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RESEARCH ARTICLE

Effect of potassium rate on yield, potassium uptake and canopy radiation interception of direct-seeded winter canola

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ABSTRACT

Direct seeded canola (*Brassica napus* L.) has become increasingly popular in China's key canola-producing regions. The studies on the K response of direct-seeded canola performance are limited. This research aimed to investigate the K utilization efficiency and canopy radiation interception rate of direct seeded winter canola at various K application rates. Two seasons field trials were done with five K levels (0, 75, 150, 225, and 300 kg K_2O ha^{-1}) utilizing two key local cultivars (Huayouza no. 9 and Zhongshuang no. 11) in Southwest China. Canola yield rose by 17.9%-82.6% in 2017-2018 and 21.1%-73.6% in 2018-2019 when K was applied, compared to K-unfertilized. Canola yield go up rapidly at first and then gradually when K ingestion grew, demonstrating the phenomena of K luxury consumption. As K levels rose, internal utilization efficiency, agronomic efficiency, and physiological efficiency all decreased. In canola pod development and maturation period, 150 kg K_2O ha^{-1} intercepted the most solar radiation (73.8%), while K-unfertilized treatment intercepted the least (61.6%) on average. The K supply rates had a significant effect on canopy radiation interception and K absorption in winter canola. When K application exceeded a specific rate, luxury consumption occurred. Canola's luxury K consumption was mostly stored in the pericarp and plant stem.

Key words: *Brassica napus*, potassium fertilizer rates, potassium uptake, winter canola, yield.

INTRODUCTION

With the increases of global challenges and population, the demand for edible oil is unprecedented on a global scale (Belouchrani et al., 2021). Winter canola (*Brassica napus* L.) is the second largest oilseed crops in the world and has a favorable fatty acid content with high nutritional value (Tian et al., 2020). As a most important winter canola producer, China has occupied a quarter of canola-planting region and contributed more than one fifth of canola production worldwide (Yin and Wang, 2012). The average yield was about 1.9 t ha^{-1} in China, slightly higher the world average of 1.8 t ha^{-1}; however, it was under half Germany average yield (3.9 t ha^{-1}) in comparison with European countries (Li et al., 2021). Therefore, a further increase of canola yield in China is vital for the global consumption of edible oil. Fertilization is a cost-effective approach for China to boost canola output and ensure the supply of edible oil (Wang et al., 2021). However, compared to N and P fertilizer applications, K fertilizer is frequently ignored by growers.

Potassium is the third important nutrient for healthy and productive crop growth, accounting for up to 10% of dry weight of canola plants (Hu et al., 2021). Winter canola could uptake 290-373 kg K ha^{-1}, which is more than any other mineral nutrient (Belouchrani et al., 2021). In China, however, K deficiency is very common in one fourth of arable areas and three-fourths of paddy fields (Song et al., 2020; Zhu et al., 2020b). Furthermore, the increased adoption of high-yielding cultivars and numerous cropping indices contribute to negative apparent

K balances and soil K insufficiency (Zhu et al., 2019). Application of K fertilizer resulted in a considerable increase in seed production, with increases ranging from 9.4% to 26.8% (Misskire et al., 2019; Hu et al., 2021). According to the study, K fertilizer application boosted average yield by 18.5%, and average K fertilizer use efficiency was 36.1% in some canola planting locations (Misskire et al., 2019; Szczepanek and Siwik-Ziomek, 2019; Hu et al., 2021).

Cheema et al. (2012) found that raising the level of K enhanced seed production considerably. Application of K fertilizers increased the number of pods per plant, number of seeds per pod, and weight of seeds in winter canola (Waraich et al., 2020; Hu et al., 2021). Yin et al. (2015) reported that effects of K fertilizer on seed yield was mainly through altering individual yield components of winter canola. The K deficiency could lead to less DM production and K uptake of individual plant in canola vegetative growth, hugely decreasing crop resistance to environmental stress in winter (Liu et al., 2011; Zhu et al., 2020a). The insufficient K uptake further impeded pod and seed development in winter canola during its reproductive growth, resulting in the loss of seed yield (Li et al., 2013; Szczepanek and Siwik-Ziomek, 2019). Some studies also suggested that the drop in seed production and yield components is primarily attributable to a decrease in the seeds each pod and seed weight due to a lack of K (Lu et al., 2019; Hu et al., 2021).

Canopy radiation interception and absorbance are of importance for yield formation during reproductive growth period (Diepenbrock, 2000; Hamzei and Soltani, 2012). The improvement of canopy solar radiation interception (SI) can increase winter canola seed yield (Denoroy et al., 2002). Mastering the variability in winter canola growth and yield production under varied K applications can be accomplished by measuring canopy SI (Elasha et al., 2001). Canola SI varies greatly across growth and development stages, ranging from 20% to 90% (Wang et al., 2015). It is evident from Cheema et al. (2012) that K supply in canola increased SI and crop growth rate. It seems that the canopy SI in winter canola lifecycle would be significantly affected by K application and other varied agronomic practices (Dreccer et al., 2000; Hamzei and Soltani, 2012; Tian et al., 2020).

Due to labor-saving benefits and advancements in the entire mechanized process of canola production, direct planting has become increasingly popular in China's key canola-producing regions (Wang et al., 2015). Some research suggested that direct-seeding canola could have significantly higher demand for the elemental nutrients comparing with transplanting seedlings (Zhu et al., 2020b). Direct-seeding canola was sensitive to nutrient deficiencies, which lead to stunt growth of individual plants and decline of plants population, low efficiency of nutrient transport in the later stage (Wang et al., 2011). In addition, Zhu et al. (2020b) reported that direct-seeded canola had larger yield reductions than transplanting plants under the nutrient deficient conditions. It suggested that direct-seeded canola might have different K uptake characteristics and fertilizer management practices compared with transplanting canola seedlings (Liu et al., 2011). However, the studies on the K response of direct-seeded canola performance are limited, and none have examined the effects of K deficiency on direct-seeded canola canopy radiation interception. Additionally, rice research suggested that direct seeding in rice cropping had no response to increasing K in Chile (Hirzel et al., 2020).

To investigate the K efficiency and SI characteristics of canola under various K application settings, we conducted a field experiment in Bijiang utilizing two key local winter canola cultivars. This research aimed to assess the yield and K uptake characteristics of winter canola at various K input levels, and investigate the K utilization efficiency and canopy radiation interception rate of direct seeded winter canola at various K application rates.

