Effects of reduced potassium fertilizer application under wheat straw incorporation on rice yield and potassium fertilizer use efficiency: Postprint

Authors: Jin Mengcan, Zhang Shuyu, Gao Hongjian, Gao Shifeng, Wang Yikun

Date: 2017-11-08T00:00:00+00:00

Abstract

Soil potassium deficiency is becoming increasingly severe in China. Crop straw contains high potassium content, and its incorporation into soil can replace part of chemical potassium fertilizer, alleviating soil potassium deficiency. To investigate the effect of straw return as a substitute for potassium fertilizer, this study employed a field experiment method, using conventional potassium application [135 kg(K2O) hm 2] as the control, and examined the effects of 10%, 20%, 30%, and 40% reductions in potassium fertilizer on potassium absorption and accumulation in rice, rice yield, partial factor productivity of potassium fertilizer, and economic benefits under the condition of straw crushing and incorporation into soil (6 000 kg hm 2). The results showed that: on the basis of straw return, the potassium content and accumulation in rice plants decreased with the reduction of potassium fertilizer application rate. When potassium fertilizer application was reduced by 10%~40%, the effective panicle number, grains per panicle, and seed setting rate of rice decreased slightly, and rice yield and output value declined. When potassium fertilizer was reduced by 10%, 20%, and 30%, the effects on rice yield and output value were not significant ($P>0.05$). The partial factor productivity of potassium fertilizer increased with the reduction of potassium fertilizer application rate. Compared with the treatment without potassium reduction, the partial factor productivity of potassium fertilizer in rice under 10%, 20%, 30%, and 40% potassium reduction treatments increased by 8.4%, 18.9%, 33.8%, and 44.4%, respectively. Overall, under conventional potassium application conditions, with the increase of potassium reduction rate (10%~40%) after straw return, potassium accumulation, yield, and output value of rice all showed a decreasing trend, while the partial factor productivity of potassium fertilizer showed an increasing trend; potassium reduction within 30% could significantly increase the partial factor productivity of potassium fertilizer in rice ($P < 0.05$), while having no significant effect on rice yield and

output value (P>0.05).

Full Text

Effects of Reducing Potassium Fertilizer on Rice Yield and Potassium Use Efficiency Under Wheat Straw Return Conditions

JIN Mengcan[1], **ZHANG Shuyu**[1], **GAO Hongjian**[1], GAO Shifeng[2], WANG Yikun[3]**

[1]Anhui Province Key Laboratory of Farmland Ecological Conservation and Pollution Prevention / School of Resources and Environment, Anhui Agricultural University, Hefei 230036, China

[2]Agricultural Technology Extension Center of Guohe Town, Lujiang County, Lujiang 200111, China

[3]Anhui Xiyangyang Agricultural Science and Technology Co., LTD, Lujiang 200111, China

Abstract

Soil potassium deficiency has become increasingly severe in China. However, crop residues contain high levels of potassium that can partially substitute for chemical potassium fertilizer after straw incorporation, thereby alleviating soil potassium deficiency. This study investigated the effects of reducing potassium fertilizer application by 10%, 20%, 30%, and 40% under wheat straw incorporation conditions (6,000 $\mathrm{kg \cdot hm^{-2}}$) on rice potassium uptake and accumulation, grain yield, partial factor productivity of potassium fertilizer, and economic benefits, using conventional potassium application [135 $\mathrm{kg(K_2O) \cdot hm^{-2}}$] as the control. The results showed that under straw return conditions, both potassium content and accumulation in rice plants decreased with reduced potassium fertilizer application. Reducing potassium fertilizer by 10%-40% slightly decreased effective panicle number, grains per panicle, and seed-setting rate, leading to lower rice yield and output value. However, reductions of 10%, 20%, and 30% had no significant effect on rice yield or output value ($P > 0.05$). Partial factor productivity of potassium fertilizer increased as potassium application rate decreased, with reductions of 10%, 20%, 30%, and 40% increasing partial factor productivity by 8.4%, 18.9%, 33.8%, and 44.4%, respectively, compared with the no-reduction treatment. Overall, under conventional potassium fertilization with straw return, rice potassium accumulation, yield, and output value all declined with increasing potassium reduction (10%-40%), while partial factor productivity of potassium increased. Reducing potassium by up to 30% significantly improved partial factor productivity ($P < 0.05$) without significantly affecting rice yield or output value ($P > 0.05$).

