

Foliar spraying of sorbitol-chelated potassium and zinc enhances winter wheat yield and quality through source-flow-sink coordination and rhizosphere feedback

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Abstract

Aims

Improving nutrient-use efficiency rather than merely increasing fertilizer inputs is essential for sustaining winter wheat productivity and grain quality. However, whether fertilizer-form innovation can synergize the coordinated utilization of Potassium (K) and zinc (Zn) under field conditions remains unclear.

Methods

To address this, two consecutive field experiments (2022–2024) systematically compared conventional fertilization (CK), foliar inorganic K-Zn (KZn), and foliar sorbitol-chelated K-Zn (SKZn). We evaluated wheat yield, grain quality, post-anthesis dry matter dynamics, mineral translocation, and rhizosphere bacterial communities.

Results

Compared with CK and KZn, SKZn consistently enhanced grain yield, thousand-grain weight, and spike number across both seasons, while promoting post-anthesis dry matter accumulation and sustaining prolonged flag-leaf photosynthetic vigor. Furthermore, SKZn markedly augmented K and Zn accumulation and their targeted translocation to grains, significantly improving the synthesis of starch components and storage proteins. In the rhizosphere, SKZn increased water-soluble K and available Zn while selectively enriched beneficial plant-growth-promoting bacterial taxa, including *Arthrobacter*, *Sphingomonas*, and *Bacillus*. Partial least squares structural equation modeling (PLS-SEM) revealed that SKZn enhanced source-flow-sink coordination via a cascade pathway: prolonged photosynthesis → optimized carbon – nitrogen metabolism → strengthened dry matter translocation → synergistic grain mineral enrichment.

Conclusions

Collectively, this morphology-driven innovation circumvents inorganic ionic antagonism and inefficient nutrient uptake, forging a robust coupling between yield and quality formation. This provides crucial theoretical insights and an efficient green paradigm for high-quality winter wheat production in the Huang-Huai-Hai Plain.

Introduction

Under the dual challenges of global food security and sustainable agricultural development, achieving the simultaneous improvement of crop yield and quality has become a central objective of modern agricultural science. As major winter wheat-producing regions in China, Shandong Province and the

broader North China Plain have experienced a gradual slowdown in yield growth. The traditional strategy of increasing fertilizer inputs has led to pronounced diminishing marginal returns, resulting in soil fertility degradation and escalating environmental risks. The fundamental challenge lies in shifting from a fertilizer quantity-driven approach toward the systematic improvement of nutrient use efficiency (Han et al. 2022; Yan et al. 2024).

Potassium (K) and zinc (Zn) play indispensable and complementary physiological roles in regulating photosynthetic carbon metabolism, long-distance assimilate translocation, and grain development in wheat. However, China relies heavily on imported K fertilizers (Liu et al. 2023), while vast areas of arable land suffer from Zn deficiency (White et al. 2009), creating dual constraints regarding nutrient resources and crop nutrition. Previous studies have demonstrated that the effectiveness of exogenous nutrients is not solely determined by application rates alone, but is instead strictly regulated by physicochemical properties, mobility, and in planta bioavailability of the fertilizers.

Conventional soil-applied fertilizers are often limited by nutrient fixation, leaching losses, and spatial heterogeneity. Although foliar application can bypass soil barriers and deliver nutrients directly to plant tissues, conventional inorganic salt-based foliar fertilizers frequently encounter physiological limitations, including low transmembrane uptake efficiency, severe ionic antagonism, and restricted phloem mobility. In contrast, sorbitol-based chelation technology, owing to its polyhydroxyl structure, can enhance nutrient stability and facilitate nutrient translocation in planta (Zhang et al. 2024; Zheng et al. 2025).

Based on the advantages of chelated nutrient transport and the complementary functions of K and Zn, we hypothesized that foliar application of sorbitol-chelated K-Zn fertilizer could overcome the absorption barriers inherent to inorganic ion. By strengthening aboveground source-flow-sink coordination, this approach may not only directly enhance grain yield and quality in winter wheat but also indirectly activate rhizosphere nutrient availability and reshape microbial communities through plant-soil feedback mechanisms.

To test this hypothesis, a two-year field experiment was conducted from 2022 to 2024 in a typical winter wheat production region of Shandong Province, China. The effects of conventional fertilization, inorganic potassium-zinc fertilizer, and sorbitol-chelated K and Zn (SKZn) applied during critical growth stages of winter wheat were systematically compared. Specifically, this study aimed to: (1) evaluate the effects of fertilizer form on wheat yield components and grain quality traits; (2) characterize the distribution and translocation dynamics of K and Zn among different plant organs; and (3) investigate the cascading feedback effects of aboveground foliar nutrient application on rhizosphere soil nutrients (including K, Zn, nitrogen, and phosphorus) and microbial community structure. Finally, partial least squares structural equation modeling (PLS-SEM) was employed to quantify the regulatory pathways among these processes, providing a fertilization strategy based on formulation innovation for further improving wheat productivity in Shandong Province and the North China Plain.

Materials and Methods

Experimental site description and plant materials

This study was conducted during two consecutive winter wheat growing seasons (2022–2023 and 2023–2024) at a field experimental site in Houhuayuan Village, Huashan Town, Jimo District, Qingdao, Shandong Province, China (36°35'42"N, 120°31'23"E). The region is characterized by a typical temperate monsoon climate with abundant solar radiation and thermal resources. The experimental field featured flat topography, fertile soil, and a history of continuous, long-term crop cultivation. Lacking direct water access, crop water requirements were met entirely by natural precipitation and supplemental irrigation.

The soil at the experimental field was classified as a brown soil with a relatively uniform texture. During the experimental period, precipitation and temperature dynamics across key growth stages were continuously monitored. The mean daily temperatures during the two growing seasons were 8.39 °C and 8.50 °C, while the total cumulative precipitation throughout the entire growth periods amounted to 229.78 mm and 215.72 mm, respectively. Specifically, during the critical period from anthesis to maturity, cumulative precipitation reached 46.40 mm and 42.49 mm, with corresponding mean temperatures averaging 18.10 °C and 19.58 °C, respectively. Detailed meteorological data are presented in Fig. 1.

To determine the background effects of initial soil fertility on fertilizer responses across different years, soil samples from the 0–20 cm plow layer were collected before sowing in each growing season for the analysis of initial soil physicochemical properties. In the 2023 growing season, soil pH was 6.13, and the contents of alkali-hydrolyzable nitrogen, available phosphorus, available zinc, available potassium, and water-soluble potassium were 30.1, 38.1, 3.91, 170.4, and 18.8 mg kg⁻¹, respectively. In 2024, these parameters changed to 6.05, 36.8, 50.5, 1.78, 92.0, and 54.5 mg kg⁻¹, respectively.

The tested winter wheat was *Triticum aestivum* L. cv. Tainong 108, a high-yielding, high-quality registered cultivar widely cultivated in Shandong Province, China. This cultivar exhibits desirable agronomic characteristics, including strong tillering capacity, high spike formation efficiency, superior grain quality, and enhanced stress tolerance. The total growth duration was approximately 232 days, with an average plant height of approximately 83.9 cm. The conventional planting density was maintained at 2.25 million plants ha⁻¹.

Experimental design and field management

A randomized complete block design was adopted in this field experiment, consisting of three treatments: (1) CK, the conventional control treatment sprayed with an equivalent volume of water; (2) KZn, foliar application of inorganic K-Zn fertilizer prepared from potassium nitrate and zinc nitrate; (3) SKZn, foliar application of sorbitol-chelated K-Zn fertilizer independently developed by our research group. Each treatment was replicated three times, and the area of each plot was 100 m² (10 m × 10 m). The concentrations of effective nutrients in all fertilizer solutions were uniformly set at 9 g L⁻¹ potassium and 2 g L⁻¹ zinc.

