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Delayed Sowing Can Improve Potassium Utilization Efficiency and Grain Potassium Concentration in Winter Wheat

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Abstract: Economic consumption and environmental impacts due to potassium (K) inputs in agriculture are gaining increasing attention. It is urgent to improve K use efficiency (KUE) for agricultural development. Delayed sowing has been shown to maintain grain yield in winter wheat. Still, there needs to be more information regarding the effect of sowing date on crop K status evaluated by the K nutrition index (KNI), KUE, K uptake efficiency (UPE), K utilization efficiency (UTE), and grain K concentration (GKC). Here, we assessed Shannong23 and Tainong18 winter wheat cultivars with three sowing date treatments composed of 26 September (early sowing), 8 October (normal sowing), and 22 October (late sowing) in the 2021–2022 and 2022–2023 growing seasons. The influences of sowing date on the KNI, tillering, grain yield formation, KUE, UPE, UTE, K transport, and GKC were examined. Our study indicated that late sowing in winter wheat was an almost optimal K nutritional situation, whereas early and normal sowing were under situations of excess K. As sowing was delayed, aboveground K uptake (AGK), UPE, and spike number per unit area decreased; UTE and grain number per spike increased; and grain yield and KUE were unchanged. A positive correlation between KNI and UPE and spike number per unit area and a negative correlation between KNI and UTE and grain number per spike were found, whereas no significant correlation between KNI and KUE was observed. Late sowing promoted K transport from pre-anthesis accumulation in vegetative organs to grain, resulting in a higher GKC, which could lead to high grain quality and K recovery. Therefore, late sowing winter wheat can use K more efficiently and increase GKC, implying that delayed sowing can reduce K input, favoring sustainable agriculture development.

Keywords: winter wheat; sowing date; potassium nutrition index; potassium utilization efficiency

Citation: Yin, L.; Liao, Y.; Mou, X. Delayed Sowing Can Improve Potassium Utilization Efficiency and Grain Potassium Concentration in Winter Wheat. *Agriculture* **2024**, *14*, 678. https://doi.org/10.3390/agriculture14050678

Academic Editor: Daniel Tan

Received: 29 March 2024
Revised: 21 April 2024
Accepted: 25 April 2024
Published: 26 April 2024

1. Introduction

Potassium (K) is one of the most important nutrient elements for crop growth [1], which can affect cell division, photosynthesis, the transport of sugar, mineral nutrition and photosynthate, and enzyme activity [2,3]. There is typically enough K in the soil to ensure high crop grain yield [4,5], but the long-term absence of K application could reduce K in the soil [6]. Hence, farmers prefer to apply additional K fertilizer during agricultural production, which can effectively improve wheat (*Triticum aestivum* L.) quality, yield, leaf area index, and harvest index [7,8]. Though K fertilizer is a costly wheat crop production component, excess K application can lead to low fertilizer use efficiency and negative environmental repercussions [9], such as soil and water pollution [10]. Furthermore, K^+ and NO_3^- exhibited synergistic transport during plant absorption [11]; however, during agricultural production, the unreasonable application of K and nitrogen fertilizers leads to a lack of N/K balance, significantly reduces the utilization rate of fertilizers, and causes environmental pollution [12–14]. Therefore, improving K use efficiency (KUE) is one of the most effective means to increase crop production and reduce environmental pollution [10].

Many researchers have defined nutritional efficiency [15–17]. Agronomic KUE was defined as crop grain yield per unit K supplied from the fertilizer and soil. KUE can be decomposed into K uptake efficiency (UPE), which is referred to as the product of plant K content per unit K supplied, and K utilization efficiency (UTE), which is referred to as the crop grain yield per unit plant K content [18]. Currently, excessive K application results in a N/K imbalance [12,14] and much K remaining in the stem at harvest, leading to a lower UTE [19]. Generally, increasing UTE can reduce K uptake, suggesting lower K consumption and K fertilizer input.

The K nutrition index (KNI) is generally used to analyze the K nutrient status of crops. The level of K deficiency and excess consumption of any kind of crop can be determined by KNI [20], which can guide when and how much fertilizer to apply to a crop. Studies have shown that nitrogen absorption can promote K absorption [21]; hence, the KNI of crops in the vegetative growth stage can be calculated using the relationship between nitrogen and K absorption to judge the K demand of crops [20,21].

Previous studies have shown that increasing the K content in leaves will significantly improve photosynthesis [22], which results in higher grain yield [23,24]. Moreover, increasing grain K concentration (GKC) is beneficial because it improves grain quality, mainly manifested as (1) an increase in protein concentration and wet gluten content and (2) the extension of dough formation time and stabilization time in grain [25]. However, many factors can influence crop K absorption, including soil, crop, and climate factors. Soil factors mainly include the nutrient concentration in the soil and the buffer ability of soil nutrients absorbed. Plant factors mainly include the rate of water flowing into the root, root length, root radius, and growth rate [10]. Climate factors mainly contain air temperature and precipitation. To obtain a high yield, farmers often increase the amount of K fertilizer [7,8]. With increased K application, K absorption of wheat significantly increases; however, more absorbed K is accumulated in the stem and leaf organs of wheat, which leads to a lower UTE [19] and higher production costs [26]. Therefore, balancing the absorption and utilization of K has attracted increasing attention in agricultural production [27–29]. Furthermore, exploring a more reasonable cultivation management measure is necessary, as this could obtain higher grain yield by optimizing K distribution and improve grain quality by increasing K concentration.

Sowing date can significantly affect crop grain yield and quality [30]. Generally, delayed sowing in wheat can decrease nitrogen uptake and grain yield [31,32]. However, as a result of global warming [33], the accumulated temperature before winter in the North China Plain reaches 600–700 °C [34], which is much higher than that in the past 70–80 years [35,36], and provides the possibility of delaying sowing in winter. In addition, many researches have verified that delayed sowing in winter wheat can obtain high grain yield [34,37–40], and only low-tillering winter wheat cultivars are more adapted to late sowing [40], mainly because of optimized nitrogen allocation and higher utility efficiency with late sowing [38,40].

Although delayed sowing in winter wheat can improve nitrogen utilization efficiency and maintain grain yield, relatively little research has focused on the effects of delayed sowing on the absorption and utilization of K. Increasing our knowledge regarding the effects of sowing date on the absorption and utilization of K will improve the production and management of winter wheat. Thus, the present study was conducted to evaluate the effects of (i) varying crop K status, expressed as the KNI, on KUE, UPE, and UTE, and (ii) delayed sowing on GKC.

2. Materials and Methods

2.1. Plant Material and Growing Conditions

We planted two low-tillering winter wheat cultivars, Shannong 23 (SN23) and Tainong 18 (TN18), at the experimental station of Shandong Agricultural University (38°36′ N, 104°02′ E), Taian, Shandong, China, during the 2021–2022 and 2022–2023 growing seasons. The last crop was summer corn. The soil is sandy loam, containing 45% sand, 3% coarse, 45% silt, and 7% clay, with a pH of 8.1 (Typic Cambisols; FAO/EC/ISRIC, 2003). The organic matter content was 14.5 g kg^{-1}, the total nitrogen content was 1.08 g kg^{-1}, available phosphorus was 27.3 mg kg^{-1}, and available K was 44.2 mg kg^{-1} in the 0–20 cm soil layer. We took fresh soil samples at five random points before sowing and fertilizing, and a 100 g soil sample was taken every 20 cm soil layer at each point, and analyzed for mineralized K. Mineralized K in the 0–100 cm soil layer was determined by a flame spectrophotometer (M410, Sherwood, UK). Soil mineralized K values before sowing in the 0–100 cm layer were 180 and 175 kg ha^{-1} in 2021 and 2022, respectively. The total rainfall was 135.4 mm in 2021–2022 and 83.6 mm in 2022–2023, and the total accumulated temperature was 2456.8 °C in 2021–2022 and 2162.5 °C in 2022–2023 (Figure 1), which could ensure the normal growth of two winter wheat cultivars.