Keywords: Rice; Straw return; Potassium fertilizer reduction; Yield; Partial factor productivity

Introduction

Rice (*Oryza sativa*) is one of China' s most important food crops, ranking first in both planting area and production among grain crops [1]. As one of the three essential mineral nutrients for plant growth, potassium is the most abundant cation in plants, accounting for 2%-10% of dry weight [2]. Potassium ions play critical roles in various plant physiological and biochemical processes, including maintaining dynamic cation-anion balance, stabilizing osmotic pressure, promoting photosynthetic efficiency, and serving as enzyme activators [3-6]. Potassium fertilizer application improves rice growth and development, facilitates normal tillering, increases seed-setting rate, thousand-grain weight, and yield [7], enhances dry matter accumulation [8] and grain yield [9], increases rice nutrient uptake including potassium [10], and improves nutrient use efficiency [11].

China' s soil total potassium content generally averages around 16.6 $g \cdot kg^{-1}$, but readily available potassium that plants can directly absorb typically does not exceed 2% of total potassium [12]. In recent years, soil potassium deficiency has intensified and the potassium-deficient area has expanded, becoming a limiting factor for further agricultural development in China. While potassium fertilizer application is a direct approach to alleviate soil potassium deficiency, China has scarce potassium resources, with 50%-70% of its potassium fertilizer supply dependent on imports [13], making it relatively expensive. Full utilization of organic potassium resources represents an important pathway to compensate for insufficient potassium mineral resources and replenish soil potassium deficiency. China is a major crop straw producer globally, with annual straw resources of approximately 811 million tons, primarily from rice, maize (*Zea mays*), and wheat (*Triticum aestivum*) straws, which account for 76.1% of total straw resources [14]. Approximately 80% of potassium absorbed by crops remains in the straw, representing about 1.5% of straw dry matter, making it an important potassium fertilizer resource [15]. Straw return increases soil water-soluble potassium, non-exchangeable potassium, and mineral potassium content, returning nutrients to the soil. The decomposition process may also promote mineral potassium release, and the potassium introduced through straw return can substitute for partial chemical fertilizer application [15-16]. Wang et al. [17] demonstrated that based on nitrogen and phosphorus application, combined potassium application with straw return is an important measure for crop yield increase and soil potassium fertility maintenance. Wheat straw return increased winter wheat yield by over 6.6%, while combined potassium application with wheat straw return increased yield by 17.6%. Therefore, if straw return can substitute for part of chemical potassium fertilizer, it could reduce potassium fertilizer application, which is important for soil fertility improvement, nutrient cycling, and compensating for potassium deficiency.

Previous studies have primarily focused on the effects of straw return on soil fertility and rice yield, but research on how potassium reduction after straw return affects rice potassium accumulation and utilization efficiency remains limited. This study employed field experiments to investigate the effects of

10%, 20%, 30%, and 40% potassium reduction after straw return on potassium content and accumulation in rice plants at different growth stages, and analyzed differences in rice yield, economic benefits, and partial factor productivity of potassium fertilizer under reduced potassium conditions, aiming to provide a theoretical basis for scientific potassium application after crop straw return.

1.1 Experimental Site

The field experiment was conducted in Nanwei Village, Guohe Town, Lujiang County, Hefei City, Anhui Province (117°E, 31°28’ N). The region has a subtropical monsoon climate with cold winters, hot summers, and mild springs and autumns. The average annual temperature is 15.7°C, with approximately 2,100 hours of sunshine and annual rainfall of about 1,000 mm. The area features typical polder landscape with flat terrain, fertile and uniform soil, and good irrigation and drainage conditions, making it suitable for rice cultivation. The cropping system is wheat-rice rotation, with wheat as the previous crop. The experimental field had the following soil nutrient contents: organic matter 27.53 $g \cdot kg^{-1}$, available potassium 136.6 $mg \cdot kg^{-1}$, available phosphorus 19.22 $mg \cdot kg^{-1}$, alkali-hydrolyzable nitrogen 92.81 $mg \cdot kg^{-1}$, total nitrogen 1.39 $g \cdot kg^{-1}$, and soil pH 5.08.