Foliar applications were performed three times during critical growth stages of winter wheat, including anthesis (6 May 2023 and 25 April 2024), early grain filling (11 May 2023 and 9 May 2024), and mid-grain filling (17 May 2023 and 17 May 2024). To maximize foliar nutrient absorption via stomatal pathways, spraying was conducted on sunny mornings between 08:00 and 12:00. The spray volume was maintained at 750 L ha^{-1} (equivalent to 7.5 L per plot) for each application. Throughout the experimental period, basal fertilization, irrigation management, pest control, and weed control practices were kept consistent across all plots.

Sample collection and processing

Plant and soil samples were concurrently collected at both the anthesis and maturity stages of winter wheat.

Soil sampling

Soil samples from the 0–20 cm plow layer were collected using a grid-point sampling method within each experimental plot using a stainless-steel shovel. Approximately 1 kg of composite soil sample was retained per plot. The collected soil samples were transported to the laboratory, naturally air-dried in a cool and well-ventilated environment, and then manually cleaned to remove plant residues, gravel, and other impurities. The dried soils were ground, passed through a 1.0mm (18-mesh) sieve, and stored in sealed polyethylene bags at room temperature for subsequent analyses.

Plant sampling

At the anthesis and maturity stages, 20 representative plants with uniform growth were randomly collected from each plot. Plant samples were separated into different organs according to growth stage characteristics. At anthesis, plants were separated into stems, leaves, and spikes; at maturity, they were separated into stems, leaves, grains, and glumes. All plant samples were placed into paper bags, oven-killed at 105°C for 30 min, and subsequently dried at 80°C in a forced-air drying oven to a constant weight for dry matter determination. The dried plant materials were ground using a stainless-steel grinder and sieved to appropriate particle sizes for subsequent elemental analyses. Samples were then sealed and stored until further determination.

Determination of plant and soil physicochemical properties

Determination of grain quality components

Grain starch content was determined via dual-wavelength colorimetry. Distinct protein fractions were quantified using a sequential extraction procedure. Phytic acid content in winter wheat grains was measured via the bipyridine spectrophotometric method.

Determination of mineral elements in plant tissues

Dried plant samples from different organs were accurately weighed and subjected to microwave digestion (Touchwin 2.0, Aopule Instrument Co., Ltd., China) in an $\text{HNO}_3\text{-H}_2\text{O}_2$ mixture. The concentrations of total K, Zn, Fe, and Mn were subsequently quantified using inductively coupled plasma optical emission spectrometry (ICP-OES; Avio 200, PerkinElmer, Massachusetts, USA).

Determination of soil physicochemical properties: Soil physicochemical properties were analyzed following standard agrochemical protocols. Soil pH was measured in a 1:2.5 (W/V) soil-water suspension using a pH meter (PHS-3E). Alkali-hydrolyzable nitrogen was determined via the alkali diffusion method, while available phosphorus was measured using standard chemical extraction procedures. Available K was extracted with $1 \text{ mol L}^{-1} \text{ NH}_4\text{OAc}$, and available Zn was extracted with $0.1 \text{ mol L}^{-1} \text{ HCl}$. The concentrations of available K and Zn were subsequently quantified using the aforementioned ICP-OES system.

Data processing and statistical analysis

All experimental data were initially compiled using Microsoft Excel 2019 and statistically analyzed using SPSS 25.0 software (IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA) was performed to evaluate the significant differences among fertilizer treatments, followed by Duncan's multiple range test for post hoc comparisons at a significance level of $P < 0.05$. Furthermore, a general linear model (GLM) was employed to assess the main and interactive effects of the growing season year (Year) and fertilizer treatment (Treatment) on the measured variables.

Duncan's multiple range test was also performed at the $P < 0.05$ significance level for multiple comparisons. Data visualization was conducted using Origin 2024b (OriginLab Corp., Northampton, MA, USA). High-throughput sequencing data of soil microbial communities were analyzed using the Onling Majorbio Cloud Platform (Shanghai Majorbio Bio-pharm Technology Co., Ltd, Shanghai, China). These analyses included microbial taxonomic composition analysis, sample – species association analysis, and principal coordinates analysis (PCoA) based on Bray – Curtis distance matrices. All graphical representations were generated using the aforementioned Origin 2024b system.

To systematically elucidate the underlying regulatory mechanisms linking wheat yield, nutrient distribution among plant organs, soil properties, and microbial communities under field conditions, partial least squares structural equation modeling (PLS-SEM) was performed. Model construction, calculation, and evaluation were conducted using SmartPLS 4 software (SmartPLS GmbH, Oststeinbek, Germany). To ensure model reliability and robustness, a comprehensive assessment of reliability and validity was performed. Internal consistency reliability and convergent validity were evaluated based on Cronbach's alpha (α) > 0.70 , composite reliability (CR) > 0.70 , and average variance extracted (AVE) > 0.50 . Discriminant validity was assessed using the heterotrait-monotrait ratio (HTMT).

The PLS-SEM framework was established based on plant physiological and nutritional theories, aiming to quantitatively characterize the complex regulatory pathways and relative contributions through which

sorbitol-chelated K-Zn fertilizer influenced the transmission of latent variables within the integrated plant-soil-microbiome system.

Results

Yield performance and economic benefits

The responses of winter wheat grain yield and yield components to different fertilizer treatments exhibited highly significant differences (Table 1). Although grain yield varied substantially between the two growing seasons due to differences in annual climatic conditions, the response patterns among fertilizer treatments remained consistent. The sorbitol-chelated K-Zn (SKZn) treatment exhibited a pronounced yield-enhancing effect. In the first growing season, SKZn increased grain yield by 50.76% compared with the CK, and it also produced significantly higher yields than both the CK and KZn treatments in the second growing season. In contrast, the yield-promoting effect of the inorganic K-Zn fertilizer (KZn) showed considerable interannual instability, with only a 1.48% increase in grain yield compared with the CK in the second growing season.

Table 1
Effects of different fertilization treatments on wheat yield and its components

Year	Treatment	Yield (t/ha)	TGW (g)	GNPS (N/S)	Spike (S/ha)	YIR(%)
2023	CK	3.31 ± 0.11c	26.88 ± 0.06b	43.55 ± 0.03c	302.31 ± 12.73b	—
	KZn	4.03 ± 0.08b	28.85 ± 0.35b	46.43 ± 0.15b	332.4 ± 17.61b	21.75
	SKZn	4.99 ± 0.32a	33.97 ± 2.13a	47.58 ± 0.04a	450.6 ± 34.71a	50.76
2024	CK	5.39 ± 0.35b	47.28 ± 0.65b	46.67 ± 1.45b	317.21 ± 9.94b	—
	KZn	5.47 ± 0.23b	46.43 ± 0.18b	47.67 ± 1.2b	318.48 ± 10.08b	1.48
	SKZn	6.54 ± 0.31a	49.42 ± 0.5a	54.67 ± 0.88a	351.43 ± 4.95a	21.34
ANOVA						
Year		***	***	***	**	
Treatment		***	***	***	***	
Year * Treatment		*	*	**	*	
Note: Data are presented as means ± standard deviations (n = 3). Different letters indicate significant differences among treatments within the same year (* <i>P</i> < 0.05, ** <i>P</i> < 0.01, *** <i>P</i> < 0.001).						

Regarding yield components, thousand-grain weight, a crucial indicator of wheat grain quality and yield capacity, was significantly improved by SKZn application. In the first growing season, the thousand-grain weight under the SKZn treatment increased by 26.38% compared with the CK, and this advantage was maintained in the following season. The number of grains per spike increased significantly by 9.25% and 17.14% compared with the CK across the two growing seasons, respectively. Meanwhile, the spike number per unit area increased consistently by 49.05% and 10.79% in the two seasons. Overall, the yield component responses followed the pattern of SKZn > KZn > CK.