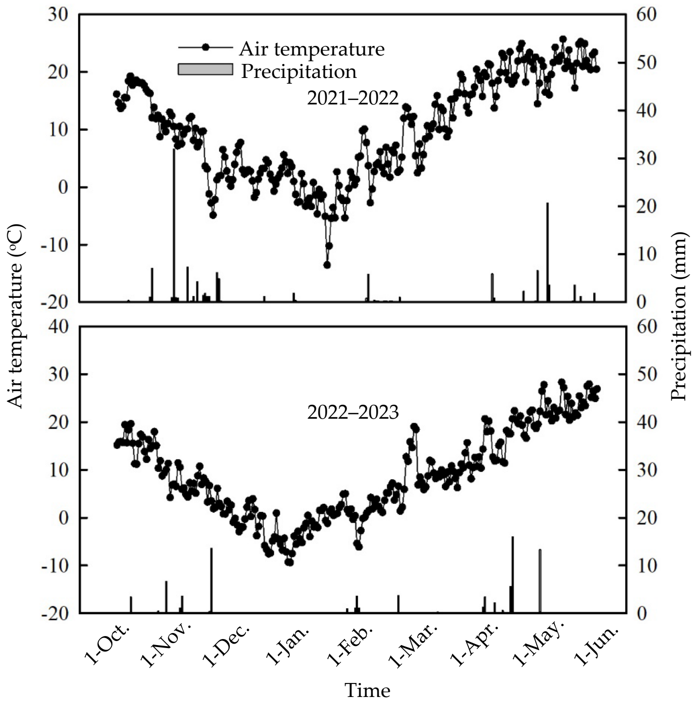

Figure 1. The average air temperature and precipitation over the two growing seasons. Top panel shows the data from the 2021–2022 growing season while the bottom panel shows the data from the 2022–2023 growing season. The data were collected by the agricultural meteorological station approximately 500 m from the experiment field.

The seeding rates of two winter wheat cultivars were 420 grains m^{-2} with a 3 cm sowing depth in 2021 and 2022 on 26 September (early sowing), 8 October (normal sowing), and 22 October (late sowing). We used a 6-row planter with 25 cm row spacing. The experiments were established in a randomized complete block design with three replicates (72 subplots). The size of each subplot was 50.0 m × 3.0 m. The basal fertilization of each subplot included N as urea, phosphorus as calcium superphosphate, and K as K chloride. Phosphorus and K rates were 80 kg ha^{-1} P and 120 kg ha^{-1} K, respectively, at each sowing date treatment, and each sowing date treatment was divided into four N fertilizer treatments with 0, 40, 80, and 120 kg N ha^{-1}, respectively. An additional 0, 40, 80, and 120 kg ha^{-1} of N was applied at the beginning of the jointing. Irrigation volume was approximately 60 mm before winter, at the jointing and anthesis stages, respectively. The fields used chemicals to control pests and diseases. No significant pests, diseases, or weeds occurred in the subplots.

2.2. Crop Measurements

2.2.1. Tillers and AGK

Tillers were counted in each subplot before wintering, at jointing and maturity in a 100 cm × 6 rows (1.5 m) quadrat of two winter wheat cultivars with three repeats.

We took aboveground plant samples (0.25 m^2) from each subplot at anthesis and maturity, those were divided into the leaves, stem, sheath, glumes, and grain (included at maturity) and were oven-dried at 75 °C for 48 h until constant weight and then weighed and recorded. Then, we milled plant material and analyzed total K concentration by a flame spectrophotometer (M410, Sherwood, UK). K accumulation was calculated by multiplying K concentration (%) by dry weight. Aboveground K uptake was calculated as the sum of the K uptake of the measured organs at each growth stage. This process was repeated three times.

2.2.2. K Transport Content and Contribution Ratio to Grain

K transport content from pre-anthesis accumulation in vegetative organs to grain (KT_{pre}) was calculated by the difference of K content in vegetative organs between anthesis and maturity:

KT_{pre} = K content in vegetative organs at anthesis − K content in vegetative organs at maturity

K transport content from post-anthesis absorption to grain (KT_{post}) was calculated by the difference of K content between grain K content at maturity and KT_{pre}:

KT_{post} = grain K content at maturity − KT_{pre}

The K contribution ratio of pre-anthesis accumulation in vegetative organs to grain at maturity (KCR_{pre}) refers to the ratio of KT_{pre} to grain K content at maturity:

KCR_{pre} = KT_{pre}/grain K content at maturity

The K contribution ratio of post-anthesis absorption to grain at maturity (KCR_{post}) refers to the difference between 1 and KCR_{pre}, as follows:

$KCR_{post} = 1 - KCR_{pre}$

2.2.3. Yield and Components

At maturity we selected a quadrat of 2.25 m^2 (3.0 m × 6 rows) at each subplot, and cut down all ears and threshed using a Pint-size Seeding Threshing Machine. The grain was air-dried and weighed. 200 g grain was removed from each experimental treatment and dried in a dryer at 75 °C for 48 h until constant weight, and the water content was measured. The grain water content was adjusted to 12%, and the grain weight and grain yield were calculated. A total of 50 spikes in each experimental subplot were randomly selected, and grain number per spike was counted. This process was repeated three times.

2.2.4. KUE and Components

KUE is defined as crop grain yield per unit K supplied from fertilizer and soil. KUE can be decomposed into K uptake efficiency (UPE), which is referred to as the product of plant K content per unit K supplied, and K utilization efficiency (UTE), which is referred to as the crop grain yield per unit plant K content [18]:

KUE = Grain dry matter/K available

UPE = Aboveground K uptake/K available

UTE = Grain dry matter/Aboveground K uptake

2.2.5. NNI and KNI

The NNI was calculated by the ratio of the actual aboveground crop N concentration ($\%N_a$) and the critical N concentration ($\%N_c$) at anthesis. The $\%N_c$ was assessed on the basis of the "critical dilution curve" confirmed for wheat by Justes et al. (1994) [41].

The KNI was calculated by the ratio of the actual aboveground crop K concentration ($\%K_a$) and the critical K concentration ($\%K_c$) at anthesis, where the latter was estimated according to the positive correlation between the concentrations of K and N in the crop [20]. The KNI is widely used to diagnose crop K status [20]. When KNI is greater than 1.0, it suggests an excessive K supply, and when KNI is less than 1.0, it indicates an insufficient K supply, whereas when KNI is equal to 1.0, it implies an optimal K supply [20].

2.3. Statistical Analysis

Results were analyzed using DPS v.7.05 software (Hangzhou RuiFeng Information Technology Co. Ltd., Hangzhou, China). Multiple comparisons were performed after a preliminary F-test. Means were tested based on the least significant difference at $p < 0.05$. Correlation analysis was performed by DPS v.7.05 software and Microsoft 2010. The figure was made using SigmaPlot 12.0.

