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ARTICLE

Comprehensive Assessment of Low Potassium Tolerance in Mature Chinese Cabbage and Physiological Differences in Responses to Potassium Deficiency

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ABSTRACT: Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) is a typical potassium (K)-demanding crop that is highly sensitive to soil K availability. Severe soil potassium deficiency in production fields frequently impairs both yield and quality. Therefore, screening for potassium-efficient varieties is essential for identifying germplasm resources and breeding materials tolerant to low-K conditions. To evaluate genetic variation in potassium utilization efficiency, 12 Chinese cabbage germplasms were assessed under two field conditions: with adequate potassium supply (K_2O 165 kg/ha) and without potassium application (K_2O 0 kg/ha). Fourteen parameters, including yield, plant growth, potassium content, and potassium accumulation, were measured and compared. Principal component analysis (PCA) was employed to identify key indicators influencing K-use efficiency, and cluster analysis was subsequently performed to classify the 12 germplasms. The results demonstrated that under K-deficient conditions, the mean values of yield, fresh plant weight, shoot K accumulation, and total plant K accumulation were significantly reduced compared to those under adequate K supply. Based on three principal components (root fresh weight, shoot potassium utilization efficiency, and yield), membership function values, and comprehensive evaluation scores (D-values), the 12 genotypes were classified into four categories: low-K tolerant (‘HK8’); moderately low-K tolerant (‘HK1’, ‘HK6’, ‘HK12’, ‘HK42’); intermediate low-K sensitive (‘HK18’, ‘HK25’, ‘HK27’, ‘HK40’); and low-K sensitive (‘HK45’, ‘HK48’, ‘HK54’). Under K-deficiency stress, significant differences were observed between the low-K tolerant genotype ‘HK8’ and the low-K sensitive genotype ‘HK48’ in terms of yield, dry matter accumulation across plant organs, potassium distribution patterns, and K^+/Na^+ and Ca^{2+}/Na^+ ratios. Notably, the low-K tolerant genotype ‘HK8’ exhibited markedly superior salt tolerance compared to the low-K sensitive genotype ‘HK48’, suggesting a potential physiological link between low-K tolerance and ionic homeostasis.

KEYWORDS: Chinese cabbage; low potassium tolerance; genotype; potassium efficiency; potassium utilization efficiency

1 Introduction

Chinese cabbage (*Brassica rapa* ssp. *pekinensis*), belonging to the *Brassicaceae* family and the genus *Brassica*, is native to China. Renowned for its nutritional richness, refreshing taste, and tender texture, it is among the most widely consumed vegetables in the country. As the most extensively cultivated vegetable crop in China, it holds a prominent position in daily vegetable consumption and is commonly referred to as the “King of Vegetables” [1]. Chinese cabbage is a typical potassium (K)-demanding crop; among the three primary macronutrients (nitrogen, phosphorus, and potassium), it exhibits the highest requirement for potassium [2]. Potassium plays crucial roles in plant growth and development, participating in numerous essential physiological and metabolic processes, including stomatal movement, photosynthesis, starch synthesis, protein synthesis, sugar transport, and the transport of water and mineral elements [3–6]. In the soil, potassium is predominantly concentrated within the upper 20 cm of the cultivated layer, with typical concentrations ranging from 10 to 20 g/kg. However, 90–98% of soil potassium exists in forms that are not readily available and cannot be directly utilized by plants [7,8]. China has limited potash reserves, relatively low domestic production of potash fertilizer, and remains unable to achieve self-sufficiency, necessitating substantial reliance on imports to meet agricultural demand [7]. Potassium fertilizer is one of the three essential mineral fertilizers required for crop growth. Although the application of potassium fertilizer can increase crop yield and generate considerable socioeconomic benefits, marked differences exist among plant species and genotypes in the efficiency of potassium absorption and utilization. The actual potassium utilization efficiency in agricultural production remains low, resulting in considerable waste of potassium resources. Therefore, it is very important to cultivate Chinese cabbage genotypes with high potassium utilization efficiency and enhanced tolerance to low-K conditions to alleviate potassium scarcity, reduce potassium fertilizer consumption, and contribute to greater fertilizer self-sufficiency.

Previous research has demonstrated the existence of genetic variation in nutrient efficiency both among different plant species and among different genotypes within the same species. Extensive studies have been conducted on screening for nutrient-efficient varieties and evaluating nutrient use efficiency in multiple crops, including wheat [9,10], soybean [11], and cotton [12,13]. Research on genotypic differences in nitrogen (N) and phosphorus (P) use efficiency has been particularly advanced, with notable efforts directed toward identifying N-efficient and P-efficient genotypes. By contrast, relatively little attention has been paid to potassium (K) use efficiency, particularly in Chinese cabbage. George et al. [14] defined nutrient use efficiency as the amount of dry matter produced per unit of nutrient present in crop tissues. Fan et al. [15] proposed that nutrient use efficiency is governed by two interrelated sets of plant factors, namely absorption efficiency and utilization efficiency. Potassium efficiency (KE) characterizes the tolerance of different genotypes to K-deficient soils and can be quantified as the ratio of growth under K-deficient conditions to that under K-sufficient conditions [16–19]. Nevertheless, assessing potassium efficiency in crops remains challenging owing to the considerable variation in K-deficiency tolerance and sensitivity exhibited by different genotypes.

Genotypic differences in plant nutrient efficiency are manifested not only in morphological characteristics but also in a range of physiological and genetic traits [20]. Efficient genotypes typically exhibit high absorption efficiency, transport efficiency, and utilization efficiency, or possess exceptionally high levels of one or two of these capacities. High potassium efficiency entails not only a strong capacity for K uptake and utilization but also the ability to effectively redistribute K among all plant organs. Potassium-efficient genotypes demonstrate superior allocation of K to sink organs, and higher K concentrations within the plant at different growth stages are closely associated with source-sink relationships [21,22]. Nutrient deficiency also affects biomass allocation and nutrient partitioning among crop tissues [20]. Increasing nutrient application rates can enhance canopy biomass, which in turn elevates photosynthetic potential.

Saline-alkaline stress frequently induces severe deficiencies of essential nutrients, particularly K^+ and Ca^{2+}, in crop plants. Both potassium (K^+) and calcium (Ca^{2+}) play critical regulatory roles in cellular osmotic adjustment, promoting cell expansion, maintaining turgor pressure, and sustaining plant growth [23–25]. The uptake of K^+ and Ca^{2+} from the soil not only fulfills the plant's nutritional requirements but also increases the K^+/Na^+ and Ca^{2+}/Na^+ ratios in various organs, thereby effectively mitigating the ionic toxicity caused by excessive Na^+ accumulation within plant tissues. Therefore, investigating the regulatory and adaptive mechanisms underlying potassium utilization efficiency (KUE), nutrient dynamics among different tissues, selective ion transport capacity, and yield formation in different Chinese cabbage genotypes under saline-alkaline stress is of considerable scientific importance.

To reduce potassium fertilizer inputs and minimize environmental pollution, the present study established K-deficient and adequate K-supply treatments under field saline-alkaline conditions, utilizing 12 Chinese cabbage germplasm accessions as experimental materials. The specific objectives of this study were to: (1) identify Chinese cabbage genotypes with high potassium utilization efficiency (KUE) for potential application in breeding programs; and (2) characterize differences between high-KUE and low-KUE genotypes in terms of yield, K utilization efficiency, dry matter and nutrient accumulation among different tissues, and selective ion transport capacity under saline-alkaline stress.

2 Materials and Methods

2.1 Plant Materials

Twelve Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) germplasm accessions ('HK1', 'HK6', 'HK8', 'HK12', 'HK18', 'HK25', 'HK27', 'HK40', 'HK42', 'HK45', 'HK48', 'HK54') were provided by the Chinese cabbage research team at the College of Horticulture and Landscape Architecture, Henan Institute of Science and Technology. These accessions were originally collected from diverse production regions with extensive cultivation areas and subsequently developed into homozygous inbred lines through phenotypic selection and continuous multi-generational self-pollination.

