healthy growth is 243 mg kg^{-1} [29]. The application of mineral magnesium fertilizer could increase the chlorophyll contents in the leaves of rice [30], increase the number of effective tillers, and increase the yield of rice by 40.7% [31]. In red soil paddy fields in southern China, the average rice yield increased by 5–18% after using magnesium fertilizers [13]. Recent researchers reported that magnesium fertilizers improved the uptake of nitrogen and phosphorus [32,33], as well as enhanced the dry matter production and its translocation in rice [34]. In the southern regions of China, it has also been reported that magnesium concentrations in rice have undergone a clear decline over the past 60 years. This is most probably due to the dilution of magnesium associated with significant increases in grain yields as well as imbalanced mineral fertilization without considering crop demand for magnesium [35]. The effect of magnesium fertilizer on crop yield was related to the amount of magnesium used in soil and the sensitivity of different crops to magnesium. It was reported that the most suitable magnesium application amount was 24.2–25.3 kg hm^{-2} according to benefit and yield analysis, and 120 kg hm^{-2} magnesium could best improve the eating quality of rice [36]. The research and development of magnesium fertilizer application technology is currently in its infancy, and it still needs to be continuously developed and further explored.

At present, the research on magnesium nutrition and magnesium fertilizer application is mostly concentrated in Sichuan, Fujian, Jiangxi, Zhejiang, and other southern provinces in China [37]. However, there are few studies involving the effect of magnesium fertilizer application on rice yield and quality in northern China. Liaoning province lies in the northeast part of China and is an important rice growth region. However, the effect of magnesium fertilizer application on improving rice yield and quality in Liaoning province remains unclear, especially where soil magnesium content is relatively abundant in the region. In this study, we carried out two magnesium fertilizer experiments at four experimental sites in Liaoning province. Different amounts of magnesium fertilizers were used in paddy soil or on rice leaves to obtain reasonable local magnesium fertilizer dosage and methods. The results are expected to provide a theoretical basis for the scientific application of magnesium fertilizer in the rice growth region.

2. Materials and Methods

2.1. Experiment Sites

The experiments were carried out at Xinmin, Shenyang (40°99′71.63″ N, 122°68′58.18″ E), Kaiyuan, Tieling (123°54′10.4″ E, 42°33′03.9″ N experiment 1; 123°54′10.8″ E, 42°33′02.7″ N experiment 2), and Dawa, Panjin (122°3′28.7″ E, 41°0′37.9″ N) in Liaoning province in 2022. The four sites were chosen because of the different geographical locations, climatic conditions, soil types, and initial soil exchangeable magnesium contents. The soil physicochemical properties are shown in Table 1. pH was determined using a pH meter after water extraction (2.5:1 = water:soil), alkali-hydrolyzed nitrogen was determined by the alkali-diffusion method, available phosphorus was determined using the sodium bicarbonate extraction–molybdenum blue colorimetric method (UV–visible Spectrophotometer 752N, Shanghai, China), available potassium was determined using ammonium acetate extraction–flame spectrophotometry (Flamephotometer6400A, Shenzhen, China), and exchangeable magnesium was determined using NH_4OAc extraction-atomic absorption photometry (AAS-4530F, Shanghai, China).

Table 1. Physicochemical properties of soils at the four experiment sites in two experiments.

	Experiment Site	pH	Alkali-Hydrolyzable Nitrogen (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})	Exchangeable Magnesium (mg kg^{-1})
Experiment 1	Kaiyuan	5.66	178.4	18.9	113.0	245.1
	Dawa	8.32	161.8	20.6	175.3	351.9
Experiment 2	Kaiyuan	5.78	163.7	17.8	117.1	257.9
	Xinmin	7.66	168.1	22.9	133.3	403.1

2.2. Experiment Design and Treatments

Experiment 1: The experiment was arranged at the Kaiyuan and Dawa sites. The rice varieties were 'Meifeng 669′ and 'Yanfeng 47′, respectively. The experiment used a randomized block design. Each treatment was repeated three times. Each plot had a 300 m^2 area, which was surrounded by a higher ridge and was fertilized and irrigated separately. At harvest, a 1 m × 1 m area was selected at the center of the 300 m^2 plot, and all rice in the 1 m^2 area was collected for yield estimation and sample analysis. Chemical protection against diseases was used three times at the pre-transplanting stage, tillering stage, and jointing stage. The six treatments were conventional fertilization treatment (CON), optimized fertilization treatment (OPT), optimized fertilization treatment +6 kg magnesium hm^{-2} applied to the soil (OPT + Mg6S), optimized fertilization treatment + 12 kg magnesium hm^{-2} applied to the soil (OPT + Mg12S), optimized fertilization treatment + 3 kg magnesium hm^{-2} applied as a foliar spray (OPT + Mg3F), and optimized fertilization treatment + 12 kg magnesium hm^{-2} + 8.7 kg Si hm^{-2} applied to the soil (OPT + Mg12S-Si). The magnesium fertilizers were $MgSO_4 \cdot 7H_2O$ (Mg $\geq$ 9.7%) applied as foliar spraying, $MgSO_4 \cdot H_2O$ (Mg $\geq$ 13.4%), and magnesium–silicon fertilizer (Mg $\geq$ 9%, Si $\geq$ 6%) applied to the soil. The amount of fertilizers in each treatment is shown in Table 2. The CON treatment was designed according to the conventional operation of farmers, and the OPT treatment was recommended according to the Nutrient Recommendation System (NE) [38] based on the soil nutrient status of the experiment sites and the amount of fertilizers applied in the previous year. The phosphate and potassium fertilizers in the CON treatment were all applied as base fertilizers, and nitrogen fertilizer (urea) was applied at two rice growth stages (67% as basal fertilizer + 33% as tilling fertilizer). The phosphate fertilizer (calcium superphosphate) in the OPT treatments was used as basal fertilizer; potassium fertilizer (potassium chloride) was used as basal fertilizer (60%) on 20 April and grain fertilizer (40%) on 19 August; and nitrogen fertilizer was applied as basal fertilizer (40%) and tilling fertilizer (35%) on 22 June and grain fertilizer (25%) on 19 August. All magnesium fertilizers applied to the soil were used as basal fertilizers, while magnesium fertilizers as a foliar spray were sprayed twice on 22 June at the tillering stage (50%) and on 19 August at the seed tilling stage (50%), respectively, with a 4% aqueous solution of $MgSO_4 \cdot H_2O$. The amount of fertilizers in each treatment is shown in Table 2.