3. Results

3.1. KNI

The KNI of the late sowing date decreased by 11.0 and 6.5% for SN23 and 14 and 8.0% for TN18, at anthesis, compared to the early and normal sowing date averaged over 2 years (Figure 2). The KNI of the early and normal sowing date treatments were >1.0, whereas the KNI of the late sowing date treatment was close to 1.0.

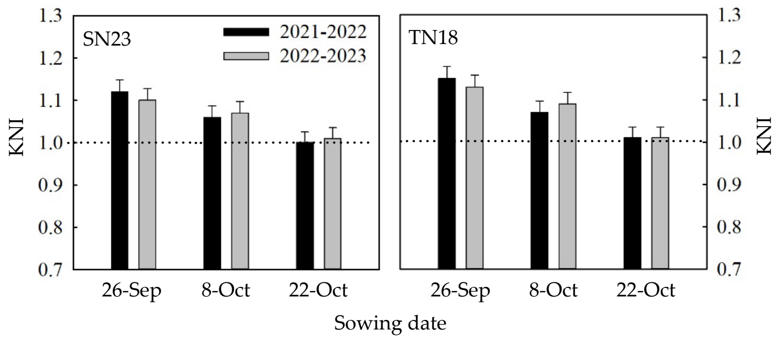

Figure 2. Effect of sowing date on the K nutrition index (KNI) at anthesis of SN23 and TN18 winter wheat cultivars in two seasons. Values are means of three replicates per treatment. Vertical bars indicate standard error.

3.2. Grain Yield Formation and GKC

As the sowing date was delayed from 26 September and 8 October to 22 October, grain yield and thousand grains weight were unchanged for SN23 and TN18 winter wheat cultivars, respectively, in the two growing seasons. The grain number per spike increased by an average of 19.5 and 11.4% for SN23 and 21.0 and 9.9% for TN18 over the two growing seasons. The spike number decreased by an average of 15.8 and 10.9% for SN23 and 13.9 and 9.5% for TN18 over the two growing seasons (Table 1).

Table 1. The grain yield formation and grain K concentration (GKC) of SN23 and TN18 winter wheat cultivars with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	Grain Yield (kg ha^{-1})	Spike Number (10^4 ha^{-1})	Grain Number Per Spike	Thousand Grain Weight (g)	GKC (%)
2021–2022	SN23	26-Sep	9210.6 ± 285.3a	702.5 ± 28.1a	34.6 ± 1.5c	39.1 ± 2.1a	0.65 ± 0.021b
		8-Oct	9316.5 ± 306.2a	665.3 ± 20.1b	37.2 ± 2.0b	39.5 ± 2.0a	0.67 ± 0.020b
		22-Oct	9385.1 ± 151.8a	590.1 ± 26.8c	41.5 ± 0.7a	39.4 ± 2.3a	0.71 ± 0.015a
	TN18	26-Sep	9482.6 ± 361.7a	717.6 ± 10.6a	32.1 ± 1.8c	38.1 ± 1.8a	0.67 ± 0.013b
		8-Oct	9681.1 ± 112.1a	680.6 ± 27.5b	36.4 ± 2.5b	38.5 ± 1.5a	0.68 ± 0.014b
		22-Oct	9499.3 ± 267.4a	615.8 ± 9.2c	39.8 ± 2.3a	38.6 ± 2.1a	0.73 ± 0.005a
2022–2023	SN23	26-Sep	9355.1 ± 403.5a	692.4 ± 21.6a	35.1 ± 1.7c	39.0 ± 0.9a	0.63 ± 0.021b
		8-Oct	9401.2 ± 332.8a	653.8 ± 13.8b	37.6 ± 0.6b	39.4 ± 2.1a	0.65 ± 0.031b
		22-Oct	9435.7 ± 187.6a	584.9 ± 16.8c	41.8 ± 1.5a	39.3 ± 2.3a	0.71 ± 0.026a
	TN18	26-Sep	9582.3 ± 258.4a	723.6 ± 23.5a	34.1 ± 2.1c	37.9 ± 1.6a	0.66 ± 0.022b
		8-Oct	9613.2 ± 365.1a	691.2 ± 20.7b	36.5 ± 2.3b	38.2 ± 1.2a	0.69 ± 0.018b
		22-Oct	9511.7 ± 218.9a	625.4 ± 30.5c	40.3 ± 1.4a	38.4 ± 1.1a	0.73 ± 0.011a
	Year (Y)		ns	ns	ns	ns	ns
	Cultivar (C)		*	***	***	**	***
	Sowing date (S)		ns	***	***	ns	***
	Y × C		ns	ns	ns	ns	ns

Table 1. *Cont.*

Season	Cultivar	Sowing Date	Grain Yield (kg ha^{-1})	Spike Number (10^4 ha^{-1})	Grain Number Per Spike	Thousand Grain Weight (g)	GKC (%)
	Y × S		ns	ns	ns	ns	ns
	C × S		ns	ns	ns	ns	ns
	Y × C × S		ns	ns	ns	ns	ns

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, ** denotes significance at $p < 0.01$, and *** denotes significance at $p < 0.001$.

Overall, the GKC was 0.64% for SN23 and 0.67% for TN18 under early sowing, 0.66% for SN23 and 0.69% for TN18 under normal sowing, and 0.71% for SN23 and 0.73% for TN18 under late sowing (Table 1).

The effects of year (Y), cultivar (C), sowing date (S), and the interaction effects of Y × C, Y × S, C × S, and Y × C × S on the grain yield and components and GKC were shown in Table 1. Only the effects of C on the grain yield and thousand grain weight were significant. The spike number, grain number per spike, and GKC were significantly affected by the C and S.

3.3. Number of Tillers

The C, S, and Y × C significantly affected the tiller number at jointing. The tiller numbers at maturity and productive tiller percentage were significantly affected by the C and S. The only effect of Y × S on the sterile tiller number was not significant (Table 2).

Table 2. The tiller number at jointing and maturity, sterile tiller number, and productive tiller percentage of SN23 and TN18 winter wheat cultivars with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	Tiller Number (10^4 ha^{-1})			Productive Tiller Percentage (%)
			Jointing	Maturity	Sterile Tillers	
2021–2022	SN23	26-Sep	1723.5 ± 51.2a	702.5 ± 23.6a	1021.0 ± 33.6a	40.8 ± 1.2c
		8-Oct	1465.8 ± 50.2b	665.3 ± 25.1b	800.5 ± 35.7b	45.4 ± 2.1b
		22-Oct	1153.2 ± 36.1c	590.1 ± 12.6c	563.1 ± 12.3c	51.2 ± 2.5a
	TN18	26-Sep	1821.6 ± 25.8a	717.6 ± 35.8a	1104.0 ± 54.2a	39.4 ± 1.6c
		8-Oct	1564.2 ± 69.2b	680.6 ± 20.7b	883.6 ± 42.6b	43.5 ± 1.2b
		22-Oct	1189.3 ± 71.5c	615.8 ± 11.9c	573.5 ± 21.2c	51.8 ± 2.3a
2022–2023	SN23	26-Sep	1684.3 ± 32.8a	692.4 ± 32.7a	991.9 ± 28.6a	41.1 ± 2.0c
		8-Oct	1420.9 ± 33.6b	653.8 ± 40.5b	767.1 ± 33.8b	46.0 ± 0.6b
		22-Oct	1092.8 ± 42.9c	584.9 ± 18.9c	507.9 ± 18.7c	53.5 ± 1.2a
	TN18	26-Sep	1768.2 ± 56.7a	723.6 ± 26.5a	1044.6 ± 26.7a	40.9 ± 0.8c
		8-Oct	1600.3 ± 27.1b	691.2 ± 23.5b	909.1 ± 13.2b	43.2 ± 2.1b
		22-Oct	1231.5 ± 16.8c	625.4 ± 37.1c	606.1 ± 8.2c	50.8 ± 3.0a
	Year (Y)		ns	ns	*	ns
	Cultivar (C)		***	***	***	**
	Sowing date (S)		***	***	***	***
	Y × C		*	ns	*	ns
	Y × S		ns	ns	ns	ns
	C × S		ns	ns	**	ns
	Y × C × S		ns	ns	**	ns