2.2 Experimental Design

The field experiment was conducted at the Horticultural Research Station of Henan Institute of Science and Technology, commencing on August 30, 2023. The basic soil physicochemical properties were as follows: pH 8.43, organic matter content 13.98 g/kg, alkali-hydrolyzable nitrogen 51.39 mg/kg, available phosphorus (P) 43.82 mg/kg, and available potassium (K) 139.59 mg/kg. The soil electrical conductivity (EC) was 1.85 dS/m, and the exchangeable sodium percentage (ESP) was 8.7%, classifying the experimental field as mildly saline-alkaline soil. Two potassium (K) supply treatments were established: K-sufficient (designated +K, K_2O at 165 kg/ha) and K-deficient (designated -K, K_2O at 0 kg/ha). Potassium sulfate (K_2O content 50%) was used as the K source and applied as a basal dressing prior to sowing. Uniform basal applications of nitrogen (N) and phosphorus (P) fertilizers were also incorporated: urea (N content 46%) at 165 kg N/ha and calcium superphosphate (P_2O_5 content 12%) at 78 kg P_2O_5/ha. A completely randomized block design was adopted, with each treatment (+K and -K) replicated three times. Each germplasm accession was sown in a single row per plot, with a row length of 16 m and both row and plant spacings of 60 cm. The plot served as the experimental unit for data collection, with 10 mixed samples collected per replicate. Variance analysis was performed on plot means. At harvest, ten representative plants per replicate (plot) were selected and their data were pooled to calculate the plot mean for yield determination and agronomic trait assessment.

2.3 Measurements and Methods

2.3.1 Determination of Chinese Cabbage Yield

Yield was determined by randomly sampling three locations per germplasm accession. At each sampling location, ten plants were weighed, and the fresh weight was converted to yield per hectare (kg/ha).

2.3.2 Determination of Dry and Fresh Weight of Chinese Cabbage

Plants were harvested at the heading stage and separated into above-ground parts and roots. Roots were thoroughly washed with tap water, and the above-ground parts were weighed immediately after separation. The above-ground portion was further divided, from the outermost to the innermost layers, into outer leaves (20 leaves), middle leaves (10 leaves), inner leaves (remaining leaves), and the shortened stem. All plant samples were inactivated at 105°C for 30 min and subsequently dried to constant weight at 75°C in a forced-air oven. Root dry weight (RDW) and shoot dry weight (SDW) were recorded, and total plant dry weight (PDW) was calculated as their sum. For the genotypes 'HK8' and 'HK48', the vertical diameter (maximum height) and transverse diameter (maximum width) of the leaf head were measured after bisecting the head longitudinally using a ruler. The heading shape index was calculated as the ratio of vertical diameter to transverse diameter.

2.3.3 Determination of Mineral ion Content

Oven-dried root and shoot samples were precisely weighed, ground to a fine powder, and digested using the H_2SO_4-H_2O_2 method [26]. The concentrations of K^+, Ca^{2+}, and Na^+ in the digest were determined by flame photometry (AP1500, Shanghai Aopu Analytical Instruments Co., Ltd., Shanghai, China). The detection limits for Na^+, K^+, and Ca^{2+} were 0.01 μg/mL, 0.01 μg/mL, and 0.1 μg/mL, respectively. Potassium ion concentration was determined for each plant organ (roots, shortened stem, inner leaves, middle leaves, and outer leaves). Whole-plant K concentration (PKC, mg/g) and K accumulation were subsequently calculated using the following formulas:

Shoot dry weight (SDW) = Shortening stem DW + Inner leaves DW + Middle leaves DW + Outer leaves DW
Plant K concentration (PKC) = [(Root K concentration × Root DW) + (Shoot K concentration × SDW)]/(RDW + SDW)
Shoot K accumulation (SKA) = Shoot K concentration × SDW
Root K accumulation (RKA) = Root K concentration × RDW
Plant K accumulation (PKA) = Root K accumulation + Shoot K accumulation
K utilization efficiency (KUE) = SDW/SKA
K utilization Index (KUI) = SDW/PKC

K^+/Na^+ and Ca^{2+}/Na^+ ratios were calculated for each tissue (roots, shortening stem, inner leaves, middle leaves, and outer leaves).

2.3.4 Calculation of Selective ion Transport Capacity

The selective transport capacity for ion X relative to Na^+ (S_{X,Na^+}) between different plant parts was calculated as:

$$S_{X,Na^+} = \text{sink}_{\{[X]/[Na^+]\}}/\text{source}_{\{[X]/[Na^+]\}}$$

where X represents either K^+ concentration or Ca^{2+} concentration. A higher SX, Na^+ value indicates that a greater preferential enrichment/partitioning of ion X relative to Na^+ from the source organ to the sink organ, reflecting a stronger selective transport capacity for X over Na^+.

2.4 Data Processing and Statistical Analysis

Fourteen key parameters were analyzed under both +K and -K treatments: Yield, Shoot dry weight, Shoot K concentration, Shoot K accumulation, K utilization efficiency, K utilization index, Root fresh weight, Root dry weight, Plant fresh weight, Plant dry weight, Root K concentration, Root K accumulation, Plant K concentration, Plant K accumulation. The average values of these parameters were compared using the low potassium tolerance coefficient (LPTC) [27], calculated as:

LPTC = Value under − K stress/Value under + K control

The comprehensive evaluation value (D-value), membership function value $U(X_j)$, and weight (W_j) for each germplasm under K-deficient stress were calculated according to Granato et al. [28]:

Comprehensive evaluation value

$$D = \sum_{j=1}^{n} \left[U\left(X_j\right) \times W_j \right] \quad j = 1, 2, \ldots n \tag{1}$$

Membership function value:

$$U\left(X_j\right) = \frac{\left(X_j - X_{\min}\right)}{\left(X_{\max} - X_{\min}\right)} \times 100\% \quad j = 1, 2, \ldots n \tag{2}$$

where $U(X_j)$ is the membership function value of the j-th comprehensive index, X_j is the measured value of the j-th index, $X_{\min}$ is the minimum value of the jth index among all germplasms, and $X_{\max}$ is the maximum value of the jth index among all germplasms.

Weight:

$$W_j = \sum_{j=1}^{n} \left| P_j \right| \quad j = 1, 2, \ldots n \tag{3}$$

where W_{j} is the weight of the jth comprehensive index, $\mathrm{P_j}$ represents the importance of the jth index, expressed as the contribution rate (eigenvalue) derived from principal component analysis (PCA).

Data were organized using Microsoft Excel 2010. When analyzing each trait, we used a mixed linear model with treatment (K level) and genotype as fixed effects, and block and plot as random effects. The plot mean served as the experimental unit for analysis. Analysis of variance (ANOVA) and significance testing of differences among means were performed using Tukey HSD test in SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Graphs were generated using GraphPad Prism 8.3.0. Correlation analysis, principal component analysis (PCA), and cluster analysis were performed on the 14 parameters measured under both +K and -K treatments for the 12 germplasms to classify the different genotypes.

3 Results and Analysis

3.1 Comparison of the Traits of Different Genotypes of Chinese Cabbage under Both +K and -K Treatments at the Harvest Stage

As shown in Fig. 1 (Table S1), the mean values of yield (Y), plant fresh weight (PFW), shoot potassium accumulation (SKA), and total plant potassium accumulation (PKA) across the 12 Chinese cabbage germplasm accessions were significantly lower under K-deficient (-K) conditions than under adequate K-supply (+K) conditions. No significant differences were observed in the mean values of the remaining parameters between the two treatments. Under the +K treatment, the coefficient of variation (CV) among genotypes ranged from 0.16 to 0.96, with root potassium accumulation exhibiting the greatest variation and plant dry weight the least. Under the -K treatment, the CV ranged from 0.15 to 0.69, with root potassium accumulation again showing the greatest variation, while plant potassium concentration showed the least.