The significant differences in grain yield were closely associated with alterations in plant dry matter accumulation and allocation patterns (Fig. 2). Data from the 2024 growing season showed that, at the anthesis stage, the SKZn-treated plants already exhibited higher dry matter accumulation in vegetative organs compared with other treatments. By maturity, SKZn resulted in the greatest total dry matter accumulation, with grain dry matter accumulation significantly increasing by 6.98% compared with CK. These findings indicate that the chelated K-Zn not only enhanced early-stage assimilate production but also improved the efficiency of post-anthesis assimilate translocation toward reproductive organs.

This yield enhancement, driven by improved biomass production and allocation, ultimately translated into substantial economic advantages under field conditions (Table 2). Although SKZn incurred the highest fertilizer input cost due to the additional chelation process, its greater marginal yield increase resulted in a lower cost per unit of yield gain under equivalent foliar application frequencies. In the 2023 and 2024 growing seasons, the cost per kilogram of additional yield under SKZn was only 0.21 and 0.30 RMB kg⁻¹, respectively, which was considerably lower than that under KZn (0.54 and 4.88 RMB kg⁻¹, respectively). After deducting all material and operational costs, the net economic benefits of SKZn reached 14,400 and 19,200 RMB ha⁻¹ in the two growing seasons, respectively. These results indicate that incorporating foliar application of sorbitol-chelated fertilizer into conventional crop management represents a highly cost-effective and promising agronomic strategy for optimizing field management while concurrently increasing wheat productivity and farmer income.

Table 2
Economic input and returns of foliar fertilization strategies in wheat production

Treatment	Fertilizer cost	Labor cost	Total cost	per unit yield increase(RMB kg ⁻¹)		Net income (10,000 RMB ha ⁻¹)	
	(RMB ha ⁻¹)			2023	2024	2023	2024
CK	-	-	-	-	-	0.99	1.61
KZn	133	300	433	0.54	4.88	1.17	1.60
SKZn	223	300	523	0.21	0.30	1.44	1.92
Note: Economic estimations were based on local market prices in 2024. The total cost represents the sum of fertilizer and labor costs, and the unit cost of yield gain was calculated by dividing the total cost by the additional yield relative to CK. Foliar applications were performed three times, labor costs were calculated as 100 RMB per day, assuming one workday is required to spray one hectare per application. The market prices of 70% sorbitol, potassium nitrate, and zinc nitrate are 4,000, 4,975, and 6,800 RMB ton ⁻¹ , respectively. The purchasing price of wheat was 3.00 RMB kg ⁻¹ .							

Dynamic changes in flag leaf SPAD values and carbon –nitrogen metabolism characteristics

This study monitored the dynamic changes in flag leaf SPAD values following three foliar fertilizer applications (Fig. 3, left). The results revealed that the SPAD values of flag leaves under the CK treatment exhibited a continuous declining trend throughout the post-anthesis growth period, whereas plants receiving exogenous K-Zn fertilizers displayed a characteristic pattern of an initial increase followed by a decrease.

After the first foliar application (at anthesis), both KZn and SKZn treatments showed immediate increases in flag leaf SPAD values. Among them, KZn exhibited the strongest early response, with SPAD

values increasing by 2.1% compared with CK, following the order of KZn > SKZn > CK. After the second application at the early grain-filling stage, SPAD values further increased across all fertilized treatments. At this stage, SKZn demonstrated a significant advantage, with SPAD values 14.41% higher than those of CK, following the pattern of SKZn > KZn > CK. Following the third application during the mid-grain filling stage, SPAD values declined markedly across all treatments. However, SKZn maintained relatively higher SPAD levels, indicating that this formulation had a sustained effect on delaying flag leaf senescence and maintaining late-season photosynthetic activity in winter wheat.

The plant carbon – nitrogen metabolic status further confirmed the above patterns. Compared with CK, SKZn treatment significantly increased the total nitrogen content by 10.13%. The KZn treatment also exhibited a significant increase of 7.60% relative to CK, but showed no significant difference from SKZn. The total carbon content followed the order of KZn > CK > SKZn. Specifically, no significant difference was observed between KZn and CK treatments, and both exhibited significantly higher total carbon contents than SKZn. The carbon-to-nitrogen (C/N) ratio showed a distinct pattern, following the order of CK > KZn > SKZn, with significant differences among all three treatments. The SKZn treatment exhibited the lowest C/N ratio, decreasing by 11.11% compared with CK and by 4.27% compared with KZn. These results indicate that SKZn promoted nitrogen accumulation and optimized the carbon-nitrogen balance by increasing total nitrogen content while reducing total carbon concentration and the C/N ratio, thereby contributing to its superior yield-enhancing performance.

Grain quality components and mineral nutrient characteristics

The fertilizer treatments significantly affected the targeted accumulation of potassium (K), zinc (Zn), iron (Fe), and manganese (Mn) in wheat grains (Fig. 4). Regarding these key mineral nutrients, the SKZn treatment resulted in the highest grain K concentration, increasing by 7.63% and 15.78% compared with CK and KZn, respectively. Notably, the grain K concentration under the inorganic KZn application was significantly lower than that under CK, indicating an apparent ion antagonism effect of the inorganic nutrient input on K accumulation. Exogenous Zn application effectively promoted Zn enrichment in grains, with KZn and SKZn increasing grain Zn concentration by 61.7% and 32.5% compared with CK, respectively. For micronutrient elements, SKZn significantly increased grain Mn concentration by 42.1% relative to CK, whereas grain Fe concentration was significantly reduced, decreasing by 13.35% and 17.20% compared with CK and KZn, respectively. In addition, no significant differences in grain phytic acid content were observed among the three treatments. These results indicate that SKZn effectively promoted the synergistic enrichment of K, Zn, and Mn in wheat grains, while exerting a certain inhibitory effect on Fe accumulation.

Starch, as the primary carbohydrate component of wheat grains, exhibited consistent differentiation patterns among fertilizer treatments (Fig. 5). Across the two growing seasons, SKZn maintained an absolute advantage in amylose accumulation, with increases of 43.37% and 34.63% compared with CK, and increases of 22.50% and 22.25% compared with KZn, respectively. Similarly, SKZn formulation

significantly enhanced amylopectin accumulation, increasing its content by 10.97% and 26.16% relative to CK, and by 26.36% and 29.22% relative to KZn across the two seasons, respectively. In contrast, inorganic fertilizer application resulted in relatively limited improvements in both amylose and amylopectin contents, with no statistically significant enhancements observed. In the first growing season, the amylopectin content under KZn was even slightly lower than that under CK. These results demonstrate that the sorbitol-chelated fertilizer form can continuously and stably promote the coordinated accumulation of amylose and amylopectin, whereas the effects of the inorganic fertilizer exhibit considerable interannual variability.

The different fertilizer treatments also exerted distinct effects on wheat grain protein fractions (Fig. 6). The metabolic proteins, including albumin and globulin, showed no significant differences among the treatments, whereas the storage proteins, which are the major determinants of gluten quality, exhibited high sensitivity to nutrient management. During the first growing season, SKZn achieved the highest contents of gliadin and glutenin, increasing by 20.08% and 29.67% compared with CK, respectively. Among these components, the glutenin content under SKZn was significantly higher than that under KZn, while no significant difference was observed between KZn and CK. During the second growing season, the positive effects of SKZn on storage protein accumulation were maintained. The gliadin content followed the order of SKZn > CK > KZn, whereas the glutenin content followed the order of SKZn > KZn > CK. Specifically, SKZn significantly increased the glutenin content by 19.55% compared with CK. Overall, the two-year results consistently demonstrated that SKZn exerted a highly stable and significant promoting effect on the accumulation of storage proteins in wheat grains.