Table 2. Treatments and fertilizer rates in experiment 1.

Site	Treatment	Fertilizer Rates (kg hm^{-2})			
		Nitrogen	Phosphorus	Potassium	Magnesium
Kaiyuan	CON	188	37	50	0
	OPT	165	30	100	0
	OPT + Mg6S	165	30	100	6
	OPT + Mg12S	165	30	100	12
	OPT + Mg3F	165	30	100	3
	OPT + Mg12S-Si	165	30	100	12
Dawa	CON	292	72	62	0
	OPT	172	24	62	0
	OPT + Mg6S	172	24	62	6
	OPT + Mg12S	172	24	62	12
	OPT + Mg3F	172	24	62	3
	OPT + Mg12S-Si	172	24	62	12

Experiment 2: The experiment was arranged at the Kaiyuan and Xinmin sites. The experimental rice varieties were 'Jinliusi' and 'Beigeng16', respectively. The six treatments were conventional fertilization treatment (CON), conventional fertilization treatment + 3 kg magnesium hm^{-2} applied as foliar spray (CON + Mg3F), conventional fertilization treatment + 6 kg magnesium hm^{-2} applied as foliar spray (CON + Mg6F), optimized fertilization treatment (OPT), optimized fertilization treatment + 3 kg magnesium hm^{-2} applied as foliar spray (OPT + Mg3F), and optimized fertilization treatment + 6 kg magnesium hm^{-2} applied as foliar spray (OPT + Mg6F). The amount of fertilization for each treatment is shown in Table 3. The nitrogen, phosphorus, and potassium fertilizers were used in the soil at the same rice growth stages as in experiment 1. Magnesium fertilizer was $MgSO_4 \cdot 7H_2O$ ($Mg \geq 9.7\%$) and was used on the leaves twice at the tillering stage (50%) and the seed tilling stage (50%), respectively, with a 4% aqueous solution of $MgSO_4 \cdot H_2O$.

Table 3. Treatments and fertilizer rates in experiment 2.

Site	Treatment	Fertilizer Rates (kg hm^{-2})			
		Nitrogen	Phosphorus	Potassium	Magnesium
Kaiyuan	CON	200	35	50	0
	CON + Mg3F	200	35	50	3
	CON + Mg6F	200	35	50	6
	OPT	180	24	100	0
	OPT + Mg3F	180	24	100	3
	OPT + Mg6F	180	24	100	6
Xinmin	CON	225	39	62	0
	CON + Mg3F	225	39	62	3
	CON + Mg6F	225	39	62	6
	OPT	180	26	83	0
	OPT + Mg3F	180	26	83	3
	OPT + Mg6F	180	26	83	6

2.3. Yield Estimation and Element Determination

At harvest, the yield of rice in each treatment was recorded. The shoot and grain samples were collected. After being dried to a constant weight at 60 °C, all the samples were ground and decomposed. The contents of nitrogen, phosphorus, potassium, and magnesium in the shoots and grains of the different treatments were determined by the Kjeldahl method for nitrogen (Automatic Kieldahl apparatus JK9870A, Beijing, China), the vanadium molybdate yellow colorimetric method for phosphorus (UV–visible Spectrophotometer 752N, Shanghai China), the flame photometric method for potassium

(Flamephotometer6400A, Shenzhen, China), and atomic absorption spectrophotometry for magnesium (AAS-4530F, Shanghai, China). Crude fat in the grain was extracted by the Soxhlet extraction method (Yasuowang CC-6683-08, Shandong, China). The crude protein in the grain was determined by the Kjeldahl method (Automatic Kieldahl apparatus JK9870A, Shanghai, China).

2.4. Statistical Analysis

The diagrams were drawn by Microsoft Office Word2016, Microsoft software 2016 (Microsoft, Redmond, WA, USA), and Origin 2021 software (OriginLab Inc., Northampton, MA, USA). All values in this study are the means of three independent replicates. The results from the statistical analysis are presented as mean ± SD (n = 3). Deviations from normality and homogeneity of variance of the data were tested using the Kolmogorov–Smirnov statistical method ($p > 0.01$). One-way analysis of variance (one-way ANOVA) was employed to test the effect of magnesium fertilization on rice yield and quality. LSD at 5% probability was operated as a post hoc test to separate the means where the ANOVA indicated that significant differences were noted. Every analysis was performed using SPSS 19.0 data analysis software (IBM Inc., Amok, NC, USA).

3. Results

3.1. Rice Yield and 1000-Grain Weight

In experiment 1, at the Kaiyuan and Dawa sites, the yields of the optimized fertilization (OPT) and OPT + magnesium fertilizer treatments were significantly higher than the yield of the conventional fertilization (CON) treatment. At the Kaiyuan site, the yields of the OPT + Mg12S and OPT + Mg12S-Si treatments were higher than the yield of the OPT treatment. While at the Dawa site, the yield of OPT + Mg3F was higher than the yield of the OPT treatment. The results showed that the application of 20 kg hm^{-2} magnesium fertilizer at the Kaiyuan experimental site could significantly increase rice yield, and the effect of adding silicon was more obvious (Table 4).