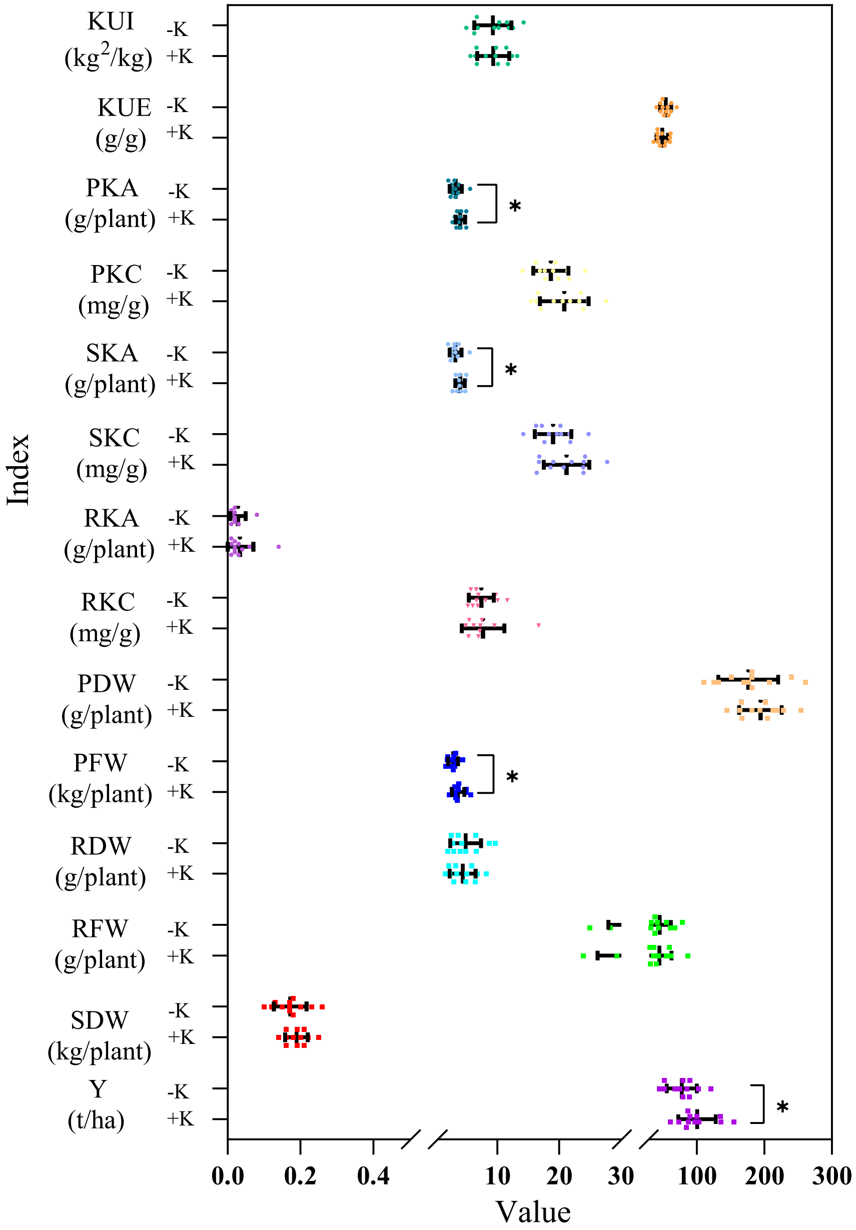

Figure 1: Variation in agronomic and physiological traits among different Chinese cabbage genotypes under K-sufficient and K-deficient treatments at the harvest stage. Note: Y: yield; SDW: shoot dry weight; RFW: root fresh weight; RDW: root dry weight; PFW: plant fresh weight; PDW: plant dry weight; RKC: root K+ concentration; SKC: shoot K^+ concentration; SKA: shoot K^+ accumulation; PKC: plant K^+ concentration; RKA: root K^+ accumulation; PKA: plant K^+ accumulation; KUE: potassium utilization efficiency; KUI: potassium utilization index. *indicates significant differences at $p < 0.05$ levels.

3.2 Analysis of the Low Potassium Tolerance Coefficient of Various Traits of Chinese Cabbage at the Harvest Stage

As shown in Table 1, the plant growth of all 12 Chinese cabbage genotypes was inhibited to varying degrees under low-K stress at the harvest stage. In 9 of the 12 genotypes—specifically all accessions except ‘HK1’, ‘HK6’, and ‘HK8’—the low-potassium tolerance coefficient (LPTC) for Y, PFW, SKA, and PKA was less than 1, indicating that the values of these four parameters under the -K treatment were lower than those recorded under the +K treatment. For the remaining individual parameters, LPTC values varied considerably among genotypes.

Table 1: Low-potassium tolerance coefficients (LPTC) of various agronomic and physiological traits in 12 Chinese cabbage genotypes at the harvest stage.

Genotype	Low Potassium Tolerance Coefficient (LPTC)													
	Y	**SDW**	**RFW**	**RDW**	**PFW**	**PDW**	**RKC**	**SKC**	**SKA**	**PKC**	**RKA**	**PKA**	**KUE**	**KUI**
‘HK1’	1.48	0.78	1.39	1.29	1.48	0.8	0.49	0.83	0.65	0.81	0.31	0.64	1.2	0.94
‘HK6’	1	1.25	0.77	0.8	1	1.22	0.7	1.03	1.29	1.03	0.56	1.26	0.97	1.21
‘HK8’	1.35	1.43	1.2	1.26	1.35	1.43	1.05	0.78	1.12	0.78	1.33	1.12	1.28	1.84
‘HK12’	0.66	1.18	1.02	1.35	0.66	1.19	1.12	0.68	0.8	0.68	1.3	0.8	1.48	1.75
‘HK18’	0.59	0.8	1.01	1.01	0.6	0.81	1.37	0.84	0.67	0.8	0.69	0.65	1.18	0.95
‘HK25’	0.75	0.86	0.53	0.47	0.75	0.85	1.28	0.85	0.73	0.87	0.6	0.74	1.17	1.01
‘HK27’	0.92	0.62	2.14	2.84	0.93	0.67	1.24	0.84	0.52	0.8	3.68	0.53	1.19	0.74
‘HK40’	0.7	0.87	1.08	1.71	0.71	0.88	0.88	0.99	0.87	1.05	1.7	0.87	1	0.87
‘HK42’	0.92	1.02	0.79	0.76	0.92	1.02	0.85	0.85	0.87	0.86	0.64	0.87	1.17	1.19
‘HK45’	0.58	0.69	0.75	0.64	0.59	0.69	1.34	1.17	0.81	1.25	0.5	0.87	0.85	0.59
‘HK48’	0.43	0.75	0.82	0.67	0.43	0.75	1.01	1.17	0.88	1.17	0.33	0.88	0.85	0.64
‘HK54’	0.5	0.7	1.56	2.67	0.5	0.72	1.22	0.9	0.63	0.88	2.45	0.64	1.11	0.78

Note: LPTC, low-potassium tolerance coefficient; Y, yield; SDW, shoot dry weight; RFW, root fresh weight; RDW, root dry weight; PFW, plant fresh weight; PDW, plant dry weight; RKC, root K^+ concentration; SKC, shoot K^+ concentration; SKA, shoot K^+ accumulation; PKC, plant K^+ concentration; RKA, root K^+ accumulation; PKA, plant K^+ accumulation; KUE, potassium utilization efficiency; KUI, potassium utilization index.

3.3 Evaluation of Low Potassium Tolerance Characteristics Based on Principal Component Analysis

Principal component analysis (PCA) was applied to the low-potassium tolerance coefficients of the 14 measured indicators, transforming them into three mutually independent composite indices, designated the first principal component (PC1), second principal component (PC2), and third principal component (PC3). Together, these three components accounted for 86.50% of the total variance in the original dataset (Table 2). Examination of the eigenvectors associated with each principal component revealed the following: Within PC1, the coefficients with the largest absolute values corresponded to SKA, RFW, RDW, and PKA, with RFW exhibiting the highest absolute coefficient (0.868); this component therefore primarily represents indicators associated with root development. Within PC2, the largest absolute coefficients were associated with SKC, KUE, KUI, and PKC, with KUE yielding the highest coefficient (0.945); this component primarily captures variation in potassium utilization efficiency. Within PC3, the largest absolute coefficients were associated with Y, PFW, and RKC, with Y exhibiting the highest coefficient (0.899); this component primarily represents indicators related to yield formation. In summary, the original 14 interrelated individual indicators were successfully condensed into three mutually independent composite indices, each reflecting a distinct aspect of low-K tolerance in Chinese cabbage.

Table 2: Loading coefficients and contribution rates of each principal component derived from principal component analysis (PCA).

Indicators	Principal Component		
	PC1	**PC2**	**PC3**
Y	−0.003	0.312	0.899
SDW	0.668	0.624	0.333
SKC	0.292	−0.921	−0.108
SKA	0.857	0.041	0.34
KUE	−0.231	0.945	0.05
KUI	0.407	0.872	0.224
RFW	−0.868	0.144	0.283
RDW	−0.829	0.158	0.09
PFW	−0.008	0.309	0.89
PDW	0.622	0.658	0.347
RKC	−0.2	0.1	−0.829
PKC	0.352	−0.889	−0.123
RKA	−0.748	0.215	−0.039
PKA	0.865	0.008	0.312
Eigenvalue	4.783	4.408	2.918
Contribution rate of variance	34.167	31.486	20.846
Cumulative contribution rate	34.167	65.653	86.498
Weight	0.4	0.36	0.24

Note: Y: yield; SDW: shoot dry weight; RFW: root fresh weight; RDW: root dry weight; PFW: plant fresh weight; PDW: plant dry weight; RKC: root K+ concentration; SKC: shoot K^+ concentration; SKA: shoot K^+ accumulation; PKC: plant K^+ concentration; RKA: root K^+ accumulation; PKA: plant K^+ accumulation; KUE: potassium utilization efficiency; KUI: potassium utilization index.