Dynamic accumulation and partitioning of potassium and zinc in different plant organs

The different fertilizer treatments significantly altered the spatial distribution patterns of potassium (K) and zinc (Zn) among various organs of winter wheat (Fig. 7). Regarding K accumulation, the SKZn treatment significantly increased stem K concentration compared with CK at both anthesis and maturity, with the increase exceeding 100% at maturity. This indicates that stems served as the primary K storage pool under SKZn application. In contrast, leaf K concentration under SKZn was lower than that under CK at both growth stages, with a significant reduction of 6.56% at maturity. For reproductive organs, SKZn resulted in the highest K concentration in spikes at anthesis. At maturity, SKZn significantly increasing grain K concentration by 28.36% compared with CK, whereas the, inorganic KZn treatment exhibited relatively higher K retention in glumes. Overall, SKZn significantly promoted the targeted accumulation of K in stems (storage pool) and grains (final sink), facilitating more efficient K allocation toward reproductive development.

The Zn distribution pattern differed markedly from that of K among fertilizer treatments. At anthesis, no significant differences were observed in stem Zn concentration among the treatments. However, at maturity, KZn treatment resulted in significantly higher Zn concentrations in stems, leaves, and glumes than both SKZn and CK, indicating pronounced Zn retention in vegetative organs. In comparison, SKZn

exhibited a strong capacity for Zn enrichment in reproductive organs at the early reproductive stage, with spike Zn concentration at anthesis increasing by 28.1% compared with CK. At maturity, both exogenous Zn fertilizer treatments significantly increased grain Zn concentration compared with CK, although no significant difference was observed between KZn and SKZn. These results suggest that the inorganic KZn primarily enhanced overall Zn accumulation within the plant, whereas the chelated SKZn facilitated early Zn enrichment in reproductive organs and promoted subsequent efficient Zn translocation toward the grains.

To further elucidate the source-to-sink translocation patterns of nutrients from anthesis to maturity, the organ-to-organ transport fluxes of K and Zn were quantified (Fig. 7). The results revealed distinct translocation characteristics between the two elements. As the major source organ for K export, stems exhibited a strong tendency for internal K retention. The amount of K retained in stems at maturity reached $15.18 \text{ g plant}^{-1}$, representing the largest K flow within the whole plant. The remaining stem K was primarily remobilized to glumes ($6.05 \text{ g plant}^{-1}$) and grains ($3.45 \text{ g plant}^{-1}$). In contrast, leaf K exhibited limited remobilization capacity after anthesis, with most of the exported K being redistributed to mature stems ($2.38 \text{ g plant}^{-1}$), while its direct contribution to grain K accumulation was only $0.54 \text{ g plant}^{-1}$.

Unlike the relatively conservative retention pattern of K, Zn exhibited a much stronger source-to-sink remobilization capacity. The Zn stored in stems at anthesis was efficiently transported to mature grains, with a translocation flux reaching $14.32 \text{ mg plant}^{-1}$, and its proportion of grain-directed transport was substantially higher than that of K. Meanwhile, the Zn accumulated in spikes at anthesis was preferentially unloaded into grains, reaching $8.74 \text{ mg plant}^{-1}$. Leaf Zn exhibited a bidirectional allocation pattern, with a portion of the Zn remaining in mature leaves ($4.15 \text{ mg plant}^{-1}$) and another portion continuously exported toward grains ($5.63 \text{ mg plant}^{-1}$). The Zn translocation flux analysis demonstrated that pre-anthesis Zn storage possesses a high capacity for subsequent remobilization toward grains, with stems serving as the most critical source organ driving targeted Zn transport and grain Zn enrichment.

Note

Anthesis stem potassium (AStK), Anthesis spike potassium (ASpK), Anthesis leaf potassium (ALK), Anthesis stem zinc (AStZn), Anthesis spike zinc (ASpZn), Anthesis leaf zinc (ALZn), Maturity stem potassium (MSK), Maturity chaff potassium (MCK), Maturity grain potassium (MGK), Maturity leaf potassium (MLK), Maturity stem zinc (MSZn), Maturity chaff zinc (MCZn), Maturity grain zinc (MGZn), Maturity leaf zinc (MLZn)

Rhizosphere soil physicochemical properties and microbial community structure

The different fertilizer treatments significantly altered the nutrient composition and availability of the rhizosphere soils (Fig. 8). Overall, soil pH exhibited relatively minor fluctuations throughout the experimental period and remained within a slightly acidic range under all treatments. Regarding available nutrients, a consistent pattern of nutrient depletion and activation was observed across the two growing seasons. The SKZn treatment significantly enhanced the depletion of soil available K, reducing its content by 21.24% and 32.42% compared with CK in the two consecutive years, respectively. Meanwhile, available P also decreased by 12.78% and 21.02%, respectively. In contrast, SKZn markedly promoted the activation of water-soluble K, increasing its content by 171.66% in the first year and 25.05% in the second year compared with CK. In terms of micronutrient and nitrogen availability, SKZn significantly increased soil available Zn and alkali-hydrolyzable N contents, with increases of 58.26% and 160.18% for available Zn and 24.45% and 9.98% for alkali-hydrolyzable N over the two growing seasons, respectively. The KZn treatment also significantly increased available Zn and alkali-hydrolyzable N contents, with increases of 33.93% and 82.81%, respectively, although the magnitude of improvement was lower than that observed under SKZn. These results indicate that SKZn application not only supplied Zn directly but also stimulated the activation and transformation of major soil nutrients, including N, P, and K, within the rhizosphere. This process was characterized by the accelerated depletion of available K and available P, substantial increases in water-soluble K, and the coordinated enhancement of alkali-hydrolyzable N and available Zn. Although KZn exhibited certain soil improvement effects, its intensity and regulatory scope were weaker than those of SKZn. The consistent patterns observed across two years further confirmed the stability and persistence of the effects induced by sorbitol-chelated K-Zn fertilizer.

At the rhizosphere microbial ecological level, OTU-based sequencing analysis demonstrated that the fertilizer treatments did not significantly alter the overall microbial species richness of the rhizosphere soils (Fig. 9a). The three treatments shared 550 microbial species, accounting for 69.71% of the total species detected, indicating that the fundamental framework of the core microbial community remained relatively stable. However, SKZn exhibited the lowest number of unique microbial species, with total species richness ranked as KZn > CK > SKZn. This suggests that SKZn promoted a more specialized and functionally oriented microbial community assembly. Despite the similarity in overall species richness, principal coordinates analysis (PCoA, Fig. 9b) revealed pronounced differentiation in microbial community spatial structures among the treatments. Samples from CK were highly dispersed, indicating greater sensitivity to stochastic environmental fluctuations. The KZn treatment showed a moderate shift in community structure, whereas the SKZn samples exhibited strong spatial clustering and were clearly separated from the other two treatments. These results confirm that SKZn induced profound systematic restructuring of the rhizosphere microbial community.

At the level of specific microbial composition and species interactions, the dominant bacterial taxa in mature-stage rhizosphere soils exhibited strong directional responses to the different fertilizer forms (Fig. 9c). The major bacterial genera were generally consistent among treatments, mainly including *Arthrobacter*, *Sphingomonas*, and *Bacillus*. However, the relative abundance of these target beneficial functional genera showed a clear increasing gradient among the treatments (CK < KZn < SKZn). The Circos species association network (Fig. 9d) further illustrated this microbial restructuring process.