MATERIALS AND METHODS

Site description

In Bijiang (109°13′ E, 27°47′ N; 470 m a.s.l.), Guizhou Province, China, two-season field trials were carried out in 2017-2018 and 2018-2019. Warm winters and cool summers characterize this humid subtropical monsoon climate. The average annual precipitation is 1260 mm, and the annual average temperature is 15.6 °C. During the winter canola (*Brassica napus* L.) growing season, the temperature is always lower and less rainfall from January to February during wintering period, more rainfall occurred from April to May during the flowering stage. The physical properties of the topsoil before the canola season were: 62.38 mg kg^{-1} Alkali hydrolysable N, 11.04 mg kg^{-1} available P and 94.53 mg kg^{-1} available K in 2017; and correspondingly 68.94, 16.70 and 106.53 mg kg^{-1} in 2018.

Experimental design

The trials were carried out in a split-plot design with three replicates, with canola cultivars assigned to main plots and five K rates assigned to subplots: 0 (K0), 75 (K1), 150 (K2), 225 (K3), and 300 (K4) kg K_2O ha^{-1}. ‘Huayouza no. 9’ (HZ9) and ‘Zhongshuang no. 11’ (ZS11), both frequently planted winter canola cultivars in China, were used. To each plot 180 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 7.5 kg B ha^{-1} were applied to ensure that nutrients other than K did not hinder canola growth. Urea (46% N), calcium superphosphate (12% P_2O_5), and borax (5% B) were the sources of N, P_2O5, and B, respectively. Half of the N fertilizer was administered as a basal fertilizer, with the other half applied as a topdressing during the overwintering phase; P_2O_5, K_2O, and B were all given as a single basal dosage. All plots received their basal fertilizers 1 d before seeding. At 30 pl m^{-2}, the planting density was kept consistent. The size of each plot was 10 m^2, with length 5 m and width 2 m. Throughout the winter canola growth stages, all other field management operations followed the local farmers’ traditional practices.

Sample collection and analysis

Ten representative plants were randomly sampled and uprooted from each plot at maturity stage. The samples were washed with deionized water, blotted dry and divided into plant tissues (seed, pericarp, stem). The DM in each sample was measured after drying for 30 min at 105 °C to deactivate the enzymes and oven-dried a constant weight at 70 °C. Then, the dried seed, pericarp, stem samples were ground to pass through a 0.5 mm sieve for the K content analysis. The sub-sample were extracted with 1.0 mol L^{-1} hydrochloric acid (HCl), and the K content of the different tissues’ samples were determined by the flame photometer method (Jiang et al., 2011). At maturity, all plants from the center of each subplot were subjected to hand harvest and threshing to measure canola seed yield and aboveground biomass yield. Canola canopy radiation interception was measured by SunScan Canopy Analysis System (Delta-T Devices Ltd., Cambridge, UK). The crop population canopy radiation intercepted were measured as previously reported by Hamzei and Soltani (2012) and Wang et al. (2015).

Parameter calculation

The K uptake, K use efficiency and K harvest index (KHI) were calculated referring to Lu et al. (2019):

K uptake by seed ($K_{up,s}$, kg ha^{-1}) = Seed yield × K content of seed (1)
K uptake by pericarp ($K_{up,p}$, kg ha^{-1}) = Pericarp yield × K content of pericarp (2)
K uptake by stem ($K_{up,t}$, kg ha^{-1}) = Stem yield × K content of stem (3)
K uptake in aboveground (K_{up}, kg ha^{-1}) = $K_{up,s} + K_{up,t} + K_{up,p}$ (4)
K harvest index (KHI, %) = $K_{up,s}/K_{up}$ (5)
Reciprocal internal efficiency (RIE, kg t^{-1}) = $(K_{up}/Y) \times 1000$ (6)
Internal use efficiency (IUE, kg kg^{-1}) = Y/K_{up} (7)
Agronomic efficiency (AE, kg kg^{-1}) = $(Y_F - Y_0)/F$ (8)
Physiological efficiency (PE, kg kg^{-1}) = $(Y_F - Y_0)/(K_{up,F} - K_{up,0})$ (9)

In Equations 1-9, F denotes the rate of K application to canola (kg ha^{-1}), and Y denotes the seed yield (kg ha^{-1}); Y_F, Y_0 are the seed yields of the plots that received K and those that did not get K, respectively. $K_{up,F}$ and $K_{up,0}$ represent the K uptake in the aboveground of plots with and without applied K, respectively.

Table 1. Results of ANOVA on the effects of K rate (K), cultivar (C), growing season (GS), and their interactions on seed yield (SY), K uptake in seed ($K_{up,s}$), K uptake in pericarp ($K_{up,p}$), K uptake in stem ($K_{up,m}$), K harvest index (KHI), reciprocal internal efficiency (RIE), internal use efficiency (IUE), agronomic efficiency (AE), and physiological efficiency (PE) for winter canola. F values and significance levels, ^{ns}: nonsignificant, $^{*}P < 0.05$, $^{**}P < 0.01$.

Source	SY	$K_{up,s}$	$K_{up,p}$	$K_{up,m}$	KHI	RIE	IUE	AE	PE
K	69.99^{**}	113.32^{**}	48.42^{**}	117.77^{**}	1.12^{ns}	19.54^{**}	17.58^{**}	12.31^{**}	11.21^{**}
GS	0.52^{ns}	1.30^{ns}	1.62^{ns}	1.50^{ns}	0.53^{ns}	3.05^{ns}	5.75^{*}	0.01^{ns}	9.24^{**}
C	221.25^{**}	336.47^{**}	177.52^{**}	543.67^{**}	23.62^{**}	98.32^{**}	78.93^{**}	3.60^{ns}	0.42^{ns}
K×GS	0.01^{ns}	3.40^{*}	1.42^{ns}	3.59^{*}	0.05^{ns}	8.56^{**}	7.99^{**}	0.01^{ns}	4.27^{ns}
K×C	1.51^{ns}	3.94^{**}	0.45^{ns}	1.58^{ns}	2.00^{ns}	1.00^{ns}	2.08^{ns}	1.45^{ns}	0.10^{ns}
GS×C	0.01^{ns}	0.09^{ns}	0.29^{ns}	0.30^{ns}	0.08^{ns}	0.15^{ns}	0.05^{ns}	2.34^{ns}	1.42^{ns}
K×GS×C	0.11^{ns}	0.40^{ns}	0.18^{ns}	0.36^{ns}	0.18^{ns}	1.04^{ns}	1.18^{ns}	0.22^{ns}	0.79^{ns}

Statistical analyses

The effects of K application rate, cultivars, and seasons on yield, K uptake of seeds, pericarps, and stems, KHI, RIE, IUE, AE, and PE of canola were studied using two-way ANOVA. Potassium level, cultivar, and season were all fixed components in the study, but repetition times was a random variable. The relationship between K supply and K uptake by aboveground biomass is modeled and correlated. These average values were used to fit K uptake by aboveground biomass and seed yield. The standard error of the average value is represented by all error bars in the graph. At the 0.05 probability level, the Fisher protection minimum significance difference test was employed to compare the mean value of each treatment. To create charts, use SigmaPlot 10.0 software (Systat Software, San Jose, California, USA).