As shown in Table 3, membership function values were calculated for each genotype under low-K stress conditions. The $U(X_1)$ values ranged from 0.00 to 1.00, with ‘HK27’ exhibiting the minimum value of 0.00, indicating the greatest sensitivity to low-K stress for this component, and ‘HK6’ exhibiting the maximum value of 1.00, indicating the highest tolerance. Similarly, $U(X_2)$ values ranged from 0.00 to 1.00, with ‘HK45’ and ‘HK48’ both recording the minimum value of 0.00 and ‘HK12’ recording the maximum value of 1.00. The $U(X_3)$ values also ranged from 0.00 to 1.00, with ‘HK48’ recording the minimum value of 0.00 and ‘HK1’ recording the maximum value of 1.00.

Table 3: Comprehensive evaluation scores (D-values), membership function values $U(X_j)$, and weights of the three principal components for each Chinese cabbage genotype.

Genotype	**$U(X_1)$ PKA**	**$U(X_2)$ KUE**	**$U(X_3)$ Y**	**Weight 1**	**Weight 2**	**Weight 3**	**D Value**
‘HK1’	0.15	0.56	1	0.4	0.36	0.24	0.5
‘HK6’	1	0.19	0.54	0.4	0.36	0.24	0.6
‘HK8’	0.81	0.69	0.88	0.4	0.36	0.24	0.78
‘HK12’	0.37	1	0.22	0.4	0.36	0.24	0.56
‘HK18’	0.16	0.53	0.15	0.4	0.36	0.24	0.29
‘HK25’	0.28	0.51	0.3	0.4	0.36	0.24	0.37
‘HK27’	0	0.55	0.47	0.4	0.36	0.24	0.31
‘HK40’	0.46	0.25	0.26	0.4	0.36	0.24	0.34
‘HK42’	0.46	0.52	0.46	0.4	0.36	0.24	0.48
‘HK45’	0.46	0	0.15	0.4	0.36	0.24	0.22
‘HK48’	0.48	0	0	0.4	0.36	0.24	0.19
‘HK54’	0.14	0.42	0.07	0.4	0.36	0.24	0.22

Note: Y: yield; PKA: plant K^+ accumulation; KUE: potassium utilization efficiency.

The weight (W_j) assigned to each composite indicator was determined based on its relative contribution rate. As presented in Table 2, the weights for PC1, PC2, and PC3 were 0.40, 0.36, and 0.24, respectively. The comprehensive evaluation value (D-value) representing the overall low-K tolerance of each genotype was subsequently calculated using Formula (3), and genotypes were ranked accordingly (Table 3). 'HK8' obtained the highest D-value, indicating the strongest low-K tolerance among all genotypes evaluated, whereas 'HK48' obtained the lowest D-value, indicating the weakest low-K tolerance.

Hierarchical cluster analysis of the D-values was performed using the between-groups linkage method, and the resulting dendrogram is presented in Fig. 2. This analysis classified the 12 Chinese cabbage genotypes into four distinct groups: Class I, comprising 'HK8' (low-K tolerant type); Class II, comprising 'HK1', 'HK6', 'HK12', and 'HK42' (moderately low-K tolerant type); Class III, comprising 'HK18', 'HK25', 'HK27', and 'HK40' (intermediate low-K sensitive type); and Class IV, comprising 'HK45', 'HK48', and 'HK54' (low-K sensitive type).

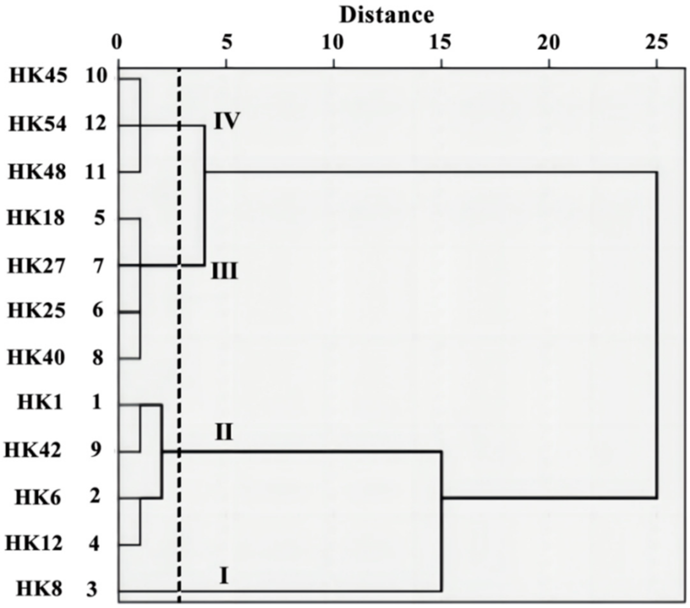

Figure 2: Cluster tree diagram of 12 Chinese cabbage varieties.

3.4 Response of the Yield of Two Genotypes of Chinese Cabbage to Potassium Deficiency Stress

As shown in Fig. 3, 'HK8' exhibited minimal phenotypic differences under -K stress relative to the +K treatment. In contrast, 'HK48' under the -K treatment showed a complete failure of head formation, along with a reduction in both leaf number and leaf size (Fig. 3A–D). Compared to the +K treatment, the vertical diameter and heading shape index of 'HK48' under the -K treatment were significantly reduced by 76.79% and 78.20%, respectively (Fig. 3E,G). Under the -K treatment, the yield of 'HK8' increased significantly by 35.29% relative to +K, whereas the yield of 'HK48' decreased significantly by 57.04%. Under the +K treatment, the yield of 'HK48' was 35.29% higher than that of 'HK8'; however, under the -K treatment, the yield of 'HK48' was 57.05% lower than that of 'HK8' (Fig. 3H). Regarding potassium utilization efficiency (KUE) and the potassium utilization index (KUI) (Fig. 3I,J), the KUE and KUI of 'HK8' under the -K treatment increased significantly by 28.29% and 84.08%, respectively, compared to the +K treatment. Conversely, the KUE and KUI of 'HK48' under the -K treatment decreased significantly by 15.25% and 36.14%, respectively. Under the +K treatment, the KUE and KUI of 'HK8' were significantly lower than those of 'HK48'; however, under the -K treatment, the KUI of 'HK8' was significantly higher than that of 'HK48' by 89.40%.