Under the SKZn application, the dominant beneficial bacterial groups belonging to the phyla *Actinobacteria* and *Proteobacteria* exhibited the highest network connectivity and the widest interaction range. Furthermore, biological replicates showed strong species aggregation, reflecting enhanced community cohesion and structural stability. The KZn treatment displayed intermediate network connectivity, microbial abundance, and stability. In contrast, CK exhibited the lowest proportion of beneficial microbial nodes, the sparsest network connections, and greater compositional variation among replicates, indicating higher sensitivity to environmental disturbances. Collectively, these findings demonstrate that the foliar application of SKZn did not disrupt the fundamental framework of the rhizosphere core microbiome; instead, it optimized the overall microbial ecosystem functionality by selectively enriching beneficial functional taxa and strengthening synergistic interactions among key microbial groups, thereby enhancing the stability of the rhizosphere microbial network.

Multivariate synergistic mechanisms underlying yield and quality formation

By integrating correlation analysis with partial least squares structural equation modeling (PLS-SEM), this study systematically elucidated the intrinsic interactions among soil nutrients, photosynthetic physiology, dry matter accumulation, yield traits, grain quality, and grain mineral nutrition from two analytical perspectives: simple linear associations and multivariate coupling pathways (Fig. 10).

The correlation heatmap clearly illustrated the coordinated variation patterns among the various evaluated indicators. The results revealed that wheat yield components were significantly and positively correlated with post-anthesis dry matter accumulation-related traits. Meanwhile, key grain quality components, including the starch and protein fractions, generally exhibited positive associations with each other, confirming the existence of a strong synergistic enhancement between high yield and improved grain quality. Regarding environmental drivers, labile soil nutrients, particularly water-soluble K and available Zn, exhibited extensive positive coupling relationships with plant dry matter accumulation, grain mineral enrichment, and ultimately, yield and quality-related traits. Only a limited number of indicators showed negative correlations, suggesting an overall coordinated regulatory network among soil nutrient availability, plant physiological performance, and grain formation.

The evaluation of the PLS-SEM model demonstrated that the average variance extracted (AVE) values for all latent variables were strictly greater than 0.5. Furthermore, the core endogenous variables, including yield ($R^2 = 0.995$) and grain quality ($R^2 = 0.904$), exhibited extremely high coefficients of determination, indicating an excellent model fit and robust explanatory power of the constructed multidimensional regulatory network. Path analysis further precisely quantified the causal transmission weights within the system. Regarding the positive regulatory pathways, dry matter weight (0.972), soil nutrients (0.924), grain quality (0.906), and grain mineral elements (0.820) exerted highly significant direct positive driving effects on yield, constituting the primary material and nutritional foundation for yield enhancement. Conversely, within the negative and non-significant pathways, the latent variable representing leaf decline, termed “flag leaf nutritional senescence”, showed a profound limiting effect on crop productivity.

Specifically, it not only exerted a significant direct negative effect on yield (-0.827) but also substantially attenuated grain mineral enrichment (-0.603). Notably, the direct pathway from soil nutrients to flag leaf nutritional senescence was highly significant and negative (-0.852), indicating that an elevated soil nutrient supply effectively counteracted and delayed the leaf senescence process. Furthermore, the model revealed that the direct effect coefficient of microbial communities on yield (0.397) and the direct pathway from soil nutrients to dry matter weight did not reach statistical significance. These findings suggest that microbial communities and soil nutrients regulate yield predominantly through indirect ecological and physiological drivers rather than direct pathways.

Note

Dry matter accumulation post-anthesis (DMAP), Grain dry weight (GDW), Grain potassium accumulation (GKAcc), Grain zinc accumulation (GZnAcc), Gliadin (Gli), Grain potassium concentration (GKC), Grain zinc concentration (GZnC), Grain magnesium concentration (GMgC), Glutenin (Glu), Amylopectin (AP), Amylose (AM), Soil available potassium (SAK), Soil available zinc (SAZn), Water-soluble potassium (WSK), Alkali-hydrolyzable nitrogen (AHN), Spike number (SN), Characteristics of flag leaf nutrition senescence (CFLNS)

Discussion

Core mechanisms underlying yield enhancement in winter wheat

Mechanisms of chelated K-Zn regulating photosynthetic physiology and source-flow-sink coordination for yield improvement

The present study demonstrated that the foliar application of sorbitol-chelated K-Zn fertilizer (SKZn) effectively overcame the physiological constraints limiting yield formation in winter wheat. The central mechanism underlying its yield enhancement can be attributed to the coordinated strengthening of the “source-flow-sink” system. Along the regulatory pathway of “SPAD value → carbon → nitrogen metabolism → dry matter translocation → yield formation”, SKZn altered the developmental and senescence trajectories of flag leaves. The dynamic changes in flag leaf SPAD values, characterized by an initial increase followed by a gradual decline, indicated a clear growth-stage-dependent regulatory effect. Specifically, the formulation primarily enhanced photosynthetic capacity during the early stage (source expansion), maintained functional assimilate output during the middle stage (flow optimization), and drove nutrient unloading toward grains during the late stage (sink strengthening). This process reflects a physiological transition in which plants respond to exogenous nutrient signals by accelerating the orderly shift from source-end assimilation to sink-end translocation (Smith et al. 2018). During the early grain-filling stage, K promotes CO₂ uptake and transpiration pull by regulating stomatal activity

(Wang et al. 2020), whereas adequate Zn availability ensures chlorophyll biosynthesis networks (Çakmak and Kutman 2018). The synergistic function of K and Zn establishes an exceptionally high initial photosynthetic potential (Bashir et al. 2023). More importantly, SKZn exhibited remarkable “stay-green” traits during the middle and late physiological senescence stages. Although plants inevitably undergo senescence as development progresses, this sustained photosynthetic retention effect effectively alleviated the limitation of short nutrient persistence commonly associated with inorganic ion fertilizers, thereby providing continuous assimilate driving force for prolonged grain dry matter accumulation (Li et al. 2020).

The improvement in photosynthetic performance further optimized the carbon – nitrogen metabolic balance in flag leaves. Benefiting from the efficient cuticular penetration and strong tissue affinity of the sorbitol ligand (Fernández and Eichert 2009), SKZn substantially enhanced transmembrane nutrient uptake, thereby promoting foliar nitrogen assimilation, as evidenced by peak total nitrogen contents. Meanwhile, the continuous and efficient transport of photosynthetic carbon assimilates toward the economic sinks (grains) may have prevented metabolic feedback inhibition typically caused by excessive carbon accumulation within the flag leaves. This physiological synergy of “enhanced nitrogen assimilation coupled with efficient carbon export” optimized the leaf C/N ratio and achieved true source–sink metabolic synergy (Liang et al. 2024). In contrast, the unfertilized CK plants experienced premature senescence due to insufficient nutrient availability during the late growth stage, whereas the KZn-treated plants suffered from erratic nutrient acquisition caused by the inefficient absorption of inorganic ions. Both suboptimal conditions resulted in excessive carbon retention and a disrupted carbon – nitrogen balance, thereby restricting the effective long-distance translocation of photosynthetic assimilates into the grains. Building upon this improved source strength and optimized carbon – nitrogen metabolism, SKZn promoted coordinated dry matter accumulation and remobilization, maintaining a superior biomass foundation through to maturity and guaranteeing a continuous supply of assimilates for grain filling. Consequently, this optimized source-flow-sink continuum significantly increased both grain number per spike and thousand-grain weight, leading to a substantial leap in overall crop productivity.

Agronomic robustness of SKZn under contrasting climatic backgrounds and extreme weather conditions

Importantly, the highly efficient physiological buffering system established by SKZn was effective not only under favorable climatic conditions but also exhibited exceptional agronomic robustness under extreme environmental stresses. During the two consecutive experimental seasons, the winter wheat experienced two contrasting climatic scenarios. The 2023–2024 growing season was characterized by relatively suitable hydrothermal conditions, providing a suitable environmental background for high yield formation (Wu et al. 2021). In contrast, the 2022–2023 growing season was subjected to multiple extreme hydrothermal stresses, including waterlogging during sowing, severe low temperatures during overwintering, and late spring frost during the jointing stage, which collectively reduced the effective field population and severely impaired young spike development (Lin et al. 2023; Wu et al. 2024; Chen et al.