RESULTS

Seed yield

Rates of K treatment and canola cultivars had a substantial effect on seed output (Table 1). The lowest yields were obtained in the absence of applied K (K0) treatment for two cultivars, with 1103.8 kg ha^{-1} for ZS11 and 1735.6 kg ha^{-1} for HZ9 in 2017-2018 and 1176.2 kg ha^{-1} for ZS11 and 1735.6 kg ha^{-1} for HZ9 in 2018-2019 (Figure 1). Application of K fertilizer considerably boosted seed production ($p < 0.05$). Canola yields increased 17.9%-82.6% in 2017-2018 and 21.1%-73.6% in 2018-2019 when K was applied. However, there were nonsignificant differences between the K2, K3, and K4 treatments, indicating that 150 kg K_2O ha^{-1} was sufficient for winter canola development. The ZS11 and HZ9 produced an average yield of 1675.4 and 2231.6 kg ha^{-1} (means of two seasons), respectively.

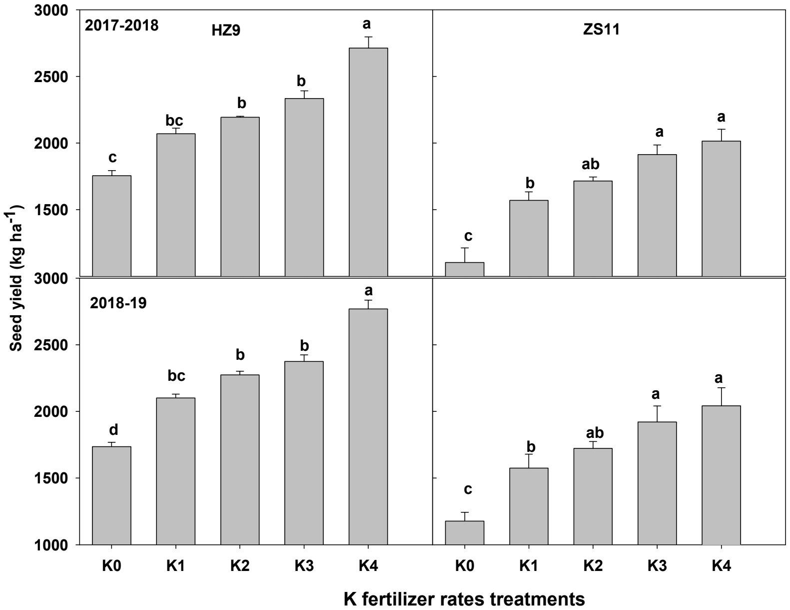

Figure 1. Effect of K fertilizer application rates on seed yield of two winter canola cultivars (HZ9 and ZS11). Means with different letters are significantly different between K rates (LSD test, $P < 0.05$). Values are means of three replicates. K0, K1, K2, K3, K4: 0, 75, 150, 225, 300 kg K_2O ha^{-1}, respectively.

Potassium uptake and distribution

The K levels had an effect on K uptake in the seed, pericarp, and stem (Table 1). As K supply enhanced, K accumulation in the seed increased dramatically at first and then steadied in ZS11 and HZ9, but continued to increase in the stem and pericarp (Figure 2). The K uptake in seed of ZS11 and HZ9 rose by 6.8-19.7 and 7.2-26.5 kg ha^{-1}, respectively, when K rate was raised. Similarly, when compared to K0, K absorption rose by 6.7-28.2 and 6.3-31.6 kg ha^{-1} in the pericarp of the ZS11 and HZ9, respectively; and by

11.7-32.4 and 10.5-38.2 kg ha^{-1} in the stem of the ZS11 and HZ9, respectively. Figure 3 showed that a substantial linear positive association between K accumulation in plant shoot and K rate was observed, indicating that winter canola acquired more K as the K treatment level improved. The K harvest index (KHI) decreased slightly as K rates increased in the 2017-2018 and 2018-2019 growing seasons, but did not differ significantly between the various K levels (Figure 4). Averagely, the KHI of canola cultivars ranged between 26.0% to 26.9% at various K rates, demonstrating that K is primarily distributed in the pericarp (35.4%-37.7%, average 36.1%) and stem (range 36.1%-38.7%, average 37.7%).