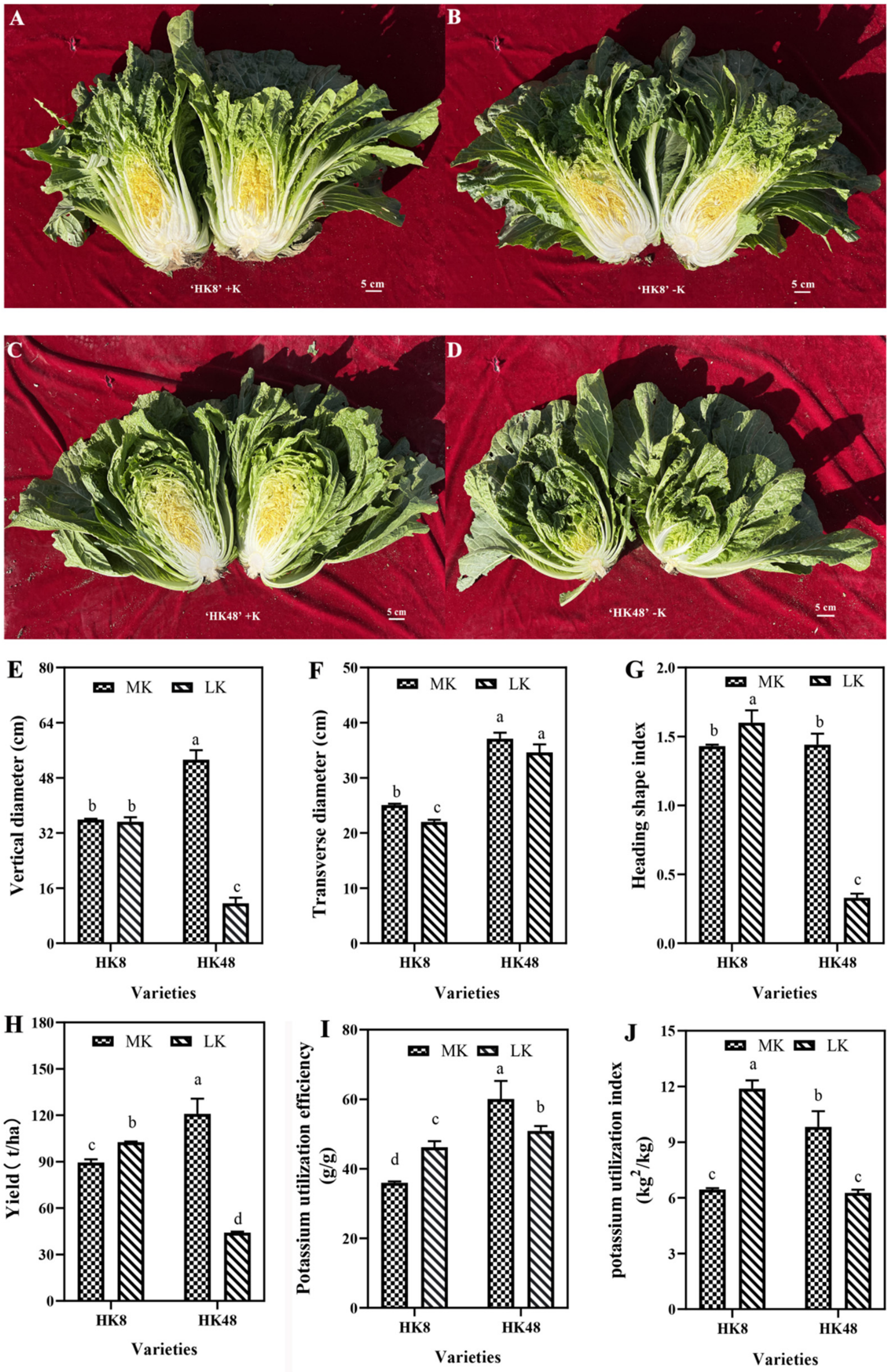

Figure 3: Responses of yield, heading morphology, potassium utilization efficiency, and potassium utilization index in two Chinese cabbage genotypes to potassium deficiency at the harvest stage. Note: (**A**) phenotype of 'HK8' under +K treatment at the harvest stage; (**B**) phenotype of 'HK8' under -K treatment at the harvest stage; (**C**) phenotype of 'HK48' under +K treatment at the harvest stage; (**D**) phenotype of 'HK48' under -K treatment at the harvest stage; (**E**) vertical diameter; (**F**) transverse diameter; (**G**) heading shape index; (**H**) yield; (**I**) potassium utilization efficiency; (**J**) potassium utilization index. Values represent the mean of three biological replicates (Mean ± SE, n = 3). Different lowercase letters indicate significant differences among treatment groups at $p < 0.05$.

3.5 Response of Dry Matter Weight in Different Parts of Two Genotypes of Chinese Cabbage to K Deficiency

Compared to the +K treatment, the dry matter weight of the outer leaves of 'HK8' decreased significantly by 88.08% under the -K treatment. Under both +K and -K treatments, the dry matter weight of the outer leaves of 'HK48' was 24.05% and 29.01% lower than that of 'HK8', respectively. In the middle leaves, the dry matter weight of 'HK48' decreased significantly by 38.41% under the -K treatment compared to the +K treatment; in the inner leaves, it decreased significantly by 46.76%.

In the shortened stem, the dry matter weight of 'HK48' was 87.07% and 31.17% lower than that of 'HK8' under +K and -K treatments, respectively; under the -K treatment, it decreased significantly by 59.43% relative to 'HK8'. In the roots, the dry matter weight of 'HK8' increased significantly by 26.20% under the -K treatment compared to the +K treatment, whereas the dry matter weight of 'HK48' decreased significantly by 33.45%. Under the -K treatment, the dry matter weight of 'HK48' was 31.49% lower than that of 'HK8' (Table 4).

Table 4: Effects of potassium deficiency on dry matter accumulation in different organs of Chinese cabbage genotypes 'HK8' and 'HK48'.

Different Organizations	**Treatments**	**Varieties**	
		'HK8'	**'HK48'**
Outer leaves (g)	+K	69.41 ± 4.23c	86.11 ± 3.38b
	-K	107.64 ± 4.23a	76.42 ± 5.40bc
Middle leaves (g)	+K	76.22 ± 6.16a	56.10 ± 3.89b
	-K	75.67 ± 6.57a	34.55 ± 1.73c
Inner leaves (g)	+K	21.08 ± 0.87b	15.60 ± 2.87b
	-K	64.25 ± 6.37a	8.31 ± 0.07c
Shortened stems (g)	+K	12.57 ± 0.58a	5.72 ± 0.24c
	-K	9.70 ± 1.17b	3.94 ± 0.13d
Roots (g)	+K	2.29 ± 0.16b	2.98 ± 0.19a
	-K	2.89 ± 0.03a	1.98 ± 0.16b

Note: Each data represents the average from three samples. Error bars represent standard error (Mean ± SE, n = 3). Different lowercase letters indicated that the differences in indicators of 'HK8' and 'HK48' varieties under +K and -K treatments at the 0.05 level.

3.6 Responses of K^+, Ca^{2+}, and Na^+ Concentrations in Different Parts of Two Genotypes of Chinese Cabbage to Potassium Deficiency

In the outer leaves, compared to the +K treatment, K^+, Ca^{2+}, and Na^+ concentrations in 'HK8' under the -K treatment decreased significantly by 6.79%, 14.64%, and 15.27%, respectively, whereas K^+, Ca^{2+}, and Na^+ concentrations in 'HK48' under the -K treatment increased significantly by 14.48%, 20.51%, and 34.64%, respectively.

In the middle leaves, K^+, Ca^{2+}, and Na^+ concentrations in 'HK8' decreased significantly by 40.19%, 21.66%, and 50.33%, respectively, under the -K treatment compared to the +K treatment. In 'HK48', Ca^{2+} and Na^+ concentrations increased significantly by 42.09% and 29.27%, respectively, under the -K treatment.

In the inner leaves, the Na^+ concentration in 'HK8' decreased significantly by 24.68% under the -K treatment, while the Ca^{2+} concentration in 'HK8' increased significantly by 12.72% under the -K treatment. In 'HK48', Na^+ concentration decreased significantly by 11.04% and Ca^{2+} concentration decreased significantly by 31.44%, while Na^+ concentration increased significantly by 20.29% under the -K treatment.

In the shortened stem, K^+, Ca^{2+}, and Na^+ concentrations in ‘HK8’ were higher than those of ‘HK48’ under both +K and -K treatments. The Na^+ concentration in the shortened stem of ‘HK8’ decreased significantly by 16.48% under the -K treatment, while that of ‘HK48’ decreased significantly by 12.91% compared to the +K treatment (Table 5).

Table 5: Effects of potassium deficiency on ion concentrations in different parts of ‘HK8’ and ‘HK48’ varieties of Chinese cabbage.

Different Organizations	**Treatments**	**K^+ Concentration**		**Ca^{2+} Concentration**		**Na^+ Concentration**	
		‘HK8’	**‘HK48’**	**‘HK8’**	**‘HK48’**	**‘HK8’**	**‘HK48’**
Outer leaves (g/kg)	+K	33.56 ± 0.06a	19.62 ± 0.45d	5.58 ± 0.47a	4.05 ± 0.24c	23.48 ± 1.42a	13.38 ± 0.86c
	-K	31.28 ± 0.67b	22.46 ± 0.57c	4.76 ± 0.47b	4.88 ± 0.33b	19.90 ± 1.98b	18.01 ± 1.39b
Middle leaves (g/kg)	+K	26.19 ± 0.91a	17.99 ± 0.74b	4.41 ± 0.07a	2.09 ± 0.14c	16.22 ± 0.50a	4.93 ± 0.42d
	-K	15.67 ± 0.15bc	15.05 ± 0.77c	3.45 ± 0.25b	2.97 ± 0.23b	8.05 ± 0.72b	6.37 ± 0.34c
Inner leaves (g/kg)	+K	16.16 ± 0.12ab	16.49 ± 0.11a	2.13 ± 0.12ab	1.85 ± 0.16b	4.69 ± 0.20a	4.34 ± 0.06a
	-K	15.64 ± 0.29b	14.67 ± 0.24c	2.34 ± 0.05a	2.00 ± 0.03b	3.54 ± 0.00b	4.47 ± 0.35a
Shortened stems (g/kg)	+K	25.04 ± 1.40a	13.66 ± 0.12b	3.70 ± 0.28a	2.36 ± 0.15b	12.52 ± 0.14b	5.50 ± 0.10d
	-K	23.45 ± 0.48a	14.34 ± 0.41b	4.02 ± 0.05a	1.62 ± 0.06c	14.11 ± 0.79a	6.62 ± 0.14c
Roots (g/kg)	+K	9.88 ± 0.33a	6.94 ± 0.74b	2.84 ± 0.25a	2.42 ± 0.01ab	10.29 ± 0.92a	8.06 ± 0.35b
	-K	9.78 ± 0.21a	6.98 ± 0.50b	2.97 ± 0.23a	2.11 ± 0.19b	8.60 ± 0.26b	6.93 ± 0.55c

Note: Each data represents the average from three samples. Error bars represent standard error (Mean ± SE, n = 3). Different lowercase letters indicated that the differences in indicators of ‘HK8’ and ‘HK48’ varieties under +K and -K treatments at the 0.05 level.