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, ** denotes significance at $p < 0.01$, and *** denotes significance at $p < 0.001$.

On a two-year average, the number of tillers at jointing under late sowing decreased by 34.1 and 22.2% for SN23 and 32.6 and 23.5% for TN18, and sterile tillers under late sowing decreased by 46.8 and 31.7% for SN23 and 45.1 and 34.2% for TN18 compared to those under early and normal sowing. The productive tiller percentage increased from 41.0 and 45.7 to 52.4% for SN23 and 40.2 and 43.4 to 51.3% for TN18, as the sowing date was delayed from 26 September and 8 October to 22 October (Table 2).

3.4. K Content

The K content of leaves per single shoot under late sowing increased by 14.7 and 9.9% for SN23 and 12.9 and 8.3% for TN18, compared with that under early and normal sowing, respectively, averaged over the two years. The K content of true stem per single shoot under late sowing was unchanged for SN23 among the three sowing dates and decreased by 6.0 and 3.7% for TN18 under late sowing compared to TN18 under early and normal sowing. The K content of the sheath per single shoot was unchanged for SN23 and reduced by 11.9 and 6.9% for TN18, the K of content of the ear decreased by 6.2 and 2.4% for SN23 and 6.2 and 4.5% for TN18, and the K content of the single shoot was unchanged for SN23 and TN18, respectively (Table 3).

Table 3. The K content per unit land area and per single stem of SN23 and TN18 winter wheat cultivars at anthesis with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	K Content Per Single Stem (mg)					K Content Per Unit Land Area (kg ha^{-1})				
			Leaves	True Stem	Sheath	Ear	All	Leaves	True Stem	Sheath	Ear	All
2021–2022	SN23	26-Sep	5.9 ± 0.1c	13.6 ± 0.4a	8.6 ± 0.2a	6.5 ± 0.2a	34.6 ± 1.1a	41.2 ± 1.2a	95.3 ± 1.1a	60.3 ± 2.1a	45.8 ± 0.6a	236.6 ± 6.2a
		8-Oct	6.1 ± 0.2b	13.3 ± 0.3a	8.4 ± 0.3ab	6.3 ± 0.1ab	34.1 ± 0.2a	40.9 ± 1.0a	88.2 ± 3.5b	55.6 ± 2.3b	41.7 ± 2.5b	226.4 ± 3.1b
		22-Oct	6.8 ± 0.1a	13.0 ± 0.6a	8.2 ± 0.2b	6.1 ± 0.05b	34.1 ± 1.3a	40.0 ± 0.5a	76.6 ± 3.6c	48.4 ± 3.5c	36.2 ± 1.6c	201.2 ± 4.5c
	TN18	26-Sep	5.9 ± 0.3c	12.6 ± 0.5a	8.5 ± 0.1a	5.7 ± 0.1a	32.7 ± 1.0a	42.6 ± 2.0a	90.5 ± 4.1a	61.3 ± 3.8a	41.2 ± 1.2a	235.6 ± 1.6a
		8-Oct	6.2 ± 0.2b	12.5 ± 0.5a	8.1 ± 0.4b	5.7 ± 0.3a	32.5 ± 0.8a	42.0 ± 1.6a	85.2 ± 3.8b	54.8 ± 2.1b	38.6 ± 1.3b	220.6 ± 5.6b
		22-Oct	6.7 ± 0.4a	11.6 ± 0.2b	7.6 ± 0.5c	5.5 ± 0.6a	31.4 ± 0.5a	41.5 ± 0.7a	71.7 ± 2.4c	46.8 ± 0.8c	33.6 ± 2.3c	192.6 ± 3.8c
2022–2023	SN23	26-Sep	5.7 ± 0.3c	13.5 ± 0.2a	8.3 ± 0.4a	6.4 ± 0.2a	33.9 ± 1.4a	39.4 ± 1.6a	93.4 ± 2.5a	57. ± 1.16a	44.5 ± 2.5a	232.4 ± 8.1a
		8-Oct	6.0 ± 0.3b	13.2 ± 0.6a	8.2 ± 0.2a	6.1 ± 0.3b	33.5 ± 0.6a	39.1 ± 2.1a	86.6 ± 1.2b	53.8 ± 1.6b	39.7 ± 2.1b	219.2 ± 7.2b
		22-Oct	6.5 ± 0.1a	12.9 ± 0.1a	8.2 ± 0.2a	6.0 ± 0.2b	33.6 ± 0.6a	38.2 ± 2.7a	75.5 ± 0.6c	47.9 ± 1.4c	35.2 ± 0.8c	196.8 ± 4.0c
	Tn18	26-Sep	5.7 ± 0.1c	12.4 ± 0.5a	8.3 ± 0.1a	5.6 ± 0.4a	32.0 ± 1.2a	41.2 ± 0.4a	89.6 ± 1.8a	59.9 ± 2.8a	40.8 ± 0.6a	234.5 ± 5.3a
		8-Oct	5.9 ± 0.4b	11.9 ± 0.2a	7.8 ± 0.3b	5.4 ± 0.1ab	31.0 ± 0.8a	41.0 ± 1.3a	82.4 ± 3.1b	53.6 ± 2.1b	37.2 ± 1.8b	214.2 ± 5.0b
		22-Oct	6.4 ± 0.2a	11.9 ± 0.3a	7.2 ± 0.4c	5.1 ± 0.2b	30.6 ± 0.7a	40.3 ± 1.1a	74.6 ± 2.1c	45.2 ± 0.3c	32.0 ± 1.1c	192.1 ± 2.1c
	Year (Y)		***	ns	**	***	**	***	ns	**	***	*
	Cultivar (C)		ns	***	***	***	***	***	***	ns	***	*
	Sowing date (S)		***	***	***	***	ns	*	***	***	***	***
	Y × C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Y × S		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	C × S		ns	ns	***	ns	ns	ns	ns	**	ns	ns
	Y × C × S		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, ** denotes significance at $p < 0.01$, and *** denotes significance at $p < 0.001$.

At anthesis, the leaves K content per single shoot was significantly affected by the Y and S. Only the effects of C and S on the true stem K content per single shoot were significant. The Y × C, Y × S, and Y × C × S did not significantly affect the sheath K content per single shoot. Only Y, C, and S significantly affected the ear K content per single shoot. The K content per single shoot was only significantly affected by the Y and C (Table 3).