Table 4. Yield and 1000-grain weight of rice under the different treatments in experiment 1.

Treatment	1000-Grain Weight (g)	Yield (kg hm^{-2})	1000-Grain Weight (g)	Yield (kg hm^{-2})
	Kaiyuan		Dawa	
CON	15.9 ± 6.7 b	10,327 ± 1062.0 c	23.4 ± 2.4 b	10,011 ± 432.0 c
OPT	22.0 ± 1.8 a	11,133 ± 352.5 bc	25.5 ± 0.4 ab	11,745 ± 238.5 ab
OPT + Mg6S	23.7 ± 0.1 a	10,969 ± 303.0 bc	25.0 ± 1.2 ab	11,568 ± 1174.5 ab
OPT + Mg12S	23.1 ± 1.2 a	12,786 ± 363.0 ab	24.2 ± 0.8 ab	11,445 ± 1101.0 ab
OPT + Mg3F	23.1 ± 1.9 a	10,848 ± 64.5 bc	24.9 ± 1.1 ab	12,967 ± 1026.0 a
OPT + Mg12S-Si	22.7 ± 2.1 a	13,615 ± 1425.0 a	26.5 ± 0.2 a	11,076 ± 1068.0 bc

Note: different letters after the data indicate significant differences between treatments at the same experimental site ($p < 0.05$), the same as below.

At the Kaiyuan and Dawa sites, the 1000-grain weight of rice under the OPT and OPT + magnesium fertilizer treatments increased significantly compared to the CON treatment, but the 1000-grain weights among several OPT + magnesium fertilizer treatments showed no significant differences (Table 4).

In experiment 2, at the Kaiyuan and Xinmin sites, the yields and 1000-grain weights of the OPT treatments decreased compared with that of the CON treatments. However, the OPT + magnesium fertilizer treatments significantly increased the yields and 1000-grain weights and thus eliminated the yield and 1000-grain weight decline induced by the OPT treatment. The magnesium fertilizer had no such influence on the yield and 1000-grain weight based on the FP treatment (Table 5).

Table 5. Yield and 1000-grain weight of rice under the different treatments in experiment 2.

Treatment	1000-Grain Weight (g)	Yield (kg hm^{-2})	1000-Grain Weight (g)	Yield (kg hm^{-2})
	Kaiyuan		Xinmin	
CON	25.6 ± 0.9 a	11,439 ± 168.0 b	27.1 ± 0.2 ab	11,263 ± 177.0 b
CON + Mg3F	24.5 ± 0.7 ab	10,830 ± 349.5 ab	26.7 ± 0.3 ab	11,407 ± 232.5 b
CON + Mg6F	24.9 ± 0.3 a	11,394 ± 294.0 b	26.5 ± 0.5 ab	11,013 ± 116.7 b
OPT	23.5 ± 0.6 b	10,308 ± 267.0 c	26.1 ± 0.4 b	10,456 ± 201.0 c
OPT + Mg3F	25.5 ± 1.1 a	12,306 ± 303.0 a	27.0 ± 0.3 ab	12,319 ± 163.5 a
OPT + Mg6F	25.4 ± 0.7 a	12,537 ± 289.5 a	27.2 ± 1.0 a	11,025 ± 141.0 b

3.2. Contents of Crude Fat, Crude Protein, and Starch in Rice Grain

In experiment 1, at the Kaiyuan site, the contents of crude fat and crude protein in the grain decreased in the OPT + Mg12S-Si treatment compared with those in the CON, OPT, OPT + Mg6S, OPT + Mg12S, and OPT + Mg3F treatments. At the Dawa site, the content of crude fat in the grain decreased in the OPT, OPT + Mg6S, OPT + Mg12S, and OPT + Mg3F treatments, but it increased in the OPT + Mg12S-Si treatment compared with the CON treatment. The content of crude protein among all treatments showed no significant differences (Figure 1).