3.7 Response of K^+, Ca^{2+}, and Na^+ Accumulations in Different Parts of Two Genotypes of Chinese Cabbage to Potassium Deficiency

In the outer leaves, compared to the +K treatment, ‘HK8’ under the -K treatment exhibited significant increases in K^+ accumulation (47.98%), Ca^{2+} accumulation (43.13%), and Na^+ accumulation (31.40%). In ‘HK48’, Na^+ accumulation increased significantly by 25.85% under the -K treatment relative to the +K treatment. Under the -K treatment, K^+, Ca^{2+}, and Na^+ accumulation in the outer leaves of ‘HK8’ were significantly higher than those in ‘HK48’.

In the middle leaves, compared to the +K treatment, ‘HK8’ under the -K treatment showed significant decreases in K^+ accumulation (40.62%), Ca^{2+} accumulation (22.23%), and Na^+ accumulation (50.69%). Similarly, ‘HK48’ under the -K treatment exhibited significant decreases in K^+ accumulation (43.44%), Ca^{2+} accumulation (12.48%), and Na^+ accumulation (20.38%). Regardless of treatment, K^+, Ca^{2+}, and Na^+ accumulation in the middle leaves of ‘HK8’ was consistently higher than in ‘HK48’.

In the inner leaves, compared to the +K treatment, ‘HK8’ under the -K treatment demonstrated remarkable increases in K^+ accumulation (206.20%), Ca^{2+} accumulation (235.67%), and Na^+ accumulation (129.50%). In contrast, ‘HK48’ under the -K treatment showed significant decreases in K^+ accumulation (51.14%), Ca^{2+} accumulation (45.12%), and Na^+ accumulation (42.39%). Under both treatments, K^+, Ca^{2+}, and Na^+ accumulation in the inner leaves of ‘HK8’ was higher than in ‘HK48’.

In the shortened stem, compared to the +K treatment, ‘HK8’ under the -K treatment exhibited significant decreases in K^+ accumulation (27.77%), Ca^{2+} accumulation (16.28%), and Na^+ accumulation (13.03%). Similarly, ‘HK48’ under the -K treatment showed significant decreases in K^+ accumulation (30.56%), Ca^{2+} accumulation (52.82%), and Na^+ accumulation (17.21%). Under both treatments, K^+, Ca^{2+}, and Na^+ accumulation in the shortened stem of ‘HK8’ was higher than in ‘HK48’.

In the roots, compared to the +K treatment, ‘HK8’ under the -K treatment showed a significant decrease in K^+ accumulation (33.09%) but a significant increase in Ca^{2+} accumulation (32.18%). In ‘HK48’ under the

-K treatment, K^+ accumulation (33.09%), Ca^{2+} accumulation (42.04%), and Na^+ accumulation (42.81%) all decreased significantly (Table 6).

Table 6: Effects of potassium deficiency on ion accumulation in different parts of 'HK8' and 'HK48' varieties of Chinese cabbage.

Different Organizations	Treatments	K^+ Accumulation		Ca^{2+} Accumulation		Na^+ Accumulation	
		'HK8'	'HK48'	'HK8'	'HK48'	'HK8'	'HK48'
Outer leaves (g/plant)	+K	2237.23 ± 92.53b	1679.44 ± 54.74c	1108.88 ± 64.21b	1104.32 ± 58.12b	1629.96 ± 39.75b	1151.85 ± 53.34d
	-K	3310.73 ± 133.53a	1716.56 ± 43.34c	1568.92 ± 110.34a	978.16 ± 53.49b	2141.84 ± 17.80a	1449.65 ± 29.20c
Middle leaves (g/plant)	+K	1995.86 ± 69.42a	919.31 ± 131.03b	335.77 ± 4.96a	117.29 ± 7.75c	1235.92 ± 38.12a	276.64 ± 23.46c
	-K	1185.08 ± 15.88b	519.95 ± 26.67c	254.00 ± 7.96b	102.65 ± 5.64d	622.18 ± 38.10b	220.26 ± 11.80d
Inner leaves (g/plant)	+K	321.94 ± 18.76b	258.75 ± 2.65c	43.96 ± 2.73b	28.83 ± 1.29c	97.47 ± 4.49b	67.37 ± 0.89c
	-K	1004.92 ± 18.51a	124.46 ± 4.62d	150.61 ± 2.91a	16.61 ± 0.26d	227.13 ± 0.30a	37.16 ± 0.06d
Shortened stems (g/plant)	+K	314.84 ± 17.59a	74.38 ± 3.70c	46.83 ± 0.89a	13.47 ± 0.76c	157.39 ± 1.82a	31.47 ± 0.59c
	-K	227.41 ± 4.64b	51.65 ± 4.78d	38.96 ± 0.46b	6.36 ± 0.22d	136.88 ± 5.56b	26.06 ± 0.54d
Roots (g/plant)	+K	21.86 ± 0.48b	29.01 ± 0.76a	6.50 ± 0.55c	8.59 ± 0.32a	23.57 ± 1.97a	24.85 ± 0.76a
	-K	20.66 ± 2.19c	13.82 ± 0.99d	7.20 ± 0.03b	4.17 ± 0.21d	23.99 ± 1.03a	13.72 ± 1.09b

Note: Each data represents the average from three samples. Error bars represent standard error (Mean ± SE, n = 3). Different lowercase letters indicated that the differences in indicators of 'HK8' and 'HK48' varieties under +K and -K treatments at the 0.05 level.

3.8 Responses of K^+/Na^+ and Ca^{2+}/Na^+ in Different Parts of Two Genotypes of Chinese Cabbage to Potassium Deficiency

In the outer leaves, compared to the +K treatment, 'HK8' under the -K treatment exhibited a significant increase of 10.00% in the K^+/Na^+ ratio, whereas 'HK48' showed a significant decrease of 12.05%. Under the -K treatment, the K^+/Na^+ ratio of 'HK48' was significantly lower than that of 'HK8' by 17.83%. Regarding the Ca^{2+}/Na^+ ratio, 'HK48' under the -K treatment demonstrated a significant decrease of 10.49% compared to the +K treatment; under the +K treatment, the Ca^{2+}/Na^+ ratio of 'HK48' was 27.31% higher than that of 'HK8'.

In the middle leaves, compared to the +K treatment, 'HK8' under the -K treatment exhibited a significant increase of 25.71% in the K^+/Na^+ ratio, while 'HK48' showed a significant decrease of 35.50%. Under the +K treatment, the K^+/Na^+ ratio of 'HK48' was significantly higher than that of 'HK8' by 127.33%. The Ca^{2+}/Na^+ ratio of 'HK8' increased significantly by 61.96% under the -K treatment, whereas under the +K treatment, the Ca^{2+}/Na^+ ratio of 'HK48' was significantly higher than that of 'HK8' by 56.12%.

In the inner leaves, compared to the +K treatment, 'HK8' under the -K treatment showed a significant increase of 28.51% in the K^+/Na^+ ratio. Under the -K treatment, the K^+/Na^+ ratio of 'HK48' was significantly lower than that of 'HK8' by 23.53%. The Ca^{2+}/Na^+ ratio of 'HK8' increased significantly by 46.26% under the -K treatment, and under the -K treatment, the Ca^{2+}/Na^+ ratio of 'HK48' was significantly lower than that of 'HK8' by 30.30%.

In the shortened stem, compared to the +K treatment, the K^+/Na^+ ratio of 'HK8' decreased significantly by 16.94% under the -K treatment, and that of 'HK48' decreased significantly by 12.73%. Under both +K and -K treatments, the K^+/Na^+ ratio of 'HK48' was significantly higher than that of 'HK8' by 23.98% and 30.27%, respectively. The Ca^{2+}/Na^+ ratio of 'HK48' decreased significantly by 43.01% under the -K treatment, and under the +K treatment, the Ca^{2+}/Na^+ ratio of 'HK48' was significantly higher than that of 'HK8' by 43.33%.

In the roots, compared to the +K treatment, 'HK8' under the -K treatment exhibited a significant increase of 17.28% in the K^+/Na^+ ratio, and 'HK48' showed a significant increase of 15.80%. Under both treatments, the K^+/Na^+ ratio of 'HK8' was significantly higher than that of 'HK48' by 11.49% and 11.40%, respectively. The Ca^{2+}/Na^+ ratio of 'HK8' increased significantly by 61.96% under the -K treatment, and under the +K treatment, the Ca^{2+}/Na^+ ratio of 'HK48' was significantly higher than that of 'HK8' by 25.41% (Table 7).