As the sowing date was delayed from 26 September and 8 October to 22 October, at anthesis over the two growing seasons, the K content of leaves per unit land area was unchanged for SN23 and TN18, respectively. The K content of the true stem per unit land area decreased by an average of 19.4 and 13.0% for SN23 and 18.8 and 12.7% for TN18. The K content of the sheath per unit land area decreased by an average of 18.3 and 12.0% for SN23 and 24.1 and 15.1% for TN18. The K content of the ear per unit land area decreased by an average of 20.9 and 12.3% for SN23 and 20.0 and 13.5% for TN18. The K content of the single shoot per unit land area decreased by an average of 15.1 and 10.7% for SN23 and 18.2 and 11.5% for TN18. (Table 3).

Only the effects of Y, C, and S on the leaves, ear, and single shoot K content per unit land area were significant. The true stem K content per unit land area was significantly affected by C and S. Only Y and S significantly affected the sheath K content per unit land area (Table 3).

At maturity the S, C × S, and Y × C × S significantly affected the leaves K content per single shoot. Only C × S and Y × C × S did not significantly affect the stem K content per single shoot. The sheath K content per single shoot was significantly affected by the Y, C, S, and C × S. The effects of Y, C, S, and Y × C on the glumes K content per single shoot were significant. Only C and S significantly affected grain K content per single shoot. The K content per single shoot was only significantly affected by the S (Table 4).

Table 4. The K content per unit land area and per single stem of SN23 and TN18 winter wheat cultivars at maturity with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	K Content Per Single Stem (mg)						K Content Per Unit Land Area (kg ha^{-1})					
			Leaves	Stem	Sheath	Glumes	Grain	All	Leaves	Stem	Sheath	Glumes	Grain	All
2021–2022	SN23	26-Sep	4.1 ± 0.1a	12.9 ± 0.3a	5.7 ± 0.2a	5.8 ± 0.2a	8.6 ± 0.2c	37.1 ± 1.1a	28.6 ± 1.0a	90.6 ± 3.2a	39.7 ± 1.2a	40.6 ± 0.2a	60.2 ± 1.6b	259.7 ± 6.8a
		8-Oct	4.0 ± 0.2a	11.8 ± 0.4b	5.4 ± 0.2b	5.5 ± 0.4b	9.4 ± 0.3b	36.1 ± 1.2a	26.3 ± 0.3b	78.2 ± 1.5b	35.9 ± 1.3b	36.8 ± 1.1b	62.7 ± 1.8b	239.9 ± 9.2b
		22-Oct	3.7 ± 0.2b	10.9 ± 1.0c	5.1 ± 0.1c	5.2 ± 0.6c	11.3 ± 1.1a	36.2 ± 0.6a	22.1 ± 0.6c	64.4 ± 2.3c	30.1 ± 0.5c	30.6 ± 0.6c	66.7 ± 2.5a	213.9 ± 7.5c
	TN18	26-Sep	4.2 ± 0.3a	11.7 ± 0.8a	6.1 ± 0.4a	5.4 ± 0.3a	8.8 ± 1.3c	36.2 ± 0.9a	30.1 ± 1.2a	84.3 ± 2.1a	43.8 ± 0.9a	39.1 ± 1.2a	63.4 ± 0.6b	260.7 ± 3.2a
		8-Oct	4.0 ± 0.2b	10.9 ± 0.2b	5.8 ± 0.1b	5.4 ± 0.5a	9.7 ± 0.6b	35.8 ± 0.5ab	27.5 ± 0.8b	74.3 ± 3.6b	39.4 ± 0.3b	37.0 ± 1.1b	65.8 ± 1.2b	244.0 ± 6.5b
		22-Oct	3.5 ± 0.1c	9.5 ± 1.1c	5.1 ± 0.3c	5.2 ± 0.4a	11.2 ± 1.0a	34.5 ± 0.3b	21.5 ± 1.7c	58.4 ± 1.7c	31.6 ± 1.1c	31.9 ± 0.9c	69.1 ± 1.5a	212.5 ± 3.4c
2022–2023	SN23	26-Sep	4.0 ± 0.1a	12.9 ± 0.6a	5.4 ± 0.3a	5.6 ± 0.2a	8.6 ± 0.3c	36.5 ± 1.1a	27.5 ± 0.5a	89.1 ± 1.2a	37.2 ± 0.5a	38.7 ± 0.6a	59.3 ± 1.2b	251.8 ± 1.2a
		8-Oct	3.9 ± 0.4a	11.5 ± 0.4b	5.4 ± 0.2a	5.4 ± 0.4a	9.4 ± 0.5b	35.6 ± 1.5a	25.6 ± 0.9b	75.3 ± 0.8b	35.3 ± 0.7b	35.3 ± 0.6b	61.4 ± 2.5b	231.7 ± 5.8b
		22-Oct	4.0 ± 0.2a	9.7 ± 0.3c	5.0 ± 0.1b	5.1 ± 0.3b	11.5 ± 0.6a	35.3 ± 1.6a	23.6 ± 0.3c	56.7 ± 2.1c	29.2 ± 0.6c	29.8 ± 1.5c	67.2 ± 2.6a	215.0 ± 6.7c
	TN18	26-Sep	4.0 ± 0.1a	11.9 ± 0.4a	6.0 ± 0.4a	5.5 ± 0.4a	8.8 ± 0.7c	36.2 ± 0.5a	29.3 ± 0.1a	86.2 ± 2.1a	43.2 ± 1.2a	40.1 ± 0.4a	63.6 ± 0.9b	262.4 ± 3.1a
		8-Oct	3.9 ± 0.1a	10.3 ± 0.8b	5.5 ± 0.4b	5.3 ± 0.5a	9.6 ± 0.6b	34.6 ± 0.7ab	27.1 ± 1.1b	71.5 ± 2.3b	37.8 ± 0.7b	36.8 ± 0.3b	66.4 ± 1.0b	239.6 ± 3.0b
		22-Oct	3.3 ± 0.4b	9.4 ± 0.4c	4.9 ± 0.3c	5.0 ± 0.1b	11.2 ± 0.2a	33.8 ± 0.8b	20.8 ± 1.0c	58.7 ± 0.5c	30.6 ± 0.6c	31.2 ± 0.6c	69.8 ± 1.6a	211.1 ± 4.8c
	Year (Y)		ns	**	**	*	ns	ns	ns	**	**	*	ns	*
	Cultivar (C)		ns	***	***	*	***	ns	***	***	***	**	ns	**
	Sowing date (S)		***	***	***	***	***	***	***	***	***	***	***	**
	Y × C		ns	**	ns	*	ns	ns	**	ns	ns	ns	ns	ns
	Y × S		ns	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
	C × S		***	ns	***	ns	ns	ns	***	ns	***	ns	ns	ns
	Y × C × S		*	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, ** denotes significance at $p < 0.01$, and *** denotes significance at $p < 0.001$.