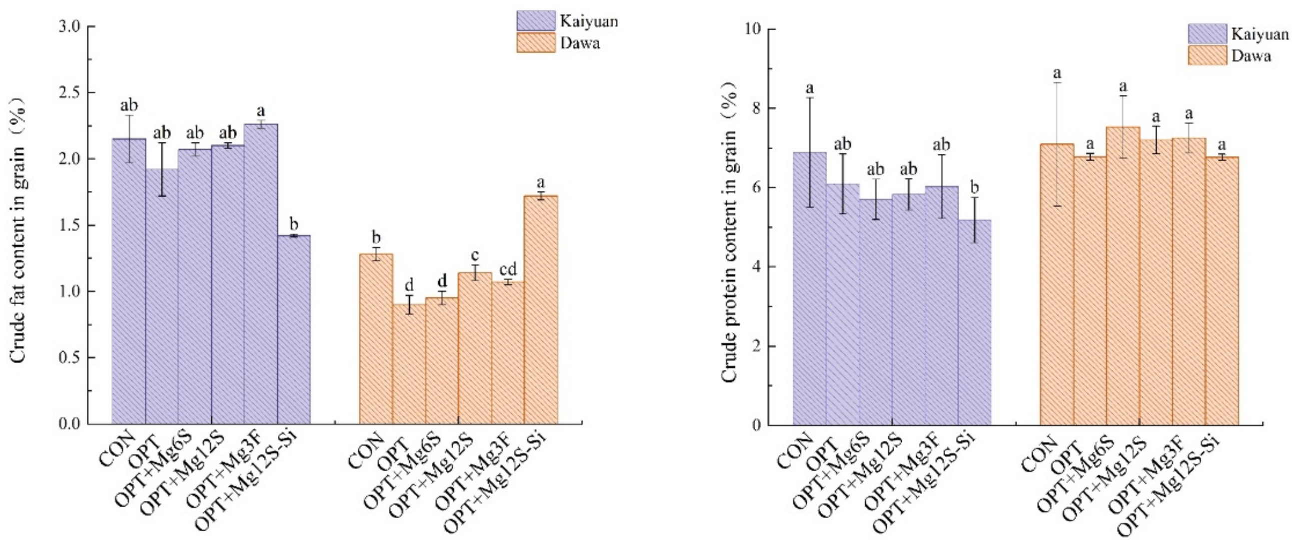

Figure 1. Crude fat and crude protein contents in rice grain in experiment 1. Different letters after the data indicate significant differences between treatments at the same experimental site ($p < 0.05$), the same as below.

In experiment 2, at the Kaiyuan site, the content of crude protein in the grain significantly increased under the OPT + Mg3F and OPT + Mg6F treatments compared with the OPT treatment, while the content of crude protein in the grain under the CON + Mg3F and CON + Mg6F treatments showed a slight increase compared to that under the CON treatment. The results suggest that the foliar spray of magnesium fertilizer helped rice accumulate protein in the grain. The starch contents in the grain showed no significant differences among all six treatments. At the Xinmin site, the content of crude protein in the grain slightly increased under the foliar spray of magnesium fertilizer treatments, while the content of starch showed no differences among the six treatments (Figure 2).

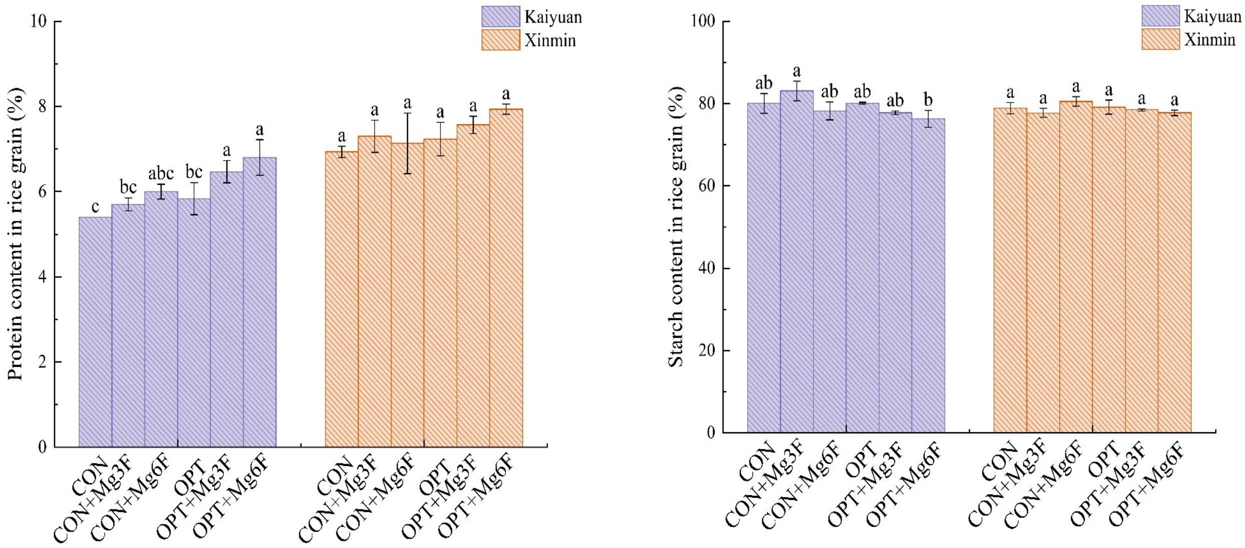

Figure 2. Crude protein and starch contents in rice grain in experiment 2.

3.3. Contents of Nitrogen, Phosphorus, Potassium, and Magnesium in Rice Shoots

In experiment 1, the nitrogen content in the shoots of rice treated with OPT was significantly lower than that of the CON treatment at the Kaiyuan and Dawa sites, which may be due to the reduced nitrogen application in the OPT treatment. The nitrogen content in the shoots increased after using magnesium fertilizers, and the OPT + Mg6S treatment had the highest shoot nitrogen content at the two experiment sites (Figure 3). The phosphorus content in the shoots of rice treated with OPT was significantly higher than that of the CON treatment at the Kaiyuan site but was not at the Dawa site. The OPT + Mg12S treatment increased the phosphorus content in the shoots at the Kaiyuan site, while the OPT + Mg6S, OPT + Mg12S, and OPT + Mg3F treatments all increased the phosphorus content in the shoots at the Dawa site compared with the OPT treatment. At the two sites, the OPT + Mg12S-Si treatment decreased the phosphorus content in the shoots, which may be because the magnesium silicon fertilizer decreased the phosphorus availability in the soil (Figure 3). The potassium content in the shoots of rice treated with magnesium fertilizer significantly increased compared with the CON and OPT treatments at the Kaiyuan site, while at the Dawa site, only the OPT + Mg12S-Si treatment increased the potassium content in the shoots (Figure 3). The magnesium content in the shoots of rice treated with magnesium fertilizer did not increase; on the contrary, the OPT + Mg6S treatment at the Kaiyuan site and the OPT + Mg6S and OPT + Mg12S treatments at the Dawa site decreased the magnesium content of the shoots (Figure 3).