Table 7: Effects of potassium deficiency on K^+/Na^+ and Ca^{2+}/Na^+ in different parts of 'HK8' and 'HK48' varieties.

Different Organizations	Treatments	K^+/Na^+		Ca^{2+}/Na^+	
		'HK8'	'HK48'	'HK8'	'HK48'
Outer leaves	+K	1.43 ± 0.03b	1.47 ± 0.03b	0.24 ± 0.02b	0.30 ± 0.00a
	-K	1.57 ± 0.02a	1.29 ± 0.14c	0.24 ± 0.01b	0.27 ± 0.01b
Middle leaves	+K	1.61 ± 0.01c	3.66 ± 0.16a	0.27 ± 0.01b	0.42 ± 0.01a
	-K	2.03 ± 0.22b	2.36 ± 0.01b	0.44 ± 0.02a	0.47 ± 0.00a
Inner leaves	+K	3.50 ± 0.14b	3.80 ± 0.03b	0.45 ± 0.01b	0.43 ± 0.02b
	-K	4.42 ± 0.08a	3.38 ± 0.19b	0.66 ± 0.01a	0.46 ± 0.04b
Shortened stems	+K	2.00 ± 0.13b	2.48 ± 0.07a	0.30 ± 0.00b	0.43 ± 0.03a
	-K	1.66 ± 0.03c	2.17 ± 0.02b	0.29 ± 0.01b	0.24 ± 0.00b
Roots	+K	0.97 ± 0.11b	0.87 ± 0.13c	0.28 ± 0.00c	0.30 ± 0.01b
	-K	1.14 ± 0.01a	1.01 ± 0.01b	0.35 ± 0.00a	0.31 ± 0.04b

Note: Each data represents the average from three samples. Error bars represent standard error (Mean ± SE, n = 3). Different lowercase letters indicated that the differences in indicators of 'HK8' and 'HK48' varieties under +K and -K treatments at the 0.05 level.

3.9 Response of ion-Selective Transport Capacity in Different Parts of Two Genotypes of Chinese Cabbage to Potassium Deficiency

For K^+ selective transport capacity from roots to the shortened stem, compared to the +K treatment, 'HK8' under the -K treatment exhibited a significant decrease of 29.79%, and 'HK48' showed a significant decrease of 26.87%. Under both treatments, the K^+ selective transport capacity of 'HK48' was significantly higher than that of 'HK8' by 41.67% and 47.02%, respectively.

For Ca^{2+} selective transport capacity from roots to the shortened stem, 'HK8' under the -K treatment demonstrated a significant decrease of 24.07%, and 'HK48' showed a significant decrease of 43.23%. Under the +K treatment, the Ca^{2+} selective transport capacity of 'HK48' was 32.41% higher than that of 'HK8'.

For K^+ selective transport capacity from the shortened stem to the inner leaves, 'HK8' under the -K treatment showed a significant increase of 51.31%. Under the -K treatment, the K^+ selective transport capacity of 'HK48' was significantly lower than that of 'HK8' by 41.45%.

For Ca^{2+} selective transport capacity from the shortened stem to the inner leaves, 'HK8' under the -K treatment demonstrated a significant increase of 54.97%, and 'HK48' showed a significant increase of 88.52%. Under both treatments, the Ca^{2+} selective transport capacity of 'HK48' was significantly lower than that of 'HK8' by 33.77% and 19.23%, respectively.

For K^+ selective transport capacity from the shortened stem to the middle leaves, 'HK8' under the -K treatment showed a significant increase of 51.35%, whereas 'HK48' exhibited a significant decrease of 26.36%. Under the +K treatment, the K^+ selective transport capacity of 'HK48' was significantly higher than that of 'HK8' by 82.06%.

For Ca^{2+} selective transport capacity from the shortened stem to the middle leaves, 'HK8' under the -K treatment demonstrated a significant increase of 71.43%, and 'HK48' showed a significant increase of 92.88%. Under the -K treatment, the Ca^{2+} selective transport capacity of 'HK48' was 22.00% higher than that of 'HK8'.

For K^+ selective transport capacity from the shortened stem to the outer leaves, 'HK8' under the -K treatment exhibited a significant increase of 31.42%. Under the -K treatment, the K^+ selective transport capacity of 'HK48' was significantly lower than that of 'HK8' by 36.84%.

For Ca^{2+} selective transport capacity from the shortened stem to the outer leaves, 'HK48' under the -K treatment demonstrated a significant increase of 58.28%, and under the -K treatment, the Ca^{2+} selective transport capacity of 'HK48' was 33.33% higher than that of 'HK8' (Table 8).

Table 8: Effects of potassium deficiency on K^+ and Ca^{2+} selective transport capacity in different parts of 'HK8' and 'HK48' Chinese cabbage cultivars.

Different Organizations	Treatments	K^+ Selective Transport Capacity		Ca^{2+} Selective Transport Capacity	
		'HK8'	'HK48'	'HK8'	'HK48'
Roots-Shortened stems	+K	2.08 ± 0.10b	2.94 ± 0.52a	1.08 ± 0.01b	1.43 ± 0.18a
	-K	1.46 ± 0.04c	2.15 ± 0.03b	0.82 ± 0.04c	0.81 ± 0.11c
Shortened stems-Inner leaves	+K	1.76 ± 0.19b	1.53 ± 0.03b	1.51 ± 0.03b	1.00 ± 0.03c
	-K	2.66 ± 0.10a	1.56 ± 0.08b	2.34 ± 0.16a	1.89 ± 0.14b
Shortened stems-Middle leaves	+K	0.81 ± 0.06c	1.48 ± 0.02a	0.91 ± 0.05c	1.00 ± 0.06c
	-K	1.22 ± 0.11b	1.09 ± 0.01b	1.56 ± 0.02b	1.91 ± 0.03a
Shortened stems-Outer leaves	+K	0.72 ± 0.03b	0.59 ± 0.03b	0.80 ± 0.08b	0.71 ± 0.05b
	-K	0.95 ± 0.01a	0.60 ± 0.06b	0.84 ± 0.09b	1.12 ± 0.01a

Note: Each data represents the average from three samples. Error bars represent standard error (Mean ± SE, n = 3). Different lowercase letters indicated that the differences in indicators of 'HK8' and 'HK48' varieties under +K and -K treatments at the 0.05 level.

4 Discussion

Genetic variation exists in potassium absorption and utilization efficiency among different Chinese cabbage genotypes, underscoring the importance of screening for potassium-efficient varieties [3,16]. Genotypic differences in the capacity of crops to absorb and utilize potassium have been widely reported [29–32]. Kathpalia and Bhatla [33] proposed that germplasms differing in yield under nutrient stress can only be classified as "efficient" or "inefficient" if they exhibit comparable yields when supplied with optimal nutrient levels. In their study of cotton, four cultivars with greater dry weight under K deficiency were classified as potassium-efficient genotypes, while four cultivars with lower dry weight were classified as potassium-inefficient genotypes. Rengel and Damon [34] similarly demonstrated that potassium-efficient genotypes can grow well and achieve higher yields even in soils with low potassium availability. Studies comparing potassium efficiency among apple rootstocks found that potassium-efficient varieties, when subjected to K-deficiency stress in sand culture, allocated a greater proportion of their dry matter to roots, suggesting that such conditions are more conducive to root growth [35].

In the present study, PCA was applied to consolidate 14 physiological indicators into three principal components to characterize the low-K tolerance of Chinese cabbage. Within PC1, root fresh weight (RFW) exhibited the highest loading coefficient (0.868), identifying it as a key indicator of root development. Potassium utilization efficiency (KUE) is also recognized as an important indicator for evaluating crop potassium utilization. Genotypic differences in KUE are manifested at the cellular or whole-plant level as variations in potassium transport capacity or the ability to substitute K^+ with other cations such as Na^+ and Ca^{2+} [35]. Within PC2, KUE had the highest loading coefficient (0.945), confirming its role as a principal determinant of potassium utilization efficiency within the plant. Within PC3, yield (Y) exhibited the highest loading coefficient (0.899), with Y, plant fresh weight (PFW), and root K concentration (RKC) all contributing substantially, collectively representing indicators of yield formation. Based on these three principal components, along with membership function values and comprehensive evaluation scores (D-values), the 12 Chinese cabbage genotypes were classified into four categories, from which the low-K-tolerant genotype 'HK8' and the low-K-sensitive genotype 'HK48' were identified. Azzawi et al. [36] similarly employed PCA to screen for potassium utilization efficiency under low-K stress in barley, and Deng et al. [37] used cluster analysis to classify 20 potato genotypes into high- and low-potassium-efficiency groups. Collectively, these findings support the use of root fresh weight, shoot potassium utilization efficiency, and yield as critical indicators for the field-based screening of potassium-efficient Chinese cabbage genotypes at maturity.