2025). Despite these compound environmental stresses, SKZn application still resulted in a remarkable 50.76% increase in grain yield compared with CK in the 2023 growing season. This finding demonstrates that the yield-promoting effect of sorbitol-chelated K-Zn fertilizer is not merely driven by nutrient supplementation; rather, results from the activation of its stress-resilience and stay-green functions under unfavorable environmental conditions (Lotfi et al. 2022). From the perspective of stress physiology, sorbitol ligands function not only as efficient nutrient carriers but also as important osmoprotectants and signaling molecules. Together with K and Zn, they contribute to maintaining guard cell turgor stability and effectively alleviating the stress-induced accumulation of reactive oxygen species (ROS) (Sharma et al. 2019). Therefore, this fertilizer system not only alleviates the nutrient absorption barriers associated with conventional fertilization but also acts as a powerful “physiological buffering system” that counteracts and compensates for the limitations in source-sink development caused by environmental stresses. These field-based findings highlight the critical application potential of sorbitol-chelated fertilizer systems for improving crop resilience under climate variability and ensuring stable and high grain production in future agricultural systems.

A three-tiered mechanisms underlying the improvement of wheat grain quality

To elucidate how the foliar-applied chelated fertilizer enhances wheat grain quality, this study proposes a three-tiered regulatory framework: “K-Zn synergistic transport → source-sink physiological coordination → quality component biosynthesis”. The primary mechanism lies in the ability of the sorbitol-chelated ligand to circumvent the inherent physiological barriers restricting the synergistic uptake and translocation of K and Zn within plants. During nutrient acquisition, conventional inorganic fertilizers (such as KZn) often induce physiological antagonism due to charge competition and interactions among cations (Liu et al. 2023). In contrast, the polyhydroxyl structure of SKZn provides an effective protective environment for nutrient ions. This prevents Zn immobilization and ion antagonism while enabling K and Zn to be simultaneously transported through hydrophilic pathways across the leaf cuticle, thereby promoting the synergistic absorption of both elements (Zhang 1992). The key advantage of this nutrient morphological shift is that it overcomes the classical physiological limitation of poor Zn mobility in the phloem. Chelation converts Zn transport from a predominantly xylem-restricted pathway into a dual transport system involving both xylem and phloem pathways (White and Broadley 2011; Li et al. 2021), thereby achieving synchronized nutrient supply and functional coupling between K and Zn. In comparison, the conventional fertilization (CK) relies mainly on intrinsic soil nutrient availability, which is insufficient to meet the escalating K and Zn requirements of the wheat plants during the late growth stages. The relatively low soil available Zn content restricts grain Zn enrichment, resulting in significantly lower grain Zn concentrations than those achieved with exogenous Zn applications. Meanwhile, the absence of additional K supplementation limits the efficient K remobilization from vegetative organs to the grains, ultimately reducing the overall nutrient utilization efficiency compared with SKZn (Liu et al. 2025; Zhao et al. 2025). Although KZn showed a strong capacity for enhancing Zn uptake and grain Zn enrichment, representing the most effective treatment for increasing grain Zn concentration – its

advantage in Zn accumulation was not accompanied by an equivalent improvement in K transport and source-sink regulation. Consequently, its contribution to yield enhancement remained limited.

Building upon the establishment efficient of K-Zn synergistic uptake and transport, SKZn further translated this nutrient advantage into an optimized source-sink coordination. By maximizing nutrient acquisition, it significantly fortified source-sink relationships during the critical grain-filling period. Specifically, K served as a powerful driver for photosynthetic activity and assimilate transport, (strengthening source capacity), while Zn directly participated in auxin biosynthesis and promoted pollen development and grain formation (expanding the sink establishment) (Cakmak 2007). The functional of K and Zn jointly facilitated photosynthate production and directed the continuous flow of assimilates toward developing grains, consequently driving synchronous increasing in both grain number per spike and thousand-grain weight (Nawaz et al. 2024; Li et al. 2026). The higher dry matter accumulation observed at anthesis established an abundant material foundation for subsequent grain filling. Concurrently, the significantly higher dry matter in stems and leaves, coupled with the minimal decline at maturity, indicated that SKZn preserved vegetative organ functionality during late grain filling, thereby sustaining the assimilate supply and delaying premature senescence. Therefore, the core yield-enhancing mechanism of SKZn can be summarized as “K-driven assimilate transport coupled with Zn-directed grain enrichment”, culminating in efficient source-sink metabolic synergy. These findings substantiate the physiological paradigm that “fertilizer morphology determines nutrient utilization efficiency, which in turn governs yield formation”. Through K-Zn synergistic regulation, SKZn achieved a dynamic equilibrium between vegetative growth and reproductive development-maintaining robust photosynthetic vigor (strong source capacity) while ensuring the efficient partitioning of assimilates toward grains (enhanced sink strength). Furthermore, the chelated formulation exhibited distinct advantages in organ-level nutrient partitioning. The substantial K and Zn accumulation in stems fortified the plant architecture and expanded the nutrient storage pool, whereas the moderate Zn enrichment in leaves avoided nutrient depletion, thereby sustaining cellular photosynthesis and metabolism. Consequently, SKZn promoted the stable accumulation of key grain mineral elements, coordinating the synergistic enrichment of K, Zn, Fe, and Mn while maintaining relatively low phytic acid levels (Gu et al. 2023). Compared with the inorganic fertilizer, the paramount advantage of SKZn lies in its capacity to achieve comprehensive nutritional balance and efficient source-sink coordination via K-Zn synergism, ultimately providing an abundant supply of both photosynthetic assimilates and mineral nutrients for subsequent starch and protein biosynthesis.

This metabolic foundation, characterized by “strong source capacity and efficient sink utilization” – was ultimately translated into the coordinated optimization of starch and protein components. Following the synergistic K-Zn uptake and improved source-sink coordination, the superiority of SKZn was manifested in significant improvements in grain quality. Crucially, the K and Zn co-application did not compromise grain quality; instead, it optimized starch composition to varying degrees. From mineral nutrient accumulation to storage compound synthesis, SKZn continued to exert synergistic effects. The stable small-molecule complexes formed by the sorbitol ligand with K and Zn not only prevented ion antagonism (Han et al. 2025; Fasani et al. 2025) but also facilitated direct entry into mesophyll cells

through hydrophilic pathways in the leaf cuticle. Under these optimized intracellular conditions, the regulatory effects of K on starch biosynthetic enzymes were fully expressed (Zou et al. 2008; Zhang et al. 2025), while the physiological functions of Zn were more effectively integrated into starch metabolic regulation. These findings indicate that the synergistic improvement in starch accumulation and quality optimization induced by the chelated K-Zn formulation originates not only from enhanced nutrient uptake but also from the improved internal coordination of K and Zn transport and metabolic regulation (Waters and Sankaran 2011; Lian et al. 2023; Jin et al. 2025). Consequently, SKZn achieved more pronounced quality enhancement than the inorganic fertilizer, and the consistent differences among the treatments across the two years further confirmed the superiority of this chelated fertilizer paradigm. Importantly, the yield improvement under SKZn was not achieved at the expense of grain quality, demonstrating a true simultaneous enhancement of productivity and quality.

Similarly, driven by the improved nutrient transport efficiency, the two-year results consistently showed that the fertilizer treatments mainly affected the storage proteins responsible for gluten quality, whereas their effects on metabolic proteins were relatively limited or less stable (Shewry and Halford 2002; Xue et al. 2019; Huang et al. 2020; Cao et al. 2024). This pattern aligns with previous studies on wheat grain quality formation. SKZn exhibited the most stable and significant promoting effect on protein quality development by optimizing the protein component composition, improving processing quality, enhancing nutrient utilization efficiency, and strengthening material translocation during grain filling. Therefore, the sorbitol chelated fertilizer treatment provides significant advantages in both nutritional and processing quality through synergistic regulation, representing an effective agronomic strategy for achieving high-quality wheat production.