In experiment 2, the OPT treatment did not influence the nitrogen, phosphorus, potassium, or magnesium contents in shoots compared to the CON treatment at the two experiment sites. At the Kaiyuan site, the foliar magnesium fertilizer slightly increased the nitrogen and phosphorus contents and significantly increased the magnesium content but did not change the potassium content in the rice shoots. At the Dawa site, foliar magnesium fertilizer increased the nitrogen, phosphorus, and magnesium contents and decreased the potassium contents in the rice shoots (Figure 4).

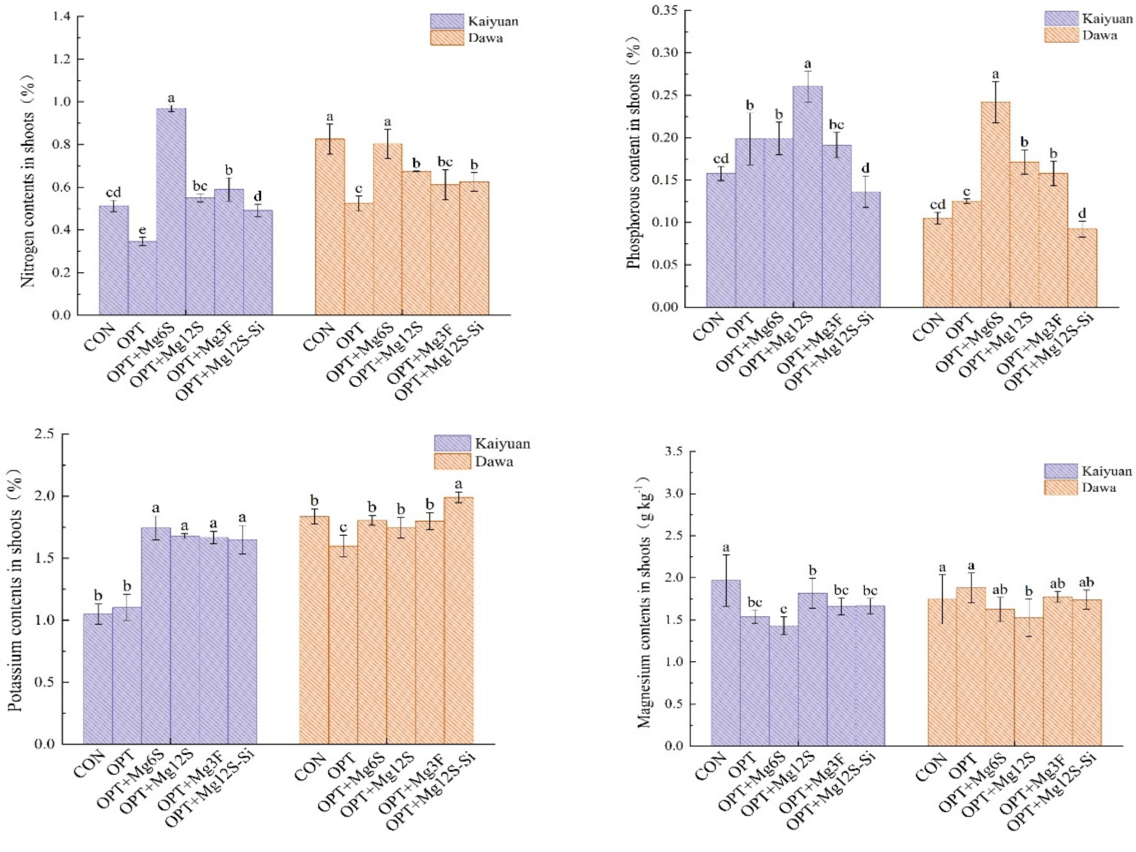

Figure 3. Nitrogen, phosphorus, potassium, and magnesium contents in rice shoots in experiment 1.