On the whole, at maturity the K content of leaves per single shoot was unchanged for SN23 and decreased by 17.1 and 13.9% for TN18, the K content of the true stem per single shoot decreased by 20.2 and 11.6% for SN23 and 19.9 and 10.8% for TN18, the K content of the sheath per single shoot decreased by 9.0 and 6.5% for SN23 and 17.4 and 11.5% for TN18, the K content of glumes per single shoot decreased by 9.6 and 5.5% for SN23 and 6.4 and 4.7% for TN18, the K content of grain per single shoot increased by 32.6 and 21.3% for SN23 and 27.3 and 16.1% for TN18, and the K content of the single shoot was unchanged for SN23 and decreased by 5.7 and 3.0% for TN18 under late sowing compared to those under early and normal sowing (Table 4). Only the effects of Y and Y × S on the leaves K content per unit land area and Y × C and C × S on the stem K content per unit land area were not significant. The sheath K content per unit land area was significantly affected by the Y, C, S, and C × S. The Y, C, and S significantly affected the glumes K content per unit land area. Only S significantly affected the grain K content per unit land area. The K content per unit land area was significantly affected by the Y, C, and S (Table 4).

Under late sowing, the K content of leaves per unit land area decreased by 18.5 and 11.9% for SN23 and 28.8 and 22.5% for TN18, compared with that under early and normal sowing, averaged over the two years. The K content of the true stem per unit land area decreased by 32.6 and 21.1% for SN23 and 31.3 and 19.7% for TN18, the K content of the sheath per unit land area decreased by 22.9 and 16.7% for SN23 and 28.5 and 19.4% for TN18, the K content of glumes per unit land area decreased by 23.8 and 16.2% for SN23 and 20.3 and 14.5% for TN18, the K content of grain per unit land area increased by 12.1 and 7.9% for SN23 and 9.4 and 5.1% for TN18, and the K content per unit land area decreased by an average of 16.1 and 9.1% for SN23 and 19.0 and 12.4% for TN18 (Table 4).

3.5. K Transport

The KCR_{pre} was the highest under late sowing, followed by normal sowing; the KCR_{pre} was 70.4% for SN23 and 56.3% for TN18 under early sowing, 78.2% for SN23 and 64.3% for TN18 under normal sowing, and 83.3% for SN23 and 71.9% for TN18 under late sowing, averaged over the two years. The KCR_{post} was the lowest under late sowing, followed by normal sowing; the KCR_{post} decreased from 29.7 and 21.8 to 16.7% for SN23 and from 43.8 and 35.8 to 28.2% for TN18, as the sowing date was delayed from 26 September and 8 October to 22 October (Figure 3). Over two growing seasons, the KT_{pre} of leaves per single shoot under late sowing increased by an average of 60.0 and 33.3% for SN23 and 85.3 and 50.0% for TN18, the KT_{pre} of the true stem per single shoot increased by an average of 307.7 and 65.6% for SN23 and 228.6 and 43.8% for TN18, the KT_{pre} of the sheath per single shoot increased by an average of 8.6 and 6.6% for SN23 and was unchanged for TN18, the KT_{pre} of glumes per single shoot increased by an average of 20.0 and 20.0% for SN23 and was unchanged for TN18, the KT_{pre} of the single shoot increased by an average of 57.0 and 29.3% for SN23 and 62.6 and 29.8% for TN18, and the KT_{post} per single shoot decreased by an average of 25.5 and 7.3% for SN23 and 18.2 and 8.7% for TN18, compared with those under early and normal sowing, respectively (Table 5).

The KT_{pre}s of leaves, stem, and glumes was significantly affected by the Y, C, S, Y × C, Y × S, C × S, and Y × C × S. Only the effects of Y × C and Y × S on the KT_{pre} of the sheath, C × S and Y × C × S on the KT_{pre} of the single shoot, and C × S on the KT_{post} were not significant.