1.2 Experimental Design

The rice variety used was ‘Wanjingkennuo 2’. Fertilizers included compound fertilizer (15-15-15), urea (N 46%), phosphate fertilizer (P_2O_5 12%), and potassium chloride (K_2O 60%). The experiment consisted of six treatments: conventional fertilization ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-135 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T1); conventional fertilization without potassium ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-0 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T6); conventional fertilization with 10% potassium reduction ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-121 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T2); conventional fertilization with 20% potassium reduction ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-108 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T3); conventional fertilization with 30% potassium reduction ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-94 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T4); and conventional fertilization with 40% potassium reduction ($N\text{-}P_2O_5\text{-}K_2O$ = 270-90-82 $kg \cdot hm^{-2}$) + straw return + decomposing agent (T5). The nitrogen fertilizer was applied as basal, tillering, and panicle fertilizer at a ratio of 60%:30%:10%; phosphorus fertilizer was applied entirely as basal fertilizer; and potassium fertilizer was applied as basal and panicle fertilizer at a ratio of 80%:20%. Different treatments were formulated using compound fertilizer (15-15-15), urea (N 46%), superphosphate (P_2O_5 12%), and potassium chloride (K_2O 60%). The conventional fertilization rate was 600 $kg \cdot hm^{-2}$ compound fertilizer, 391 $kg \cdot hm^{-2}$ urea, 75 $kg \cdot hm^{-2}$ potassium chloride, and 30 $kg \cdot hm^{-2}$ decomposing agent. Wheat straw return amount was approximately 6,000 $kg \cdot hm^{-2}$, with total nitrogen, phosphorus, and potassium contents in straw of 7.4 $g \cdot kg^{-1}$, 1.01 $g \cdot kg^{-1}$, and 23.5 $g \cdot kg^{-1}$, respectively.

1.3 Planting and Management

The experiment included six treatments with three replications each, arranged in a randomized block design. The net plot area was 100 m^2. A 2 m wide protective row was established around the experimental field, with field ridges surrounding each plot and covered with plastic film to ensure separate irrigation and drainage and prevent water and fertilizer leakage. Wheat was harvested on June 8, 2016, using a combine harvester with straw chopping and incorporation. Basal fertilizer and decomposing agent were applied, followed by deep rotary tillage and burial, then irrigation and soaking for 3–4 days. A second rotary tillage was performed on June 12–13 after water drainage, followed by 3 days of settling. Rice was sown on May 19, 2016, and seedlings were transplanted on June 19, with harvest in early November. The planting specification (row spacing × plant spacing) was 25 cm × 12 cm, with a planting density of 300,000 plants $\cdot$ hm^{-2} (3,000 plants $\cdot$ $plot^{-1}$). At maturity, samples were taken for yield component analysis. Except for fertilizer application according to experimental requirements, other management practices were consistent across treatments, with pest, disease, and weed control conducted uniformly across all plots following standard field practices.

1.4 Measurements and Methods

At the tillering, jointing, heading, and maturity stages, three rice plants were randomly sampled from each plot. Samples were first rinsed with tap water, then washed with distilled water. Stems, leaves, and panicles were separately placed in sample bags, killed out at 105°C for 30 minutes, then dried to constant weight at 75°C. After grinding, plant samples were digested with H_2SO_4-H_2O_2, and total potassium content was determined using a flame photometer. At maturity, effective panicles, grains per panicle, thousand-grain weight, and other yield components were measured. Potassium accumulation and utilization efficiency in rice plants at different growth stages were calculated using the following formulas:

Potassium accumulation (g $\cdot$ $plant^{-1}$) = Potassium accumulation at later stage − Potassium accumulation at previous stage
Potassium net accumulation (g $\cdot$ $plant^{-1}$) = (Crop yield in potassium-fertilized area − Crop yield in non-potassium area) / Crop yield in potassium-fertilized area
Partial factor productivity of potassium fertilizer (kg $\cdot$ kg^{-1}) = Grain yield / Potassium application rate

Data processing and graphing were performed using Microsoft Excel 2007. Statistical analysis was conducted using SPSS 20.0, with significance analysis performed using Duncan’ s method.