Reports on the evaluation of low-potassium tolerance and potassium efficiency in Chinese cabbage remain scarce, and no unified standard has been established for classifying low-K-tolerant and potassium-efficient varieties. Genotypic differences in nutrient efficiency within plant species arise from variations in absorption efficiency and utilization efficiency, or both [33]. Plants with high utilization efficiency can achieve substantial dry matter production at lower internal potassium concentrations, whereas those with high absorption efficiency can extract more potassium from the soil under reduced supply, thereby sustaining growth [31]. Graham and Gregorio [38] proposed that genotypes capable of achieving higher yields under low soil potassium conditions may be classified as potassium-efficient varieties. KUE is a key physiological indicator of plant adaptation to low-K stress, as high KUE enables plants to maintain growth and development under limited potassium supply, enhancing survival in low-potassium environments. The divergent responses of different Chinese cabbage genotypes to K-deficiency stress are primarily attributable to two key characteristics: the ability to absorb potassium from the soil and the efficiency with which potassium is utilized to produce biomass [30]. Unlike KUE, the potassium utilization index (KUI), defined as biomass produced per unit tissue potassium concentration, additionally accounts for differences in biomass production. In screening maize varieties for low-K tolerance, KUI proved to be a more reliable indicator than potassium uptake at the seedling stage for identifying low-K-tolerant genotypes; a higher KUI indicates stronger tolerance to low-K stress [39].

The present study found that under K-deficient conditions, the yield of the low-K-tolerant genotype 'HK8' increased significantly by 35.29%, whereas the yield of the low-K-sensitive genotype 'HK48' decreased significantly by 57.04%. Concurrently, 'HK8' showed significant increases in both KUE and KUI under K deficiency, while 'HK48' exhibited significant decreases in both parameters. However, the yield of 'HK8' under +K treatment was lower than that under -K treatment. We speculate that the possible reasons are as follows: first, this genotype may be insensitive to luxury potassium absorption, meaning that the elevated potassium supply (165 kg K_2O/ha) did not substantially promote its growth. Second, 'HK8' possesses exceptionally high internal potassium reuse and redistribution efficiency (Tables 5–8), enabling it to allocate potassium preferentially to growth centers and inner leaves under limited potassium availability, thereby maintaining or even promoting leaf head formation and economic yield. In contrast, the sensitive genotype 'HK48' relies heavily on external potassium fertilizer supply; under K deficiency, its potassium allocation becomes disrupted, preventing head formation (Fig. 3A–D) and causing a sharp yield decline. This highlights the unique physiological advantage of 'HK8' as a nutrient-efficient genotype, and also suggests that under non-limiting potassium conditions, 'HK48' may possess greater yield potential. This trade-off implies that in soils with limited potassium resources or under saline-alkaline stress, selecting 'HK8' can ensure stable yield and resource use efficiency, whereas in regions with ample potassium fertilizer and favorable soil conditions, the yield potential of high-yielding genotypes such as 'HK48' may be more fully realized. Future breeding efforts could aim to integrate the stress tolerance of 'HK8' with the high-yield potential of genotypes such as 'HK48' to develop cultivars with broader adaptability. Furthermore, the present study observed that dry matter accumulation in various tissues of 'HK8' under K deficiency was consistently higher than under adequate K supply, particularly in the inner leaves and roots, whereas the opposite trend was observed in 'HK48'. This result is consistent with findings reported by Zhao et al. [40], who demonstrated that high-potassium-efficiency maize genotypes possess longer root lengths, larger root volumes, and greater root surface areas.

Research on potassium efficiency has primarily focused on potassium absorption or utilization efficiency, both of which are essential for selecting potassium-efficient crop varieties [41]. Potassium accumulation and redistribution capacity are critical parameters for evaluating crop potassium efficiency, with the primary mechanisms of KUE involving the transport of potassium ions to different organs and the maintenance of cytosolic potassium ion concentrations within optimal ranges [34]. It has been reported that sucrose, the primary photosynthetic assimilate in potato, is transported via the phloem from shoots to tubers, where it is metabolized to provide energy and carbon skeletons for cell division and tuber expansion. Potassium, as the most abundant inorganic cation in phloem conduits, plays an additional role in balancing mobile anions within the phloem [8]. Deng et al. [37] demonstrated that phloem potassium content exceeds that of leaves and roots, and that allocation of dry matter to tubers is substantially reduced under K deficiency, ultimately lowering yield [42]. The present study found that under K deficiency, dry matter accumulation in the outer leaves, inner leaves, and roots of 'HK8' was substantially higher than under adequate K supply, whereas all tissues in 'HK48' showed reduced values. Potassium accumulation in the outer and inner leaves of 'HK8' under K deficiency was significantly higher than under sufficient K supply, while 'HK48' exhibited reduced potassium accumulation in all tissues except the outer leaves. These findings indicate that 'HK8' possesses superior dry matter accumulation and potassium allocation capabilities across tissues compared to the sensitive genotype 'HK48' under K-deficient conditions, enabling it to preferentially allocate potassium to actively growing organs under low-K stress and thereby increase KUE. This potassium allocation strategy supports higher growth rates and yield maintenance in low-potassium environments.

High-potassium-efficiency genotypes exhibit greater potassium absorption and redistribution capacities, with effective redistribution ensuring high utilization efficiency [34]. Early studies identified the following as central mechanisms: effective distribution and redistribution of potassium within the plant, maintenance of metabolic activity through optimal intercellular potassium transfer, and substitution by soluble sugars or other cations to reduce vacuolar potassium demand [39]. Under K deficiency, the concentrations of soluble sugars, Na^+, Ca^{2+}, and Mg^{2+} in plant tissues increase substantially [43,44], and this substitution capacity is more pronounced in varieties with higher KUE. The present study observed that under K deficiency, K^+, Na^+, and Ca^{2+} concentrations in the outer leaves of the tolerant genotype 'HK8' were lower than under normal K supply, yet the accumulation of these ions in the outer and inner leaves of 'HK8' was higher under K deficiency. Conversely, the sensitive genotype 'HK48' showed reduced K^+, Na^+, and Ca^{2+} accumulation in the middle and inner leaves under K deficiency. These results indicate that under low-K stress, 'HK8' maintains superior ionic homeostasis, associated with its higher K^+/Na^+ ratio across tissues. In contrast, 'HK48' exhibited a significantly reduced K^+/Na^+ ratio under K deficiency, reflecting a weaker capacity to maintain ionic balance and potentially inhibiting growth in low-K environments.

The selective ion transport coefficient reflects a plant's ability to selectively transport mineral nutrient ions acropetally. Under salt stress, a higher value indicates a stronger capacity to promote upward nutrient ion transport while retaining more Na^+ in the roots, which correlates with enhanced salt tolerance [45]. A high cytosolic K^+/Na^+ ratio is critical for normal cellular processes in plants and is widely used as an effective indicator of salt tolerance, with higher values under salt stress signifying stronger tolerance [46]. Based on the data for ion concentration, accumulation, K^+/Na^+ ratio, and K^+ selective transport capacity

(Tables 5–8), we propose that the key mechanism by which 'HK8' maintains a higher K^+/Na^+ ratio under saline-alkaline and low-potassium stress relies primarily on superior shoot ion compartmentalization and selective transport capacity, rather than on root-level Na^+ exclusion. Specifically, 'HK8' more efficiently transports and sequesters limited K^+ and Ca^{2+} into critical tissues such as the inner leaves, thereby preserving favorable ionic homeostasis in photosynthetically active organs. This coordinated strategy of uptake, transport, and compartmentalization constitutes the primary physiological basis for its low-K tolerance.

5 Conclusion

The results of this study demonstrated that significant genetic variation exists among Chinese cabbage genotypes in root fresh weight, shoot potassium utilization efficiency, and yield at maturity. Based on these three principal components, along with membership function values and comprehensive evaluation scores (D-values), the 12 genotypes were classified into four categories: low-K-tolerant ('HK8'); moderately low-K-tolerant ('HK1', 'HK6', 'HK12' and 'HK42'); intermediate low-K-sensitive ('HK18', 'HK25', 'HK27' and 'HK40'); and low-K-sensitive ('HK45', 'HK48' and 'HK54').

Under K-deficient conditions, significant differences were observed between 'HK8' and 'HK48' in yield, dry matter accumulation, potassium distribution patterns, and K^+/Na^+ and Ca^{2+}/Na^+ ratios across plant organs. The low-K-tolerant genotype 'HK8' exhibited markedly superior salt tolerance compared to the low-K-sensitive genotype 'HK48', suggesting that low-K tolerance and ionic homeostasis maintenance are closely linked physiological traits in Chinese cabbage.

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