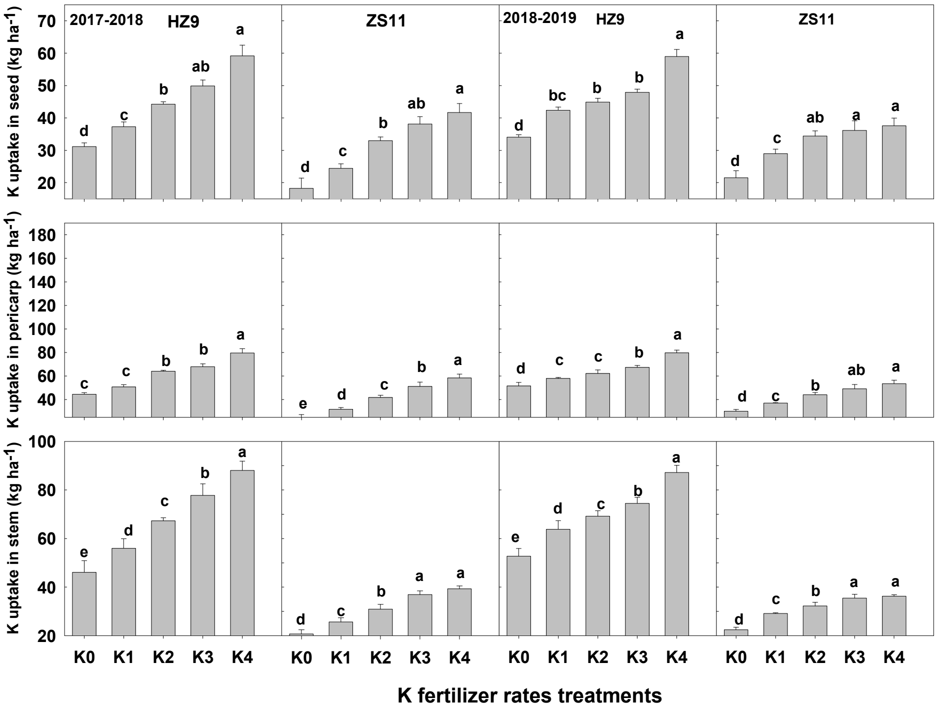

Figure 2. Effect of K fertilizer application rates on K uptake in seed, pericarp and stem of two winter canola cultivars (HZ9 and ZS11). Means with different letters are significantly different between K rates (LSD test, P < 0.05). Values are means of three replicates. K0, K1, K2, K3, K4: 0, 75, 150, 225, 300 kg K_2O ha^{-1}, respectively.

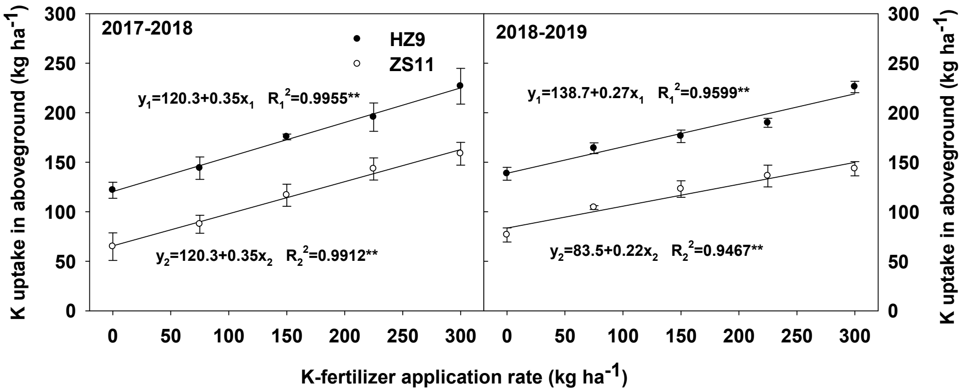

Figure 3. Correlation and regression of K fertilizer application rates with K uptake in aboveground biomass at harvest stage in 2017-2018 and 2018-2019 growing season of two winter canola cultivars (HZ9 and ZS11). The x represents the K fertilizer application rate, y represents K uptake by aboveground biomass.

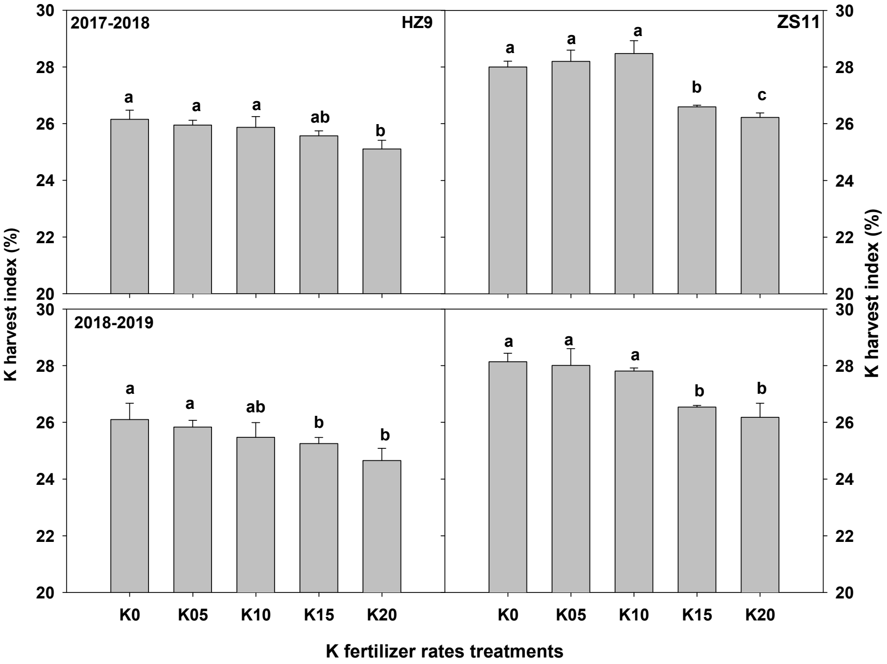

Figure 4. Effect of K fertilizer application rates on K harvest index of two winter canola cultivars (HZ9 and ZS11). K0, K1, K2, K3, K4: 0, 75, 150, 225, 300 kg K_2O ha^{-1}, respectively.

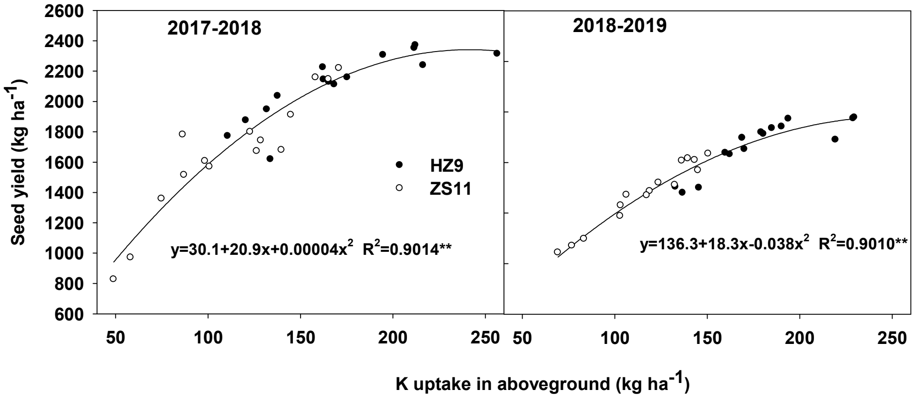

Figure 5. Relationships between K uptake in aboveground biomass and seed yield of two winter canola cultivars (HZ9 and ZS11) at harvest stage in 2017-2018 and 2018-2019 growing season. The x represents K uptake in aboveground biomass, y represents the seed yield.