Rhizosphere microbial restructuring associated with aboveground – belowground feedback regulation

Although the foliar application of chelated K-Zn fertilizer does not directly introduce nutrients into the soil, it activates the aboveground source-flow processes and enhances assimilate production, thereby promoting the transmission of carbon signals from the shoots to the roots. This process synergistically stimulates the dynamics of soil available nutrients and rhizosphere microbial proliferation, amplifying root acquisition and the targeted depletion of major soil nutrients. Consequently, this mechanism ultimately establishes a mutually reinforcing positive feedback loop between the plants and the soil (Li et al. 2022; Du et al. 2023).

This systemic regulatory effect profoundly manifested as a dynamic “selective depletion and activation” of rhizosphere nutrients. Specifically, the SKZn application drove significant reductions in rhizosphere available K and available P, alongside concurrent surges in water-soluble K and available Zn. Rather than indicating soil nutrient exhaustion or elemental antagonism, this divergent dynamic provides compelling evidence of a robust “sink-pulling effect” initiated by chelated formulation. As SKZn maximized aboveground photosynthetic capacity and assimilate partitioning, the resulting amplified sink strength exerted a powerful demand on the root system, accelerating the uptake of available K and P from the

rhizosphere (Broadley et al. 2007; Richardson et al. 2011). Simultaneously, this heightened aboveground physiological vigor stimulated root exudation—such as organic acids and secondary metabolites—which enhanced the activation capacity of the rhizosphere and subsequently elevated water-soluble K levels (Meena et al. 2016). Coupled with Zn-mediated improvements in root architectural traits, SKZn established a highly efficient nutrient-acquisition loop. In stark contrast, the inorganic KZn treatment acted merely as a passive foliar supplement, failing to ignite this deep “activation-uptake” cycle, while the unfertilized (CK) exhibited a completely stagnant plant – soil feedback system.

Changes in soil nutrient availability further reshaped the rhizosphere microbial communities through plant-mediated processes, particularly via root exudate regulation. Venn diagram analysis and microbial diversity assessment demonstrated that the core microbiomes of the three treatments were highly overlapping. However, SKZn exhibited the lowest number of unique microbial taxa. This suggests that this treatment did not simply increase microbial species richness but instead reduced ineffective “diversity redundancy” under natural conditions, promoting a more functionally specialized and selectively assembled microbial community. Regarding key microbial responses, SKZn selectively enriched three groups of beneficial functional bacteria, including *Arthrobacter*, *Sphingomonas*, and *Bacillus* (Sasse et al. 2018). The improvement in plant photosynthetic performance and soil available Zn status jointly promoted the release of carbon-rich root exudates (Sharma et al. 2021; Chen et al. 2024), providing abundant metabolic substrates for these functional microbial groups. Among them, *Arthrobacter* possesses strong capabilities for utilizing recalcitrant carbon sources and exhibits relatively high Zn requirements, giving it a competitive advantage in the SKZn-treated soils with enhanced Zn availability (Shen et al. 2021). *Sphingomonas* is highly responsive to improved plant nutritional status and can proliferate under rhizosphere conditions associated with delayed root senescence. Meanwhile, primary metabolites such as polysaccharides and organic acids directly stimulate the colonization and proliferation of *Bacillus*. This plant – microbe interaction-mediated selective recruitment resulted in a microbial community functionally oriented toward nutrient cycling and plant health maintenance, thereby achieving structural optimization of microbial functions (Yang et al. 2024). Principal coordinates analysis (PCoA) and Circos association network analysis further demonstrated that SKZn not only significantly altered the microbial community distribution patterns but also enhanced the network connectivity and within-group stability of beneficial microbial networks dominated by the phyla *Actinobacteria* and *Proteobacteria*. From an ecological perspective, this restructuring process demonstrates that sorbitol-chelated nutrients exert effects far beyond improving nutrient uptake at the plant cellular level. More importantly, they modify rhizosphere ecological selection pressures and establish a stable, efficient, and continuously functioning soil microbial support system through aboveground-to-belowground regulatory feedback.

System-level mechanisms underlying the coordinated enhancement of yield and grain quality by sorbitol-chelated K-Zn fertilizer

A major challenge in conventional agricultural production is the inherent trade-off between high yield and superior grain quality. However, the correlation analysis and PLS-SEM results in this study demonstrated that the application of sorbitol-chelated K-Zn fertilizer (SKZn) successfully overcame this constraint by establishing a strong positive coupling network between yield formation and grain quality improvement. According to the regulatory pathways revealed by the model, SKZn sustained elevated SPAD values, delayed flag leaf senescence, and optimized carbon – nitrogen metabolism, thereby allowing the wheat plants to maintain vigorous photosynthetic capacity deep into the late grain-filling stage. More importantly, sorbitol functions as an affinity-based nutrient transport carrier that effectively neutralizes charge competition and antagonistic interactions between inorganic K^+ and Zn^{2+} during transmembrane uptake. This unobstructed dual-channel synergistic transport system drove the coordinated accumulation of K and Zn within the developing grains. Ultimately, this synergy not only provided an abundant supply of carbon substrates for sustained starch biosynthesis but also delivered the essential metallic cofactors required for the activation of multienzyme systems. As validated by our structural equations, this optimized dry matter dynamics and targeted mineral translocation constituted the foundational drivers for the simultaneous enhancement of wheat yield and grain quality (Sun et al. 2024; Zhang et al. 2025).

The cross-domain network analysis further revealed an apparently counterintuitive statistical relationship: residual soil available K showed significant negative correlations with yield, thousand-grain weight, and amylose and amylopectin contents. This finding does not contradict the conventional agronomic assumption that higher soil nutrient availability promotes greater yield; instead, it reflects the consequence of enhanced nutrient utilization efficiency by the plants. Under the SKZn application, the strengthened aboveground sink capacity stimulated the root uptake and translocation of K and Zn, resulting in massive transfer of available soil K into plant tissues and grains, thereby causing an apparent reduction in residual soil available K at maturity. Meanwhile, the significant positive correlations between water-soluble K and yield- and quality-related traits further indicate that crop productivity is determined not by the absolute amount of residual soil nutrients, but rather by the dynamic turnover capacity of rhizosphere nutrients and the actual nutrient acquisition and utilization efficiency of the plants. Furthermore, targeted foliar supplementation with chelated Zn effectively avoided the potential negative effects associated with excessive soil-applied Zn, such as the inhibition of carbon metabolic enzymes and chlorophyll degradation. This represents a distinctive advantage of the foliar sorbitol-chelated K-Zn fertilizer compared with conventional soil-based Zn fertilization. Regarding microbial-mediated regulatory pathways, the PLS-SEM model indicated that the direct contribution of microbial communities to yield formation was relatively weak, suggesting that their regulatory functions primarily operate through indirect ecological support mechanisms (Berendsen et al. 2012). The SKZn-induced enrichment of carbon-rich root exudates selectively recruited beneficial microbial groups, such as the phylum *Actinobacteria*. These plant growth-promoting microorganisms can accelerate the decomposition of recalcitrant organic matter and nutrient mineralization, optimize the rhizosphere microenvironment (Philippot et al. 2013), and indirectly enhance plant growth through improved nutrient cycling efficiency (Trivedi et al. 2020). Furthermore, certain targeted microbial taxa can regulate endogenous hormone

balance, thereby strengthening plant stress resistance and root activity (Ait Barka et al. 2016). Therefore, the microbial communities mainly function by optimizing soil nutrient cycling processes and maintaining rhizosphere ecological stability, ultimately providing continuous ecological support for nutrient acquisition during the later growth stages (Muller et al. 2016).