2.1 Effects of Potassium Reduction on Potassium Content in Rice Plants

As shown in Table 1 , potassium content in different rice plant parts at various growth stages consistently followed the pattern: stem > leaf > panicle across all potassium levels. Potassium content in different plant parts decreased with reduced potassium fertilizer application. Among all treatments, potassium content in rice plants with potassium application after straw return (T1, T2, T3, T4, T5) was higher than in the no-potassium control (T6), with the highest content observed in the 100% potassium treatment after straw return (T1). At the tillering stage, stem potassium content in the conventional fertilization treatment (T1) was 56.58 $g \cdot kg^{-1}$, which was 14.2%, 14.5%, 15.3%, 15.8%, and 19.2% higher than in potassium reduction treatments (T2, T3, T4, T5, and T6, respectively), with significant differences ($P < 0.05$). However, no significant differences were observed in stem and leaf potassium content among different potassium reduction treatments ($P > 0.05$). At the jointing stage, potassium content in stems and leaves followed the trend T1 > T2 > T3 > T4 > T5 > T6, with T1 being the highest and the no-potassium control (T6) the lowest. Stem potassium content in the no-potassium control (T6) was significantly lower than in potassium reduction treatments ($P < 0.05$). At the heading stage, potassium content in stems, leaves, and panicles was highest in the conventional potassium treatment (T1) and lowest in the no-potassium control (T6), though differences among treatments were not significant. At the maturity stage, stem and leaf potassium content remained highest in T1, while panicle potassium content was highest in the 20% potassium reduction treatment (T3) and lowest in the no-potassium treatment (T6).

2.2 Effects of Potassium Reduction on Potassium Accumulation in Rice Plants

Rice potassium accumulation gradually increased with growth progression (Figure 1 [Figure 1: see original paper]), reaching maximum values at maturity (0.73 $g \cdot plant^{-1}$). Total potassium accumulation increased rapidly from tillering to jointing and from jointing to heading stages, with relatively slower increase from heading to maturity. At all growth stages, potassium accumulation was highest in the 100% potassium treatment after straw return (T1) and lowest in the no-potassium control (T6), decreasing progressively with increasing potassium reduction rate. At the jointing stage, potassium accumulation in the 100% potassium treatment (T1) was slightly higher than in potassium reduction treatments (T2, T3, T4, T5, T6). At the jointing stage, potassium accumulation in T1 was significantly higher than in all potassium reduction treatments (T2, T3, T4, T5, T6, $P < 0.05$), while the 10% reduction treatment (T2) was significantly higher than other reduction treatments (T3, T4, T5, T6, $P < 0.05$), though differences among reduction treatments were not significant ($P > 0.05$). At the heading stage, potassium accumulation in T1 was significantly higher than in all reduction treatments (T2, T3, T4, T5, T6) ($P < 0.05$), with significant differences between the 10% reduction treatment (T2) and treatments with 20% reduction (T3) and above ($P < 0.05$). However, no significant difference was observed between the 30% reduction (T4) and 40% reduction (T5) treatments ($P > 0.05$). At maturity, potassium accumulation in reduction treatments (T2, T3, T4, T5, T6) was 15.04%, 22.12%, 25.66%, 28.31%, and 35.40% lower than in the 100% potassium treatment (T1), respectively, with significant differences ($P < 0.05$).

Potassium net accumulation in rice plants was highest at the heading stage, accounting for 35.50%-59.82% of total accumulation, followed by the jointing stage (26.53%-30.8%) (Figure 1b). At the tillering stage, potassium net accumulation ranged from 0.0479 to 0.0561 $g \cdot plant^{-1}$ across treatments, with no significant differences among potassium reduction treatments (T2–T6) ($P > 0.05$). At the jointing and heading stages, potassium net accumulation gradually decreased with increasing potassium reduction rate, with all reduction treatments (T2–T5) showing significantly lower net accumulation than the 100% potassium treatment (T1, $P < 0.05$). At maturity, potassium net accumulation followed the trend T4 > T5 > T6 > T3 > T1 > T2.

2.3 Effects of Potassium Reduction on Rice Yield and Yield Components

As shown in Table 2 , rice yield across different fertilization treatments followed the trend T1 > T2 > T3 > T4 > T5 > T6, with the highest yield in the 100% potassium treatment after straw return (T1) and the lowest in the no-potassium treatment (T6). Rice yield gradually decreased with increasing potassium reduction rate, with yield reduction ranging from 2.5% to 16.4%. The 40% potassium reduction treatment (T5) and no-potassium treatment (T6) had significantly lower yields than other fertilization treatments ($P > 0.05$), though no significant difference was observed between T5 and T6. Regarding yield components, effective panicle number, grains per panicle, and seed-setting rate decreased with reduced potassium application, with no significant differences in effective panicle number and seed-setting rate ($P > 0.05$). Grains per panicle in T5 and T6 were significantly lower than in T1 ($P < 0.05$), while no significant differences were observed in thousand-grain weight among treatments.