To gain a better understanding of the relationship between seed yield and K uptake in aboveground biomass, regression models were applied for the two cultivars (Figure 5). The results indicated that a substantial curve relationship existed between yield and K intake. Within a particular range (no more than 200 kg ha^{-1} in 2017-2018 and 150 kg ha^{-1} in 2018-2019), yield grew rapidly in proportion to the rate of K absorbed by the aboveground biomass. When the threshold for K accumulation was exceeded, seed yield did not rise considerably. Specifically, the amount of K absorbed increased while yield remained constant, demonstrating the phenomena of K luxury consumption.

Potassium use efficiencies

The pace of K application has a substantial effect on the efficiency of K utilization (Table 1). With rising K rate, there was a steady increase in reciprocal internal efficiency (RIE) (Table 2). Winter canola required 56.0-83.6 kg K at various K values to generate 1 t canola seed (average 73.2 kg). During the two experimental seasons, internal utilization efficiency (IUE) decreased significantly as the K level was raised in both cultivars. Across two cultivars and K treatments, plant uptake 1 kg K produced 12.0-18.1 kg canola seed. With a rise in the K level, agronomic efficiency dropped. However, nonsignificant variations in the K2, K3, or K4 treatments were seen across the two seasons ($P > 0.05$). Physiological efficiency (PE) followed the similar pattern as IUE: it dropped as the level of K fertilizer increased. The PE of two cultivars was 7.8 to 17.2 at various K treatment rates. In compared to K1, the PE of K2, K3, and K4 declined by 41.2%, 45.7%, and 48.1% in 2017-2018 and 8.5%, 13.0%, and 14.2% in 2018-2019, respectively, indicating that excessive K fertilizer resulted in inefficient K utilization.

Canopy radiation interception

Canopy intercepted radiation during different growing periods significantly differed across different K levels and canola cultivars (Figure 6). The K0 intercepted relatively less radiation than other K levels before crop flowering stage and podding stage. Intercepted solar radiation at K0 and K1 was lower than K2, K3 and K4 throughout canola seedling stage. Significant differences in radiation interception were detected among different K levels in canola podding stage. The treatments of K1 and K2 gained significantly higher solar radiation than other K levels. Averagely, K2 intercepted the highest one (73.8%), followed by K1 (73%) and K4 (72.4%), while K0 recorded the lowest value (61.6%) in canola pod formation and maturity period (Figure 6A). Figure 6B showed that canopy intercepted radiation was significantly poorer in ZS11 than HZ9. For the entire growing seasons, HZ9 enhanced solar radiation by more than 20% compared with ZS11.

Table 2. Effect of K fertilizer application rates on K use efficiencies of winter canola. RIE: Reciprocal internal efficiency; IUE: internal use efficiency; AE: agronomic efficiency; PE: physiological efficiency. K0, K1, K2, K3, K4: 0, 75, 150, 225, 300 kg K_2O ha^{-1}, respectively. Means with different letters are significantly different between treatments ($P < 0.05$). Values are means of three replicates.

		2017-2018			2018-2019		
Parameters	Treatments	HZ9	ZS11	Mean	HZ9	ZS11	Mean
RIE	K0	69.4b	56.0d	62.7c	77.5b	65.0b	72.2b
	K1	69.8b	58.9cd	64.4c	78.1ab	66.3ab	72.4b
	K2	80.2a	67.8bc	73.5b	79.7ab	70.3ab	74.4ab
	K3	83.6a	74.9ab	79.3a	79.9ab	70.9ab	75.4ab
	K4	83.7a	79.0a	81.3a	81.6a	71.3a	76.0a
	Mean	77.4	67.3	72.3	79.4	68.7	74.1
IUE	K0	14.5a	18.1a	16.3a	12.9a	15.4a	14.0a
	K1	14.4a	17.0ab	15.8a	12.8ab	15.1 ab	14.0a
	K2	12.4b	14.8bc	13.7b	12.6ab	14.2b	13.5ab
	K3	12.0 b	13.4c	12.7b	12.5ab	14.1b	13.3ab
	K4	12.0b	12.7c	12.3b	12.3b	14.0b	13.2b
	Mean	13.1	15.2	14.1	12.6	14.6	13.6
AE	K0						
	K1	943.5a	1395.9a	1169.7a	1097.8a	1195.8a	1146.8a
	K2	796.0a	917.3b	817.4b	807.9b	819.9b	813.9b
	K3	569.6a	809.6b	700.6b	774.3b	744.5b	711.9bc
	K4	556.7a	683.4b	694.3b	698.9bc	649.5b	691.7c
	Mean	716.5	951.6	845.5	844.7	852.4	841.1
PE	K0						
	K1	16.0a	17.2a	16.6a	14.5a	14.3a	14.4a
	K2	11.0ab	10.9ab	9.8b	14.4ab	12.9a	13.2ab
	K3	8.2b	9.5b	9.0b	12.5ab	12.6a	12.5ab
	K4	7.8b	9.0b	8.6b	11.8b	11.9a	12.4a
	Mean	10.8	11.6	11.0	13.3	12.9	13.11

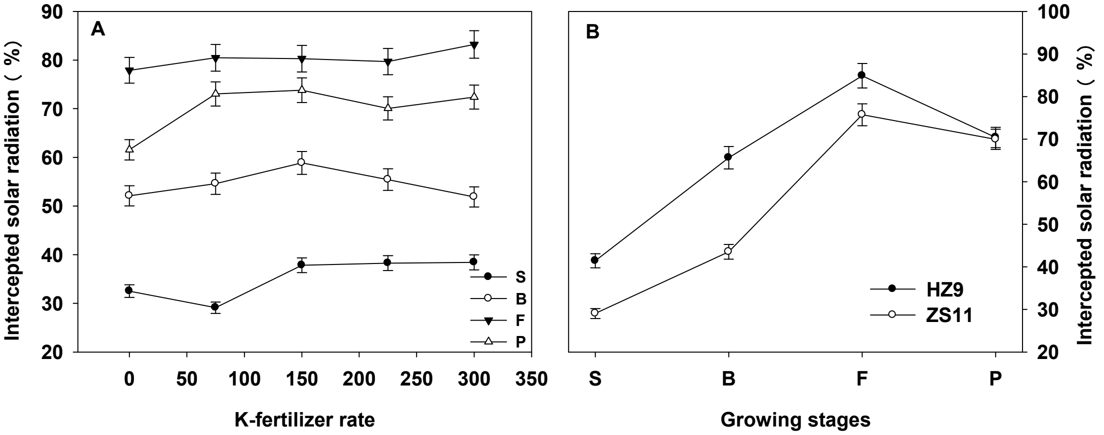

Figure 6. Effect of different K fertilizer rates on canopy radiation interception at the seedling (S), budding (B), flowering (F) and podding (P) stages (A) and for two winter canola cultivars (HZ9 and ZS11) (B). Data are averaged across two seasons (2017-2019).