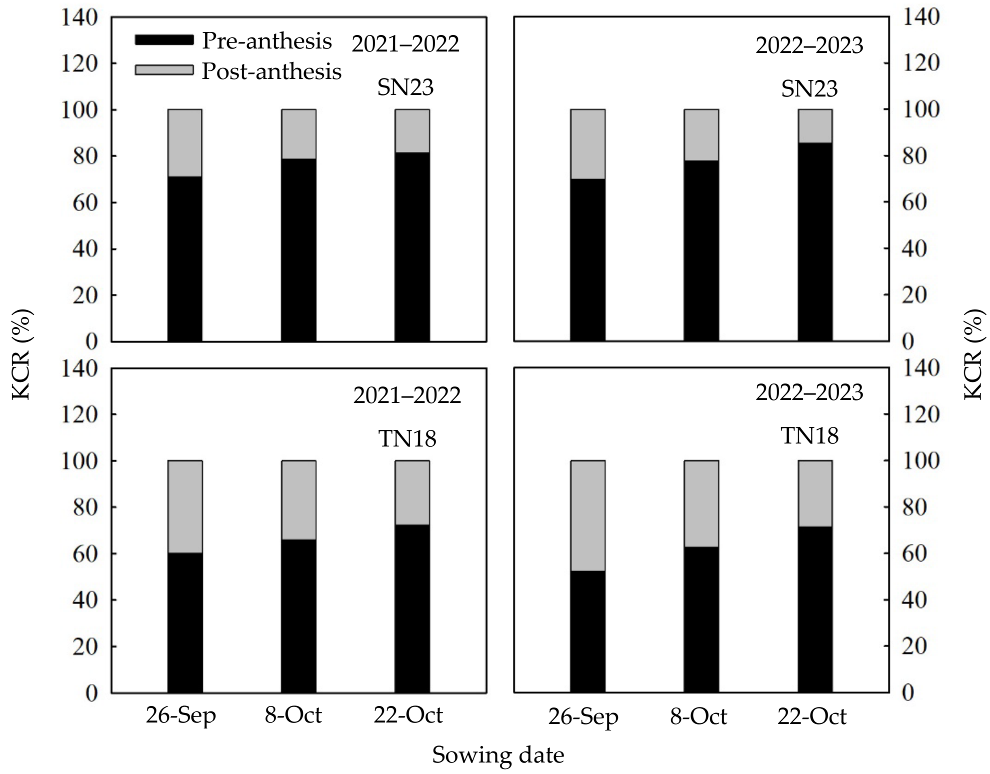

Figure 3. The K contribution ratio (KCR) of pre-anthesis accumulation and post-anthesis absorption in grain of SN23 and TN18 winter wheat cultivars at anthesis with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Table 5. The K transported from K accumulated in vegetative organs at pre-anthesis (KT_{pre}) and from K absorbed at post-anthesis (KT_{post}) in grain of SN23 and TN18 winter wheat cultivars with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	KT_{pre} (mg)					KT_{post} (mg)
			Leaves	Stem	Sheath	Glumes	All	
2021–2022	SN23	26-Sep	1.8 ± 0.2c	0.7 ± 0.1c	2.9 ± 0.1a	0.7 ± 0.02c	6.1 ± 0.3c	2.5 ± 0.1a
		8-Oct	2.1 ± 0.1b	1.5 ± 0.1b	3.0 ± 0.1a	0.8 ± 0.03b	7.4 ± 0.4b	2.0 ± 0.2b
		22-Oct	3.1 ± 0.1a	2.1 ± 0.2a	3.1 ± 0.2a	0.9 ± 0.05a	9.2 ± 0.5a	2.1 ± 0.06b
	TN18	26-Sep	1.7 ± 0.1c	0.9 ± 0.2c	2.4 ± 0.2a	0.3 ± 0.01a	5.3 ± 0.1c	3.5 ± 0.09a
		8-Oct	2.2 ± 0.2b	1.6 ± 0.3b	2.3 ± 0.1a	0.3 ± 0.02a	6.4 ± 0.5b	3.3 ± 0.2b
		22-Oct	3.2 ± 0.3a	2.1 ± 0.4	2.5 ± 0.2a	0.3 ± 0.03a	8.1 ± 0.6a	3.1 ± 0.3c
2022–2023	SN23	26-Sep	1.7 ± 0.2c	0.6 ± 0.05c	2.9 ± 0.1b	0.8 ± 0.06b	6.0 ± 0.5c	2.6 ± 0.1a
		8-Oct	2.1 ± 0.1b	1.7 ± 0.1b	2.8 ± 0.2b	0.7 ± 0.07c	7.3 ± 0.4b	2.1 ± 0.05b
		22-Oct	2.5 ± 0.1a	3.2 ± 0.3a	3.2 ± 0.1a	0.9 ± 0.05a	9.8 ± 0.6a	1.7 ± 0.1c
	TN18	26-Sep	1.7 ± 0.1c	0.5 ± 0.06c	2.3 ± 0.3a	0.1 ± 0.004a	4.6 ± 0.1c	4.2 ± 0.3a
		8-Oct	2.0 ± 0.3b	1.6 ± 0.1b	2.3 ± 0.2a	0.1 ± 0.005a	6.0 ± 0.3b	3.6 ± 0.2b
		22-Oct	3.1 ± 0.3a	2.5 ± 0.2a	2.3 ± 0.1a	0.1 ± 0.006a	8.0 ± 0.3a	3.2 ± 0.08c
	Year (Y)		***	***	**	***	*	***
	Cultivar (C)		***	***	***	***	***	***
	Sowing date (S)		***	***	***	***	***	***
	Y × C		**	***	ns	***	***	***
	Y × S		***	***	ns	***	**	***
	C × S		***	***	**	***	ns	ns
	Y × C × S		***	***	**	***	ns	**

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, ** denotes significance at $p < 0.01$, and *** denotes significance at $p < 0.001$.

3.6. KUE and Its Components

As the sowing date was delayed from 26 September and 8 October to 22 October, the KUE was unchanged for SN23 and TN18, respectively, in both years. Over the two growing seasons the UPE decreased from 85.3 and 78.6 to 71.5% for SN23 and 87.2 and 80.6 to 70.6% for TN18. The UTE increased by an average of 20.8 and 10.6% for SN23 and 23.2 and 12.5% for TN18, averaged over 2 years (Table 6).

Table 6. The K use efficiency (KUE), K uptake efficiency (UPE), and K utilization efficiency of SN23 and TN18 winter wheat cultivars with different sowing dates in the 2021–2022 and 2022–2023 growing seasons.

Season	Cultivar	Sowing Date	KUE (kg kg^{-1})	UPE (%)	UTE (kg kg^{-1})
2021–2022	SN23	26-Sep	30.7 ± 1.1a	86.6 ± 3.5a	35.5 ± 1.5c
		8-Oct	31.1 ± 0.8a	80.0 ± 2.5b	38.8 ± 0.9b
		22-Oct	31.3 ± 0.3a	71.3 ± 3.5c	43.9 ± 0.3a
	TN18	26-Sep	31.6 ± 1.5a	86.9 ± 6.8a	36.4 ± 2.1c
		8-Oct	32.3 ± 2.1a	81.3 ± 3.7b	39.7 ± 3.0b
		22-Oct	31.7 ± 0.6a	70.8 ± 1.0c	44.7 ± 0.9a
2022–2023	SN23	26-Sep	31.2 ± 2.1a	83.9 ± 0.8a	37.2 ± 2.1c
		8-Oct	31.3 ± 3.1a	77.2 ± 2.8b	40.6 ± 1.9b
		22-Oct	31.5 ± 1.6a	71.7 ± 1.7c	43.9 ± 3.1a
	TN18	26-Sep	31.9 ± 1.9a	87.5 ± 4.4a	36.5 ± 2.8c
		8-Oct	32.0 ± 1.5a	79.9 ± 3.8b	40.1 ± 1.1b
		22-Oct	31.7 ± 2.7a	70.4 ± 0.9c	45.1 ± 1.0a
	Year (Y)		ns	ns	*
	Cultivar (C)		*	ns	ns
	Sowing date (S)		ns	***	***
	Y × C		ns	ns	ns
	Y × S		ns	ns	ns
	C × S		ns	ns	ns
	Y × C × S		ns	ns	ns

Values followed by the same letter within a column in the same year are not significantly different at $p < 0.05$ as determined by the LSD test. ns denotes non-significance at the 0.05 probability level. * denotes significance at $p < 0.05$, and *** denotes significance at $p < 0.001$.

Only the effects of C on the KUE and S on the UPE were significant. The UTE was significantly affected by the Y and S (Table 6).

3.7. Correlations

The key characteristics, including KNI, grain yield, spike number, grain number per spike, grain weight, KUE, UPE, and UTE, were tested to determine their relationships using correlation analysis (Figures 4 and 5). The KNI was significantly positively correlated with spike number per unit land area and UPE and significantly negatively correlated with grain number per spike and UTE.

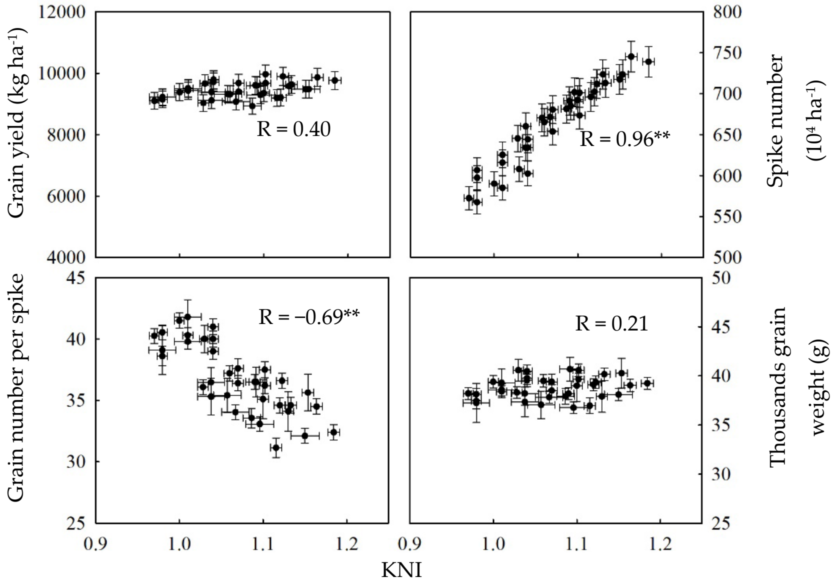

Figure 4. Relationship between K nutrition index (KNI) of SN23 and TN18 winter wheat cultivars at anthesis and grain yield, spike number, grain number per spike, and grain weight for different sowing dates over two seasons. Values are means ± standard errors of three replicates per treatment. ** denotes significant difference at the 0.01 probability level.