2.4 Effects of Potassium Reduction on Economic Benefits and Partial Factor Productivity of Potassium

Fertilizer input costs and rice output value decreased while partial factor productivity of potassium fertilizer increased with reduced potassium application (Table 3). The 100% potassium treatment after straw return (T1) had the highest output value, while the no-potassium treatment (T6) had the lowest. Output values in potassium reduction treatments (T2, T3, T4, T5, T6) were 2.5%, 4.9%, 6.3%, 13.4%, and 16.4% lower than T1, respectively. No significant differences in output value were observed between the 10%-30% reduction treatments (T2, T3, T4) and the no-reduction treatment (T1) ($P > 0.05$), nor between the 40% reduction treatment (T5) and the no-potassium treatment (T6) ($P > 0.05$). Among all potassium application treatments, partial factor productivity was highest in the 40% reduction treatment (T5) and lowest in the no-reduction treatment (T1). Potassium reduction treatments (T2, T3, T4, T5) increased partial factor productivity by 8.4%, 18.9%, 33.8%, and 44.4%, respectively, compared with T1.

3.1 Effects of Potassium Reduction on Potassium Absorption in Rice

Potassium is one of the three essential elements for crop growth, and its absorption and distribution significantly affect rice growth and development [18]. Rice plant potassium absorption and accumulation follow a pattern of slow increase during tillering, rapid increase during jointing, peak at heading, and gradual decline thereafter [19]. Yan et al. [20] reported that potassium content in rice plants decreases with delayed growth stages. This study showed that at tillering and jointing stages, stem potassium content in treatments with 10%-40% potassium reduction was significantly lower than in the no-reduction treatment, while differences were not significant at heading and maturity stages. This may be because chemical potassium fertilizer application increases the potassium concentration gradient between the soil matrix and root surface during early rice growth, enhancing potassium diffusion and migration to roots [21] and promoting potassium absorption. Potassium reduction decreases soil available potassium content, while straw potassium release requires time, reducing potassium absorption during early growth stages [22]. After straw return, gradual potassium release partially substitutes for chemical potassium functions [23], increasing soil available potassium content and rice potassium absorption, thereby reducing differences in stem potassium content between reduction and no-reduction treatments during later growth stages.

With decreasing potassium application, potassium accumulation in rice at different growth stages showed a declining trend, with differences becoming more pronounced at later growth stages. Zhang et al. [9] demonstrated that potassium accumulation in different rice varieties increases with potassium application rate, consistent with our findings. This may occur because after chemical potassium enters the soil, it can be accommodated and adsorbed by the water-soil system, with some potassium ions fixed by clay minerals and transformed into non-exchangeable forms, reducing soil available potassium content and crop potassium absorption during early growth stages. During straw decomposition, companion cations such as Na^+ and $NH_4{}^+$ with hydration radii similar to K^+ are released, occupying some interlayer adsorption sites in soil clay minerals and reducing straw potassium fixation [15]. When the amount of potassium released from straw and chemical fertilizer is less than that fixed by soil clay minerals, soil water-soluble potassium content decreases and crop accumulation reduces; conversely, soil water-soluble potassium content increases and crop accumulation increases.

3.2 Effects of Potassium Reduction on Rice Yield and Yield Components

This study demonstrated that potassium reduction treatments decreased effective panicles, grains per panicle, and seed-setting rate, thereby reducing yield. Hu et al. [24] reported that potassium fertilizer application increases effective panicle number and grains per panicle. Yuan et al. [25] found that reduced potassium nutrition decreases cytokinin in plants, affecting fertilized embryo development and increasing empty grain rate while decreasing seed-setting rate. Li et al. [26–27] showed that exogenous potassium application enhances cytokinin promotion of plant growth, producing more primary and secondary branch meristems, ultimately increasing grains per panicle and seed-setting rate. This indicates that potassium primarily increases rice yield by increasing effective panicle number, grains per panicle, and seed-setting rate. Our study showed that under straw return conditions, potassium reduction of 10%–30% did not significantly affect rice yield compared with the no-reduction treatment, while 40% reduction significantly decreased yield. This suggests that under straw return conditions, when potassium reduction exceeds 30% of conventional application, potassium released from straw cannot completely substitute for chemical potassium functions, resulting in yield reduction.