DISCUSSION

When the soil is lacking in accessible K, an appropriate K application level is critical to achieving optimal output (Song et al., 2020). As demonstrated in this study, the K fertilization rate had a significant effect on the increase of seed yield for all K treatments ranging from 17.9% to 82.6%. When 150 kg K_2O ha^{-1} was broadcasted, the increase in K level resulted in a large sequential increase in yield. These data reveal that more K had no effect on yield when the K level reached a certain point, this conclusion comparable to that of Hu et al. (2021). The two cultivars yielded the least in K0, which could be attributable to decreased total photosynthetic assimilate production when K levels were insufficient.

The nutritional state of the population plants has a strong influence on canola seed output (Szczepanek and Siwik-Ziomek, 2019; Hu et al., 2021). The K fertilization has been demonstrated to boost seed output due to higher K uptake by aboveground biomass in previous research (Liu et al., 2011). The results showed that K acquiring of winter canola aboveground increased sharply as the amount of K input was increased in this research (Figure 3). Seed yield also followed a similar trend of K uptake by aboveground biomass at different K levels (Figure 5), which was consistent with a recent study by Tian et al. (2020). Canola seed yield increased linearly with K intake rising within the relatively low K levels, then changed slowly in relatively high K levels (Figure 6), demonstrating that excessive K consumption resulted in luxury use. The K uptake in the seed increased significantly at first and then fluctuated within a certain range as K application levels increased, whereas K uptake in the pericarp and stem of canola plants increased linearly all the time, indicating that the luxury absorption of K by winter canola was primarily stored in the no-seed tissues of plants (Figure 2). At harvest, 42.1% (range 32.0%-49.4%) of the K taken up by winter canola was stored in the pericarp and 44.6% (range 33.6%-58.9%) in the stem, respectively. Furthermore, the higher the K sprayed, the higher the K in the pericarp and stem, providing an essential supplemental supply of K for the following crop when crop wastes were returned to the field (Li et al., 2013). In general, crop residue K is released to increase soil K supply, so reversing the soil's apparent negative K balance. Therefore, returning no-seed canola plant tissues to replenish soil K could be an effective way to maintain soil fertility in locations where soil accessible K is low.

The four parameters RIE, IUE, AE, and PE provide diverse viewpoints on the acquire and utilization of K nutrition by canola. Several previous investigations have demonstrated that when the amount of K increases, the efficiency of K consumption generally decreases (Jiang et al., 2011; Ye et al., 2022). The amount of K required to generate 1 t canola seed rose in this study as the K application rate increased, demonstrating that canola plants' K uptake was less effective for seed production when K was sufficient. The K-efficiency values fell as the rate of K supply improved. The IUE happened to the highest when K was scarce (K0), owing to the crop's decreased K uptake. However, the lowest IUE occurred when K was abundant (K4), owing to bigger plant organs development and increased K uptake by the plants (Lu et al., 2019). There were nonsignificant variations in K-efficiency values between ZS11 and HZ9 in this study, indicating that the two cultivars' K absorption and translocation efficiency to various K levels were basically consistent.

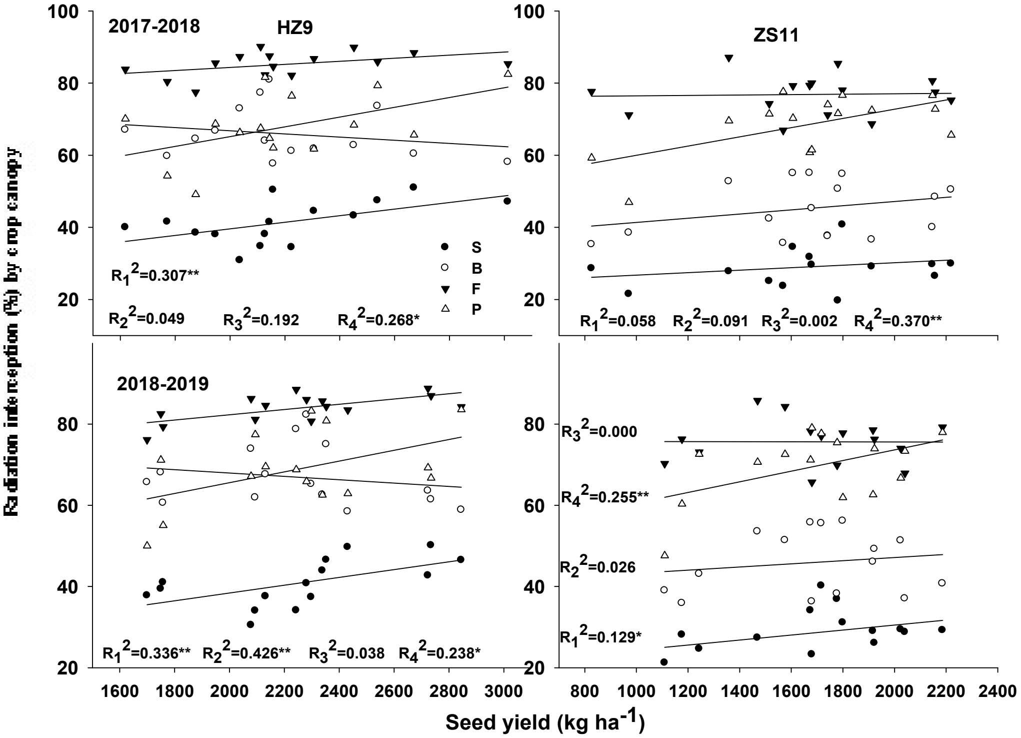

Figure 7. Relationships between seed yield and canopy radiation interception of two winter canola cultivars (HZ9 and ZS11) at different growing stages in 2017-2018 and 2018-2019. S: Seedling; B: budding; F: flowering; P: podding. R_1, R_2, R_3, R_4: regression ecoefficiency between seed yield and canopy radiation interception of winter canola at the seedling, budding, flowering, and podding stages.