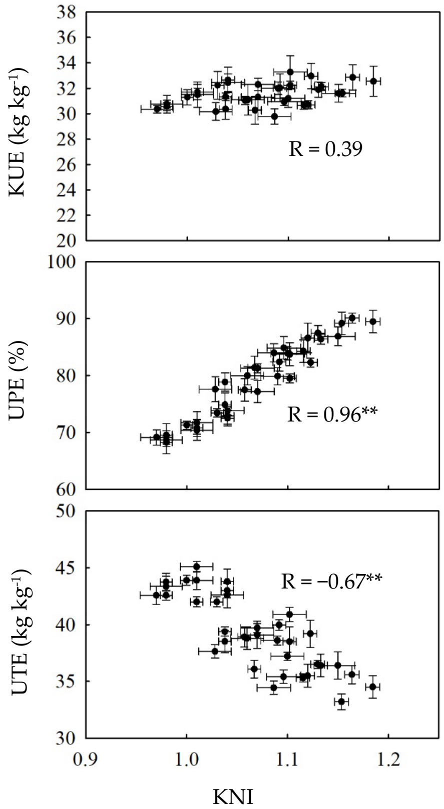

Figure 5. Relationship between K nutrition index (KNI) of winter wheat at anthesis and K use efficiency (KUE), K uptake efficiency (UPE), and K utilization efficiency (UTE) for different sowing dates over two seasons. Values are means ± standard errors of three replicates per treatment. ** denotes a significant difference at the 0.01 probability level, with grain number per spike and UTE. However, no significant correlation was observed between the KNI and grain yield, grain weight, and KUE in both winter wheat cultivars.

4. Discussion

Generally, the vegetative period is critical for the accumulation of biomass and nutrients that contribute to yield formation, and it is during the vegetative period that most nutrient absorption occurs [20,42]. In our study, the KNI under the late sowing at anthesis was close to 1.0, suggesting that the K nutrient status verged on optimal and very little K was wasted, mainly because of higher UTE. Nevertheless, the KNI under the early and normal sowing was markedly >1.0, suggesting luxurious K nutrition, which may lead to K waste [12–14] and a lower UTE.

Tillering is nearly related to wheat grain yield, and it can determine spike number per unit land area and grain number per spike [43]. Nevertheless, excessive tillering is undesirable, as about less than 50% of tillers are fertile [44]. This was consistent with our finding. Unfertile tiller greatly wastes wheat yield resources, as mostly dry matter has been shown not to translocate to surviving tillers [45]. In our study, although late sowing resulted in a lower maximum tiller number at jointing and tiller number at maturity, possibly being attributed to the decreased accumulated temperature before wintering, the fertile tiller percentage significantly increased, compared with those at the early and normal sowing date treatments. Furthermore, the number of unfertile tillers significantly decreased with the late sowing date, which would reduce resource waste [45]. In addition, the spike number per unit land area was positively correlated with KNI, indicating that a lower spike number per unit land area in the late sowing treatment made it easier to achieve a near-optimal KNI, suggesting a higher UTE with late sowing.

A previous study has shown that delayed sowing significantly decreased grain yield in winter wheat [46]. However, currently, with global warming [33], the accumulated temperature before winter in winter wheat has increased significantly [36], which can produce adequate tillers to maintain high grain yield with late sowing [34,38,39]. Moreover, much research has shown that delayed sowing could obtain a high grain yield in winter wheat [34,37–40]. This is consistent with our results. In our study, the KNI was negatively related to grain number per spike, mostly because of superfluous K status under early and normal sowing and optimal K status under late sowing. No correlation was found between grain weight and KNI, mainly because grain weight was not affected by sowing date.

Generally, a lower spike number results in a high nutrient element content per single shoot in winter wheat [34]. A similar phenomenon was found in our experiment. In our study, although delayed sowing significantly decreased aboveground K uptake per unit land area at anthesis, the K content assigned to leaves per single shoot at anthesis increased significantly, which is beneficial to enhancing the photosynthesis of green leaves and thus ultimately ensuring high grain yield [22,24]. This was consistent with previous research [23,24]. Lower K uptake with higher grain yield suggested a higher UTE with late sowing.

Previous studies have shown that nutrition use efficiency was negatively related to the nutrition index [47–49]; nevertheless, in our study, KUE was not significantly related to KNI. This difference was because KUE was not affected by sowing date, and this is mainly attributed to the consistent available K content and same grain yield (interestingly, a trade-off between spikes per unit area and grain number per spike was found as sowing date was delayed from early and normal sowing to late sowing, while grain weight was maintained unchanged). Though sowing date did not significantly influence KUE, UPE and UTE changed dramatically. In general, the decrease in UPE was mainly due to the decrease in AGK, resulting in a lower KNI (close to the optimal value); meanwhile, the increase in UTE was mainly due to consistent grain yield and decreased AGK. Furthermore, a positive correlation between UPE and KNI and negative correlation between UTE and KNI were obtained, indicating that optimal K absorption and distribution will improve UTE.

The nutrient element in the grain comes mainly from the KT_{pre} and KT_{post} [50,51]. In our study, most of the K absorption occurred at pre-anthesis, and this was same as in previous research [19,26]. Promoting the translocation of pre-anthesis nutrients accumulated in grain would effectively improve grain nutrition [52]. Compared with the early and normal sowing, the late sowing improved the KCR_{pre} and decreased the KCR_{post}; this was mostly because of the higher KT_{pre} of all organs, especially the leaves and true stem, leading to a higher GKC that would be beneficial in improving grain quality [25]. The higher GKC with the late sowing date resulted in higher K recovery, suggesting a higher UTE in the late-sowed winter wheat. The lower K residual amount of non-grain organs at maturity with the late sowing suggested a lower K waste.

5. Conclusions

Higher K utilization efficiency and grain K concentration were obtained under late sowing, and the grain yield was consistently maintained for low-tillering winter wheat cultivars among the three sowing dates. When the sowing date was delayed from early and normal to a late date, reduced K uptake efficiency and an optimal K nutrition index was obtained, resulting in increased K utilization efficiency. Meanwhile, there was an increased K transport content from pre-anthesis accumulation in vegetative organs and K contribution ratio of pre-anthesis accumulation in vegetative organs to grain, which led to a higher grain K concentration. Lower K uptake efficiency and higher K utilization efficiency under late sowing led to more soil residual K; therefore, increasing K use efficiency by combining delayed sowing and reduced K fertilizer rates that meet but do not exceed crop K requirements for low-tillering winter wheat cultivars is possible. The prospects for reducing K fertilizer input under optimized sowing dates for low-tillering winter wheat cultivars should be verified by future research.

Author Contributions: Conceptualization, L.Y.; methodology, L.Y.; software, L.Y. and Y.L.; validation, L.Y., Y.L. and X.M.; formal analysis, L.Y.; investigation, Y.L. and X.M.; resources, L.Y.; data curation, L.Y.; writing—original draft preparation, L.Y.; writing—review and editing, L.Y.; visualization, Y.L. and X.M.; supervision, L.Y.; project administration, L.Y.; funding acquisition, L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fund for Scientific Research and Development of Yangtze University, grant number 802100270402.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

K	potassium
KUE	K use efficiency
KNI	K nutrition index
UPE	K uptake efficiency
UTE	K utilization efficiency
GKC	grain K concentration
AGK	above-ground K uptake
SN23	Shannong 23
TN18	Tainong 18
N	nitrogen
P	phosphorus
KT_{pre}	K transport content from pre-anthesis accumulation in vegetative organs to grain
KT_{post}	K transport content from post-anthesis absorption to grain
KCR_{pre}	K contribution ratio of pre-anthesis accumulation in vegetative organs to grain
KCR_{post}	K contribution ratio of post-anthesis absorption to grain

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