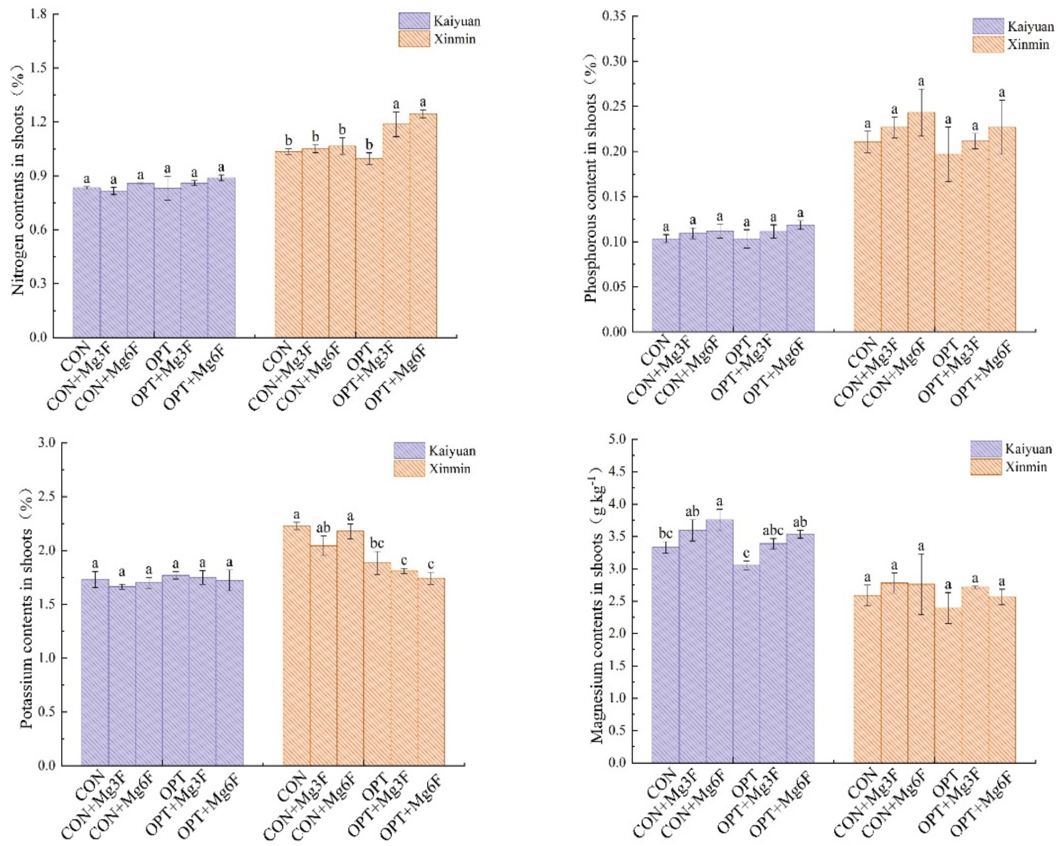

Figure 4. Nitrogen, phosphorus, potassium, and magnesium contents in rice shoots in experiment 2.

3.4. Contents of Nitrogen, Phosphorus, Potassium, and Magnesium in Rice Grain

In experiment 1, at the Kaiyuan site, the nitrogen contents in the grains were significantly lower in the OPT and OPT + magnesium fertilizer treatments than in the CON treatment. Compared with the OPT treatment, the OPT + magnesium fertilizer treatments increased the nitrogen contents in the rice grains; specifically, the OPT + Mg6S and OPT + Mg3F treatments had a larger increase extent. At the Dawa site, the nitrogen contents in the grains showed no notable differences among all treatments. The phosphorus, potassium, and magnesium contents in the rice grains at the two sites showed no consistent changes (Figure 5).

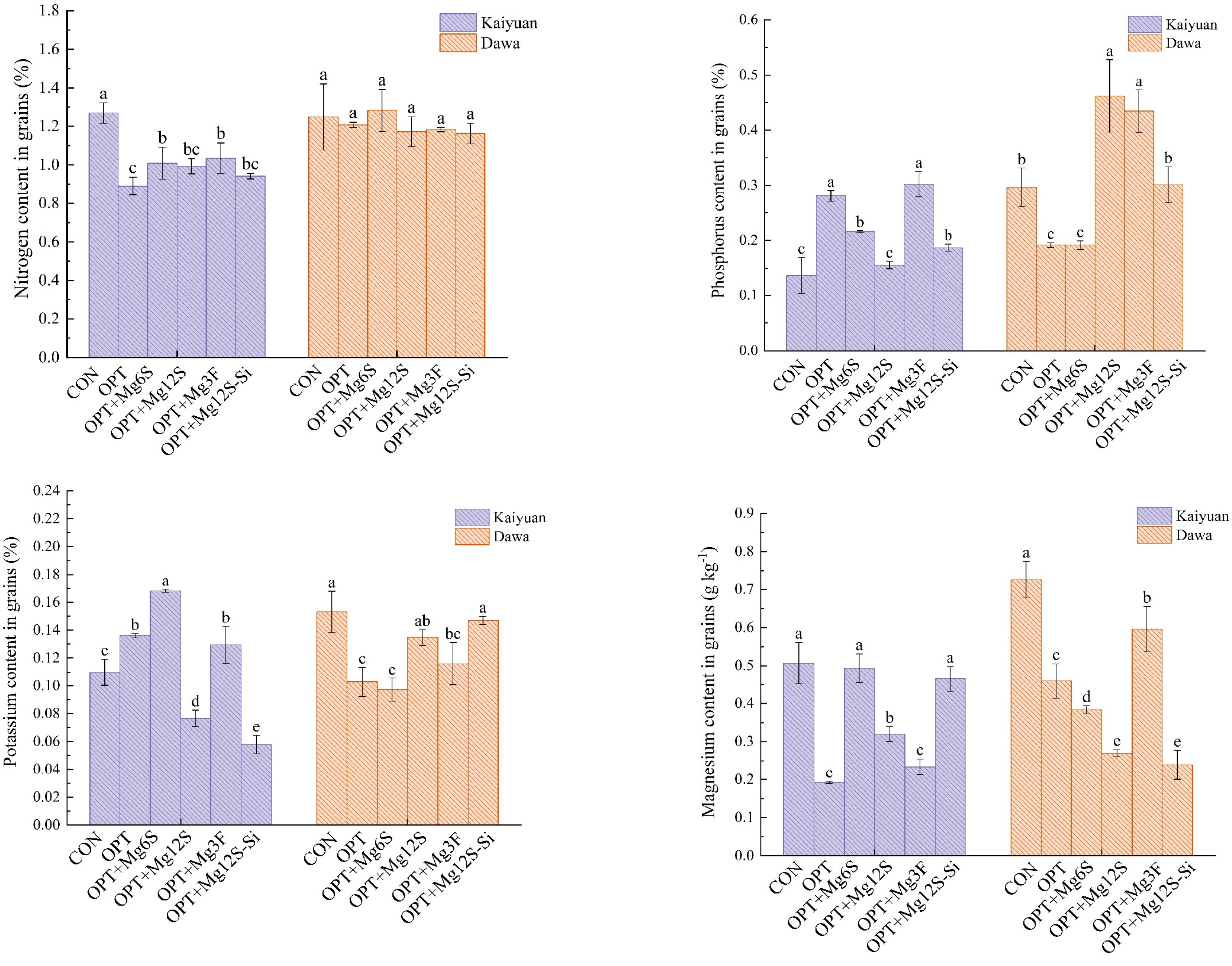

Figure 5. Nitrogen, phosphorus, potassium, and magnesium contents in rice grains in experiment 1.