Crop canopy radiation interception is a significant physiological element affecting crop output (Diepenbrock, 2000), owing to the fact that the crop's green organs of the canopy are the primary source of photosynthesis prior to and following flowering (Rathke et al., 2006). Consequently, canopy radiation interception was continuously monitored to ascertain the association between improved production and K fertilizer application. In this study, application K fertilizer treatments could receive more solar energy to transform into photosynthate as a consequence of higher radiation interception among five K levels during canola in the seedling growing period (Figure 6). Previous research has demonstrated that early canopy development speeds surface coverage, lowers soil surface water evaporation and mineral nutrient loss, and ultimately results in quicker vegetative growth and photosynthetic product accumulation in winter rapeseed (Lu et al., 2019; Hu et al., 2021). After flowering, pods contribute up to 70% to 100% of photosynthetic energy to seed production (Diepenbrock, 2000). Irrespective of cultivars and experimental seasons, seed yield was significantly related to canopy radiation interception during the pod filling period (R^2 = 0.129-0.370, in Figure 7), representing canola pods as the major part of the photosynthetic surface of crop for post-anthesis growth of the whole canola canopy. It has been demonstrated that canopy radiation interception maintained a close relationship with K uptake in aboveground biomass (Figure 8). Only existing experimental data makes it difficult to explain the radiation interception mechanism between aboveground K uptake and seed yield. Nevertheless, canopy radiation interception measured at the four growing stages underestimates optimal crop K input and winter canola growth and seed yield formation.

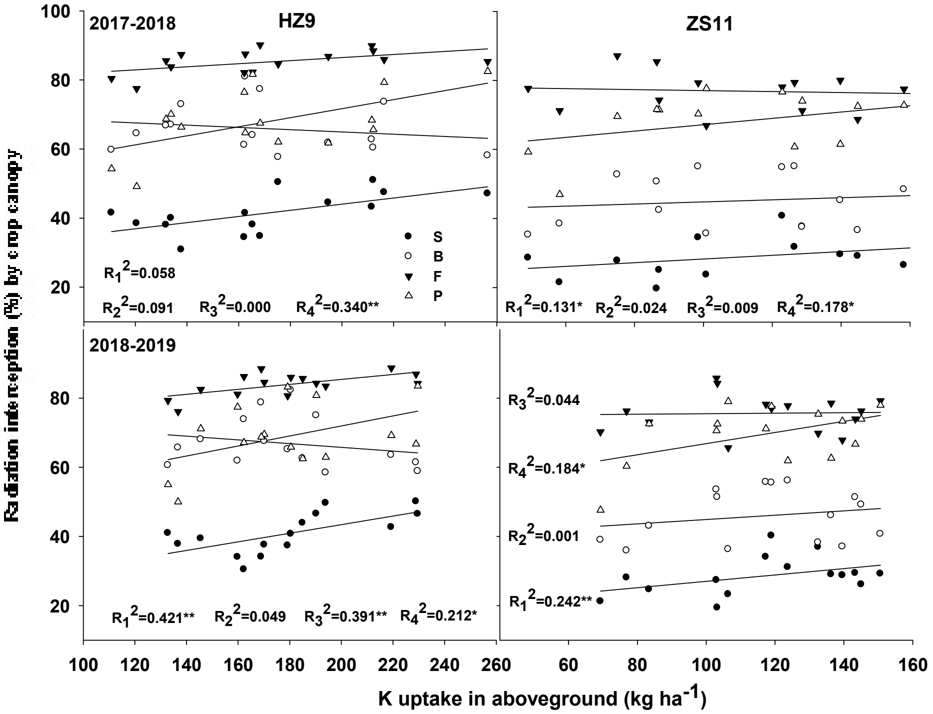

Figure 8. Relationships between the K uptake in aboveground biomass and canopy radiation interception of two winter canola cultivars (HZ9 and ZS11) at different growing stages in 2017-2018 and 2018-2019. S: Seedling; B: budding; F: flowering; P: podding. R_1, R_2, R_3, R_4: regression ecoefficiency between seed yield and canopy radiation interception of winter canola at the seedling, budding, flowering, and podding stages.

CONCLUSIONS

Proper K application is important to increase crop yields in agricultural soils with low accessible K. When compared to no K application, using K enhanced winter canola output by 19.5%-78.1%. With greater K treatment, the yields of the two canola cultivars initially climbed and then gradually decreased. The K uptake by seed followed a similar pattern; however, the uptake of K by pericarp and stem rose dramatically in response to increased K. Excessive K supply resulted in luxury use and inefficient use, with no yield benefits for K application. With increased K rates, K is mostly distributed in the pericarp and stem, resulting in the K harvest index decreased. The above results suggested that K supply rates had an effect on K absorption and utilization in winter canola, and that luxury accumulation occurred when K levels were high. Winter canola's luxury acquire of K was primarily stored in the pericarp and stem.

Author contributions

Conceptualization: R.W., W.P. Methodology: R.W., A.L., W.P. Software: A.L., X.C. Validation: A.L. Formal analysis: A.L., X.C. Investigation: R.W., A.L., X.C., Y.W., W.P. Resources: X.C., W.P. Data curation: A.L., X.C., Y.W., W.P. Writing-original draft: R.W., A.L., Y.W. Writing-review & editing: R.W., W.P. Supervision: R.W., W.P. Funding acquisition: R.W. All co-authors reviewed the final version and approved the manuscript before submission.

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References

Belouchrani, A.S., Bouderbala, A., Drouiche, N., Lounici, H. 2021. The interaction effect to fertilization on the mineral nutrition of canola under different salinity levels. Journal of Plant Growth Regulation 40(2):848-854.

Cheema, M.A., Wahid, M.A., Sattar, A., Rasul, F., Saleem, M.F. 2012. Influence of different levels of potassium on growth, yield and quality of canola (*Brassica napus* L.) cultivars. Pakistan Journal of Agricultural Sciences 49(2):163-168.

Denoroy, P., Thiebeau, P., Gosse, G. 2002. Une méthode pour estimer l'interception du rayonnement par un couvert bas: application au colza avant montaison. Ocl-Oleagineux Corps Gras Lipides 9(1):54-63.

Diepenbrock, W. 2000. Yield analysis of winter oilseed rape (*Brassica napus* L.): A review. Field Crops Research 67(1):35-49.