3.3 Effects of Potassium Reduction on Economic Benefits and Partial Factor Productivity of Potassium

Under straw return conditions, rice production costs decreased with reduced potassium application, while output value increased with yield. Conventional fertilization had the highest cost and output value. Output values in potassium reduction treatments were lower than in the no-reduction treatment, indicating that potassium reduction decreased rice output value to varying degrees. However, under straw return conditions, potassium released from straw could partially substitute for chemical potassium fertilizer, and when potassium reduction was less than 30%, the effect on rice output value was not significant.

Partial factor productivity is an important indicator reflecting the combined effects of local soil baseline nutrients and chemical fertilizer application rate, and is a suitable parameter for evaluating fertilizer effects [28]. Wang et al. [29] reported that partial factor productivity of potassium fertilizer is significantly negatively correlated with potassium application rate and positively correlated with grain yield after potassium application. Our results showed that partial factor productivity of potassium fertilizer increased with decreasing potassium application rate, being lowest in the no-reduction treatment and highest in the 40% reduction treatment. Lower potassium application rates resulted in lower dependence of rice on fertilizer potassium and higher dependence on soil potassium.

In summary, reducing potassium fertilizer application decreases potassium content and accumulation in rice plants at different growth stages, reduces effective panicle number, grains per panicle, and seed-setting rate, and consequently decreases rice yield and output value to varying degrees. Although high chemical potassium input can increase grain crop yield to some extent, excessive potassium input transforms potassium into non-exchangeable forms and greatly increases potassium resource consumption [30]. After straw return, the release of companion cations such as Na^+ and ${NH_4}^+$ along with potassium reduces straw potassium fixation, making it more available for plant absorption. Considering partial factor productivity, production cost, and rice output value, reducing conventional potassium application by 30% (T4) under straw return conditions can reduce potassium fertilizer costs and improve partial factor productivity.

Conclusions

1) Under straw return conditions, potassium content and accumulation in rice plants decreased with reduced potassium application, with differences becoming more pronounced at later growth stages.

2) Reducing potassium fertilizer application under straw return conditions affected rice effective panicle number, grains per panicle, and seed-setting rate, thereby influencing rice yield. Potassium reduction of less than 30% under straw return conditions had no significant effect on rice yield ($P > 0.05$).

3) From the perspective of rice yield and income, conventional fertilization (T1) produced the best results. However, considering production costs, output value, potassium use efficiency, and sustainable development, reducing conventional potassium application by 30% under straw return conditions can reduce potassium fertilizer costs and improve partial factor productivity.

References

[1] Li C J, Liu J P, Jia L Y, et al. Current situation and preview of rice seed breeding in China[J]. China Seed Industry, 2007, (1): 11-12

[2] Gierth M, Mäser P. Potassium transporters in plants-involvement in K+ acquisition, redistribution and homeostasis[J]. FEBS Letters, 2007, 581(12): 2348-2356

[3] Amtmann A, Hammond J P, Armengaud P, et al. Nutrient sensing and signaling in plants: Potassium and phosphorus[J]. Advances in Botanical Research, 2005, 43: 209-257

[4] Wang Y, Wu W H. Potassium transport and signaling in higher plants[J]. Annual Review of Plant Biology, 2013, 64: 451-476

[5] Hawkesford M, Horst W, Kichey T, et al. Functions of macronutrients[M]//Marschner P. Marschner' s Mineral Nutrition of Higher Plants. 3rd ed. London: Academic Press, 2012: 135-189

[6] Anschütz U, Becker D, Shabala S. Going beyond nutrition: regulation of potassium homoeostasis as a common denominator of plant adaptive responses