In experiment 2, at the Kaiyuan site, the OPT treatment decreased the nitrogen and phosphorus contents but did not affect the potassium and magnesium contents in the rice grains compared to the CON treatment. Foliar magnesium fertilizer use significantly increased the nitrogen, phosphorus, and potassium contents in grains only based on the OPT treatment but not on the CON treatment. Foliar magnesium fertilizer use had no notable influence on the magnesium content in the rice grains at the Kaiyuan site. While, at the Dawa site, the OPT treatment increased the phosphorus and magnesium contents but did not affect the nitrogen and potassium contents in the rice grains compared to the CON treatment. Foliar magnesium fertilizer use increased the nitrogen, phosphorus, and potassium contents in the grains based on both the OPT and CON treatments (Figure 6).

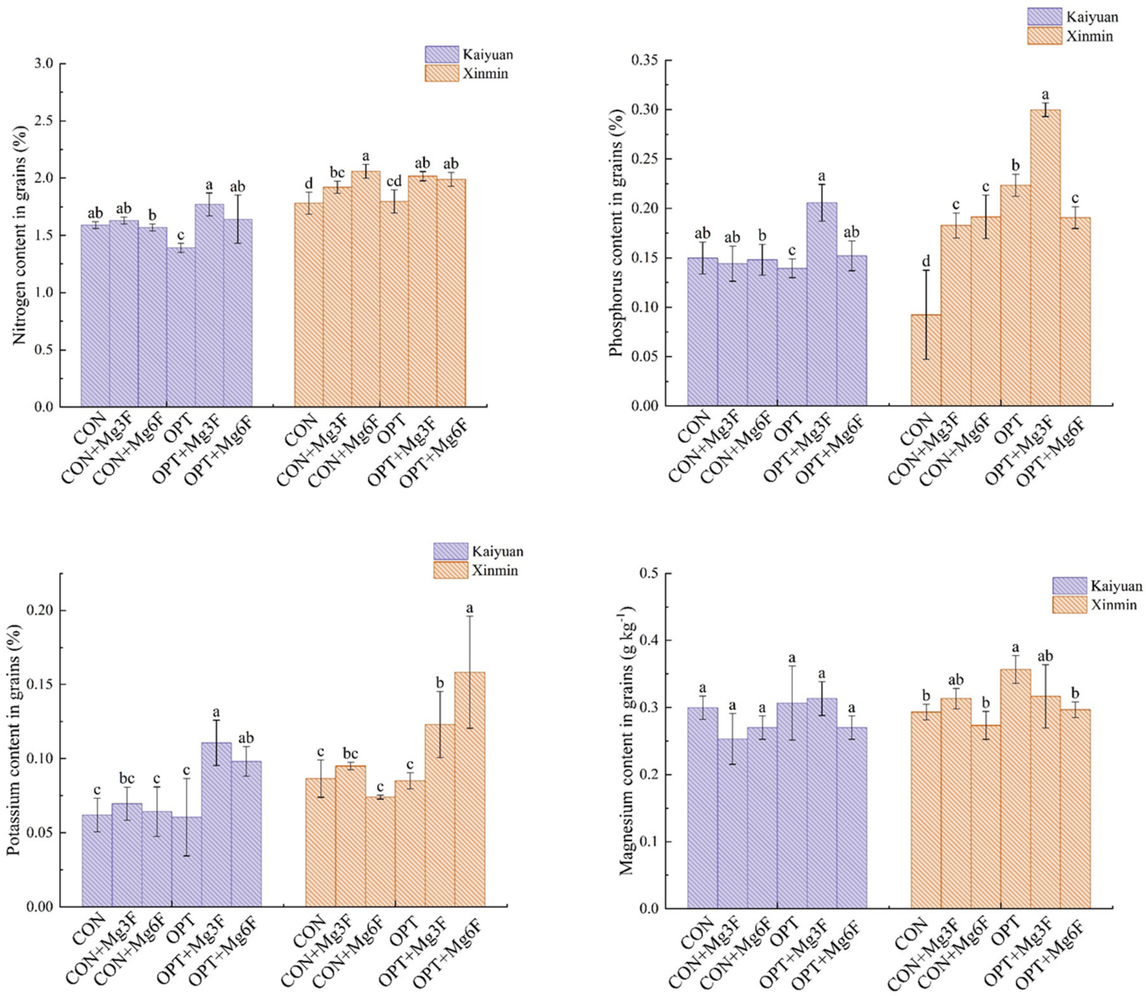

Figure 6. Nitrogen, phosphorus, potassium, and magnesium contents in rice grains in experiment 2.