Dreccer, M.F., Schapendonk, A.H.C.M., van Oijen, M., Pot, C.S., Rabbinge, R. 2000. Radiation and nitrogen use at the leaf and canopy level by wheat and oilseed rape during the critical period for grain number definition. Australian Journal of Plant Physiology 27(10):899-910.

Elasha, E.A., Bidinger, F.R., Reddy, B.B. 2001. Intercepted radiation as a tool to document plant population effects on leaf area and dry matter in sorghum (*Sorghum bicolor* L.) Indian Journal of Agricultural Sciences 71(7):480-482.

Hamzei, J., Soltani, J. 2012. Deficit irrigation of rapeseed for water-saving: Effects on biomass accumulation, light interception and radiation use efficiency under different N rates. Agriculture Ecosystems and Environment 155:153-160.

Hirzel, J., Paredes, M., Becerra, V., Donoso, G. 2020. Response of direct seeded rice to increasing rates of nitrogen, phosphorus, and potassium in two paddy rice soils. Chilean Journal of Agricultural Research 80:263-273.

Hu, W.S., Lu, Z.F., Meng, F.J., Li, X.K., Cong, R.H., Ren, T., et al. 2021. Potassium fertilization reduces silique canopy temperature variation in *Brassica napus* to enhance seed yield. Industrial Crops and Products 168:113604.

Jiang, C.C., Xia, Y., Chen., F., Lu, J.W., Wang, Y.H. 2011. Plant growth, yield components, economic responses, and soil indigenous K uptake of two cotton genotypes with different K efficiencies. Agricultural Sciences in China 10:705-713.

Li, X.Y., Li, Z., Xie, Y., Wang, B., Kuai, J., Zhou, G.S. 2021. An improvement in oilseed rape (*Brassica napus* L.) productivity through optimization of rice-straw quantity and plant density. Field Crops Research 273:108290.

Li, H., Ma, C., Lu, J., Li, X., Ren, T., Cong, R. 2013. Increasing effect of N, P and K fertilizer on rapeseed in different regions of China. Scientia Agricultura Sinica 46(9):1837-1847.

Liu, X., Lu, J., Li, X., Bu, R., Liu, B., Ci, D. 2011. Dry matter accumulation and N, P, K absorbtion and utilization in direct seeding winter oilseed (*Brassica napus* L.) Scientia Agricultura Sinica 44(23):4823-4832.

Lu, Z.F., Hu, W.S., Ren, T., Zhu, C., Li, X.K., Cong, R.H., et al. 2019. Impact of K deficiency on leaves and siliques photosynthesis via metabolomics in *Brassica napus*. Environmental and Experimental Botany 158:89-98.

Misskire, Y., Mamo, T., Taddesse, A.M., Yermiyahu, U. 2019. The effect of potassium on yield, nutrient uptake and efficiency of teff (*Eragrostis tef* Zucc. Trotter) on vertisols of North Western Ethiopian Highlands. Journal of Plant Nutrition 42(4):307-322.

Rathke, G.W., Behrens, T., Diepenbrock, W. 2006. Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (*Brassica napus* L.): A review. Agriculture Ecosystems & Environment 117(2-3):80-108.

Song, X.D., Liu, F., Wu, H.Y., Cao, Q., Zhong, C., Yang, J.L., et al. 2020. Effects of long-term K fertilization on soil available potassium in East China. Catena 188:104412.

Szczepanek, M., Siwik-Ziomek, A. 2019. P and K Accumulation by rapeseed as affected by biostimulant under different NPK and S fertilization doses. Agronomy-Basel 9(9):477.

Tian, C., Zhou, X., Liu, Q., Peng, J.W., Zhang, Z.H., Song, H.X., et al. 2020. Increasing yield, quality and profitability of winter oilseed rape (*Brassica napus* L.) under combinations of nutrient levels in fertiliser and planting density. Crop and Pasture Science 71(11-12):1010-1019.

Wang, R., Cheng, T., Hu, L.Y. 2015. Effect of wide-narrow row arrangement and plant density on yield and radiation use efficiency of mechanized direct-seeded canola in Central China. Field Crops Research 172:42-52.

Wang, Y., Lu, J., Li, X., Li, J., Liu, P., Xu, W., et al. 2011. Study on nitrogen fertilizer effect and optimum fertilizer rate for transplanting and direct-seeding rapeseed. Scientia Agricultura Sinica 44(21):4406-4414.

Wang, C.Y., Yan, Z.K., Wang, Z.K., Batool, M., El-Badri, A.M., Bai, F., et al. 2021. Subsoil tillage promotes root and shoot growth of rapeseed in paddy fields and dryland in Yangtze River Basin soils. European Journal of Agronomy 130:126351.

Waraich, E.A., Rashid, F., Ahmad, Z., Ahmad, R., Ahmad, M. 2020. Foliar applied potassium stimulate drought tolerance in canola under water deficit conditions. Journal of Plant Nutrition 43(13):1923-1934.

Ye, T.H., Xue, X.X., Lu, J.W., Yan, J.Y., Ren, T., Cong, R.H., et al. 2022. Effects of potassium fertilization on crops yield, potassium uptake, and soil potassium fertility in rice-oilseed rape cropping systems. Archives of Agronomy and Soil Science 68(7):873-885.

Yin, W., Tao, L., Li, X., Tao, R., Cong, R., Lu, J.W. 2015. Nutrient deficiency limits population development, yield formation, and nutrient uptake of direct sown winter oilseed rape. Journal of Integrative Agriculture 14(4):670-680.

Yin, Y., Wang, H. 2012. Achievement, problem and scientific policy of rapeseed industry development in China. Review of China Agricultural Science and Technology 14(4):1-7.

Zhu, D.D., Lu, J.W., Cong, R.H., Ren, T., Zhang, W.J., Li, X.K. 2020b. Potassium management effects on quantity/intensity relationship of soil potassium under rice-oilseed rape rotation system. Archives of Agronomy and Soil Science 66(9):1274-1287.

Zhu, B., Xu, Q.W., Zou, Y.G., Ma, S.M., Zhang, X.D., Xie, X.Y., et al. 2020a. Effect of potassium deficiency on growth, antioxidants, ionome and metabolism in rapeseed under drought stress. Plant Growth Regulation 90(3):455-466.

Zhu, D.D., Zhang, J.L., Wang, Z., Muhammad, R.K., Lu, J.W., Li, X.K. 2019. Soil available potassium affected by rice straw incorporation and potassium fertilizer application under a rice-oilseed rape rotation system. Soil Use and Management 35(3):503-510.