to environment[J]. Journal of plant physiology, 2014, 171(9): 670-687
[7] Zhang Y Y, Lu J W, Wang Y Z, et al. Effects of potassium fertilizer application method on yield and potassium apparent efficiency of direct-sowing rice and transplanting rice[J]. Crops, 2016, (1): 110-114
[8] Suo W W, Fu L D, Wang Y, et al. Effect of potash fertilizer on rice yield and ratio of potash fertilizer utilization[J]. North Rice, 2014, 44(2): 18-21
[9] Zhang Y P, Cao W X, Zhu D F, et al. Effects of potassium fertilizer rate on growth and yield formation of super high yielding rice in red paddy soil[J]. Chinese Journal of Rice Science, 2009, 23(6): 633-638
[10] Chen M, Ma T T, Ding Y P, et al. Effects of formula fertilizer application on nutrient uptake and grain yield of rice[J]. Plant Nutrition and Fertilizer Science, 2014, 20(1): 237-246
[11] Wang W N, Lu J W, He Y Q, et al. Effects of N, P, K fertilizer application on grain yield, quality, nutrient uptake and utilization of rice[J]. Chinese Journal of Rice Science, 2011, 25(6): 645-653
[12] Zhan L P, Li X K, Lu J W, et al. Research advances on influence factors of soil potassium movement[J]. Soils, 2012, 44(4): 548-553
[13] Qi Z Y, Duan S Q, Liu F C, et al. Production and supply of potash fertilizer in China in the recent years and its development forecast[J]. Phosphate & Compound Fertilizer, 2012, 27(6): 1-3
[14] Gao X Z, Ma W Q, Ma C B, et al. Analysis on the current status of utilization of crop straw in China[J]. Journal of Huazhong Agricultural University, 2002, 21(3): 242-247
[15] Li J F, Ren T, Lu J W, et al. Study on characteristics of release and distribution of rice straw potassium and chemical potassium by lab simulation[J]. Soils, 2013, 45(6): 1017-1022
[16] Tan D S, Jin J Y, Huang S W, et al. Effect of long-term application of potassium fertilizer and wheat straw to soil on yield of crops and soil potassium in fluvo-aquic soil and brown soil of northcentral China[J]. Plant Nutrition and Fertilizer Science, 2008, 14(1): 106-112
[17] Wang H T, Jin J Y, Wang B, et al. Effects of long-term potassium application and wheat straw return to cinnamon soil on wheat yields and soil potassium balance in Shanxi[J]. Plant Nutrition and Fertilizer Science, 2010, 16(4): 801-808
[18] He M, Zhang W Z, Song G Y, et al. Effect of potassium on growth and development of high-yield rice[J]. Liaoning Agricultural Sciences, 2007, (1): 12-14
[19] Zhang X L, Jiang F C, Li S Q, et al. Studies on K uptake regularity of rice plant and K balance[J]. Journal of Northwest Agricultural University, 1994, 25(4): 319-327
[20] Yan L Y, Qin S, Yang G L, et al. Effects of postponing nitrogen and potassium application on yield, yield components and nutrient content of super high-yielding rice[J]. Southwest China Journal of Agricultural Sciences, 2016, 29(1): 103-108
[21] Liu H L, Chen Y H, Duan Y L, et al. The advance of soil potassium[J]. Journal of Agricultural University of Hebei, 2002, 25(S1): 66-68

[22] Jiang C Q, Zheng Q S, Zu C L. Research progress on effects of straw returning on soil potassium and its substitute for potassium fertilizer[J]. Chinese Journal of Ecology, 2015, 34(4): 1158-1165
[23] Liao Y L, Zheng S X, Nie J, et al. Effects of long-term application of fertilizer and rice straw on soil fertility and sustainability of a reddish paddy soil productivity[J]. Scientia Agricultura Sinica, 2009, 42(10): 3541-3550
[24] Hu H, Wang G H. Influence of potassium fertilizer on nutrient accumulation and physiological efficiency of hybrid rice[J]. Plant Nutrition and Fertilizer Science, 2003, 9(2): 184-189
[25] Yuan L, Huang J G. Effects of potassium on the variation of hormones in developing hybrid rice seeds[J]. Journal of Southwest University, 1993, 15(1): 38-41
[26] Li L Y, Cui G X. Advances in studies on endogenous hormones in plants under nutrient stress[J]. Crop Research, 2002, (S1): 29-33
[27] Ashikari M, Sakakibara H, Lin S Y, et al. Cytokinin oxidase regulates rice grain production[J]. Science, 2005, 309(5735): 741-745
[28] Zhang F S, Wang J Q, Zhang W F, et al. Nutrient use efficiencies of major cereal crops in China and measures for improvement[J]. Acta Pedologica Sinica, 2008, 45(5): 915-924
[29] Wang W N, Lu J W, Lu M X, et al. Effects of potassium fertilizer and potassium use efficiency on early-, mid-and late-season rice in Hubei Province, China[J]. Journal of Plant Nutrition and Fertilizer, 2011, 17(5): 1058-1065

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.