4. Discussion

The application of magnesium fertilizer can significantly affect the absorption and utilization of nutrient elements in plants [39–41]. Magnesium can promote the activation of many enzymes in nitrogen metabolism and promote the synthesis of nitrogen compounds [42]. The present experiment showed that the addition of a small amount of magnesium could promote the absorption of nitrogen by rice, while the high content of magnesium would inhibit the absorption of nitrogen by rice. Further, under optimized fertilization conditions, the content of nitrogen in the stems, leaves, and grains decreased, but after optimizing fertilization together with the application of magnesium fertilizer, the degree of decline decreased. In this research, the soil application of 6 kg hm^{-2} magnesium had the best effect on promoting nitrogen accumulation (Figure 4). Based on conventional fertilization and optimized fertilization, foliar spraying with magnesium fertilizer can significantly increase the content of nitrogen in grains (Figure 6). Therefore, foliar spraying with magnesium fertilizer can not only promote the absorption of nitrogen by rice but also promote the transport of nitrogen to grains. Magnesium can participate in various chemical reactions within plants, including oxidative phosphorylation, so the application of magnesium fertilizer will promote the absorption of phosphorus by crop plants. The phosphorus content in rice stems, leaves, and grains will change with the change in rice growth and the development cycle [23]. The study showed that after foliar spraying with magnesium fertilizer for 10 days, the phosphorus content in rice stems, leaves, and panicles increased, and the effect was more significant after the rice matured. Many scholars investigated the interaction between potassium and magnesium in plants. For example, the study suggested that a higher concentration of potassium in the growth medium can inhibit the absorption of magnesium by plant roots, resulting in antagonism between the two elements [43]. But sometimes, a low potassium concentration can reversely promote the absorption of magnesium, showing a synergistic effect [44]. In the rice magnesium–potassium interaction experiment, the magnesium concentration in rice leaves and roots decreased significantly when the potassium concentration in the nutrient solution increased, and the higher the magnesium concentration in the nutrient solution, the more significant the effect of potassium on inhibiting magnesium uptake [45]. According to the results of this experiment, the effects of using magnesium fertilizer in the soil and foliar spraying with magnesium fertilizer on the contents of phosphorus and potassium in rice stems, leaves, and grains were unstable and varied with different fertilization methods, fertilizer application rates, fertilizer types, and experimental sites. For example, in experiment 1, the magnesium fertilizer used in soil significantly increased the content of potassium in the rice stems and leaves but had no different effects on the content of potassium in grains. In experiment 2, foliar spraying with magnesium fertilizer decreased the potassium content in the stems and leaves but increased the potassium content in the grains. The application of magnesium fertilizer in the soil had no significant effect on the content of magnesium in the rice stems and leaves, but foliar spraying with magnesium fertilizer significantly increased the content of magnesium in the rice stems and leaves (Figures 4 and 6).

Many studies have shown that the application of magnesium fertilizer can improve the yield and quality of many crops [12,46]. It has been suggested that the application of magnesium fertilizer has a positive effect on the number of tillers and yield of rice [47]. When magnesium in the soil is sufficient, the yield of rice can increase by 67.5–178.5 kg hm^{-2} under suitable magnesium fertilizer [26]. Magnesium fertilizer can increase the contents of starch, crude protein, and other substances in grains, thus improving the quality of rice [14]. In this experiment, the application of 20 kg hm^{-2} magnesium fertilizer at the Kaiyuan experimental site could significantly increase rice yield, and the effect of magnesium–silicon fertilizer was more obvious (Table 4). While at the Dawa experimental site, foliar spraying with magnesium fertilizer could increase rice yield and also increase the content of crude fat in the rice grain (Figure 1). In recent years, many scholars used foliar spraying to study the effect of magnesium fertilizer on the yield and quality of crops. For example, foliar spraying a certain amount of magnesium fertilizer improved the yield and quality of grapes [48]. Spraying magnesium fertilizer on the leaves of tobacco not only achieved the best smoking state but also improved the yield and quality of flue-cured tobacco [49]. Foliar spraying proper magnesium fertilizer caused a significant increase in rice yield, but when magnesium fertilizer and nitrogen -phosphorus compound fertilizer were applied together, the rice yield did not increase and the seed setting rate decreased with the increase of the compound fertilizer [26]. In this experiment, based on conventional fertilization in two experimental sites, spraying magnesium fertilizer had no significant effect on rice yield or 1000-grain weight, but spraying magnesium fertilizer based on the optimized fertilizer application significantly increased rice yield and 1000-grain weight (Table 2). Due to the reduction in nitrogen and phosphorus application rates in optimized fertilization, foliar spraying with magnesium fertilizer can compensate for the yield decline caused by the reduction in nitrogen and phosphorus. In addition, based on conventional fertilization and optimized fertilization, foliar spraying with magnesium fertilizer could increase the protein content of rice grains, especially based on optimized fertilization. The effect of applying magnesium fertilizer to increase yield and improve quality may be related to the promotion of nitrogen, phosphorus, potassium, and other nutrients, the mechanism of which needs to be further studied.

In this research, experiment 1 and experiment 2 were carried out only during one growth season, although they were set at two sites, respectively. The mechanism of magnesium fertilizers to improve the yield and quality of rice remains unknown. These topics will be studied in future research. However, the present results of this research provided important evidence that magnesium fertilizers could increase the yield and quality of rice in relatively magnesium-rich soil in Liaoning province. In addition, magnesium fertilizer can, to some extent, compensate for the decrease in yield induced by a reduction in nitrogen and phosphorus fertilizer use.

5. Conclusions

Using magnesium fertilizer in the soil and on leaves significantly increased the nitrogen content in the shoots and grains of rice, and the soil application of 6 kg hm^{-2} magnesium had the best effect on promoting nitrogen accumulation. Foliar spraying with magnesium fertilizer can not only promote the absorption of nitrogen by rice but also promote the transport of nitrogen to grains. Based on conventional fertilization and optimized fertilization, foliar spraying with magnesium fertilizer significantly increased the content of nitrogen in the grains and affected the content of nutrients in the shoots and grains. In the results of this experiment, the effects of magnesium fertilizer and foliar spraying with magnesium fertilizer on the contents of phosphorus and potassium in the rice shoots and grains were unstable and varied with different fertilization methods, fertilizer application rates, fertilizer types, and experimental sites. Using magnesium fertilizer in soil and on leaves could significantly improve the yield and quality of rice. The application of 12 kg hm^{-2} magnesium in the soil of Kaiyuan could significantly increase rice yield, and the effect of adding silicon was more obvious, while in the Dawa experimental site, foliar spraying with 6 kg hm^{-2} magnesium could increase rice yield. In the Kaiyuan and Xinmin experimental sites, foliar spraying with 3 and 6 kg hm^{-2} magnesium fertilizer based on optimized fertilization could significantly increase rice yield and 1000-grain weight. The application of magnesium fertilizer could also increase the content of crude fat and crude protein in rice grains.

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