In summary, the correlation analysis and PLS-SEM results jointly delineated a comprehensive causal framework linking physiological regulation with the coordinated enhancement of yield and grain quality. Overall, the foliar application of the sorbitol-chelated K-Zn fertilizer, leveraging the advantages of small-molecule chelation, effectively mitigated ionic antagonism and enhanced nutrient bioavailability. Through an integrated regulatory network characterized by “soil nutrient activation → efficient photosynthate transport → synergistic grain K and Zn enrichment → rhizosphere microbial optimization”, SKZn precisely fulfilled the high nutrient demands of the wheat plants during the critical grain-filling stage, ultimately achieving the simultaneous optimization of grain yield and nutritional quality.

Conclusions

This study demonstrated that foliar application of sorbitol-chelated K-Zn (SKZn) can systematically overcome the physiological constraints limiting the simultaneous improvement of yield and grain quality in winter wheat. The key advantage of this chelated formulation lies in its ability to transcend the limitations of conventional inorganic fertilizers, which primarily provide passive nutrient supplementation. Driven by fertilizer morphological innovation, SKZn synergistically enhanced the plant “source-flow-sink” system and established beneficial feedback interactions with the rhizosphere microbial ecosystem.

At the physiological and metabolic levels, SKZn strengthened the photosynthetic “source” by delaying flag leaf senescence. Meanwhile, the superior transmembrane absorption and phloem mobility of the chelated nutrient molecules facilitated the coordinated transport of K, Zn, and assimilates toward the reproductive organs, thereby optimizing the “flow” process. This ultimately expanded the “sink” capacity of the grains by promoting the accumulation of starch and storage proteins. At the ecological feedback level, this highly efficient aboveground nutrient translocation induced a strong root-mediated “sink-pulling effect”, which not only activated major nutrient pools in the rhizosphere but also selectively enriched beneficial plant growth-promoting microbial groups, including *Sphingomonas* and *Arthrobacter*. This process established an efficient aboveground – belowground positive feedback loop that effectively bypassed the major limitations of inorganic K-Zn fertilizers, namely low nutrient uptake efficiency and severe ionic antagonism.

In conclusion, the sorbitol-chelated K-Zn paradigm enabled simultaneous improvements in winter wheat yield and grain quality while achieving superior agronomic and economic benefits, characterized by a lower cost per unit of yield increase and higher net economic returns. This technology provides a highly viable and efficient nutrient management strategy for wheat production systems constrained by K and

Zn limitations in China and globally. Future studies should further evaluate the agronomic robustness of this fertilizer system across diverse soil textures and under compound extreme climate scenarios.

Declarations

The authors declare that they have no known competing financial interests or non-financial interests that could have appeared to influence the work reported in this paper.

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Author contributions

Ma Zongbin: Writing – original draft, Formal analysis, Data curation, Visualization. Zhang Jing: Investigation, Experiment operation, Sample testing, Data curation. Liu Shichang: Auxiliary experimental operation and resource assistance. Wang Fei: Investigation, Partial data collection, Preliminary statistical analysis. Gao Zhi'en: Sample pretreatment, Laboratory assay, Sorting of experimental raw data. Wang Guangxin: Drawing of partial figures and tables, Literature collation and sorting. Zhang Niancheng: Field management and daily maintenance of experimental materials. Ma Houguang: Preliminary data verification and manuscript format polishing. Wang Xiaocui: Methodology and technical guidance. Liu Kezhong: Scientific interpretation and quality control of papers. Huang Mingli: Guidance on research plans and experimental systems. Yan Dongyun: Responsible for research conception and overall design, project management and resource coordination, financial support, as well as comprehensive academic review of research results and paper quality.

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Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

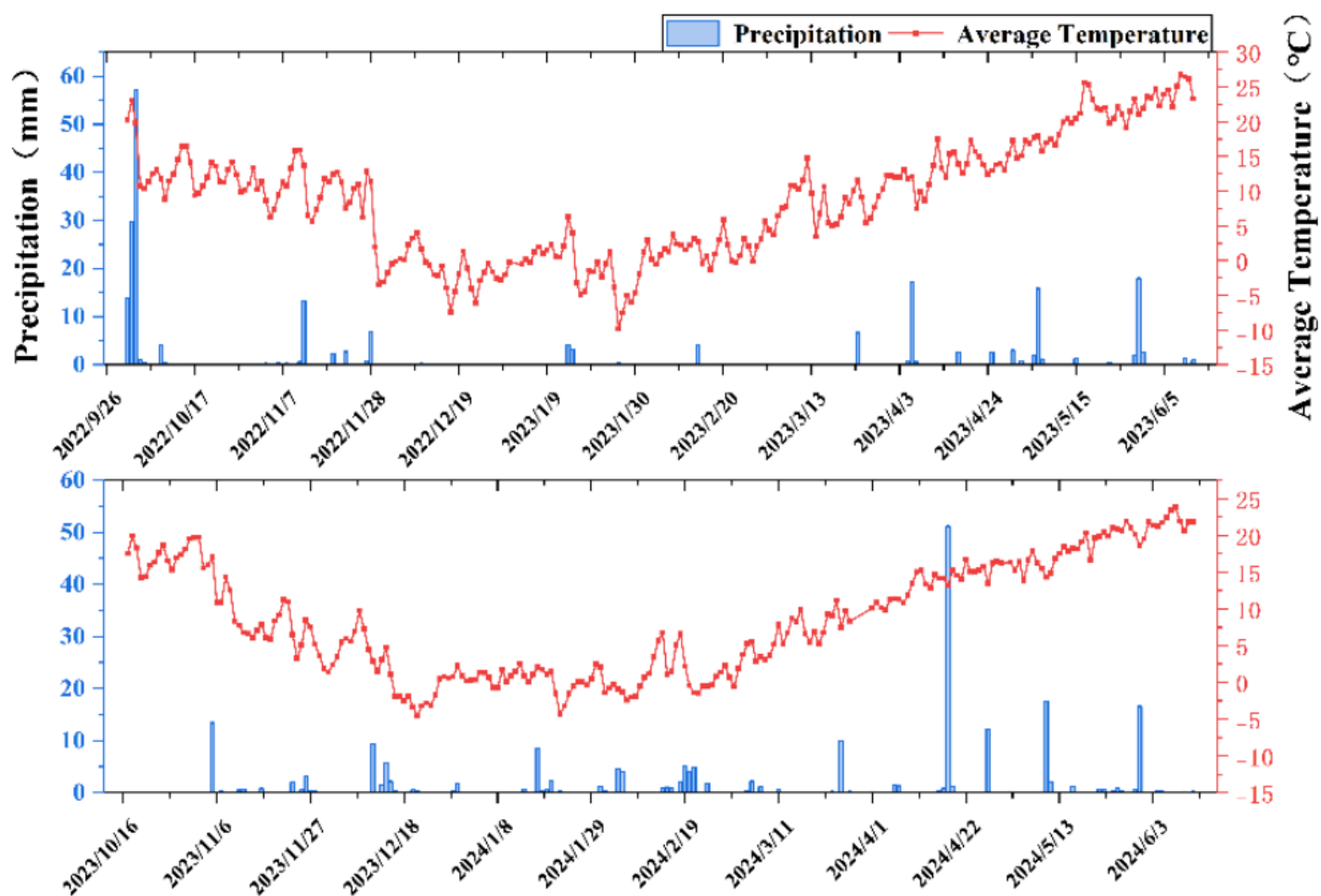


Figure 1

Daily mean temperature and cumulative rainfall throughout the two-year winter wheat growing season

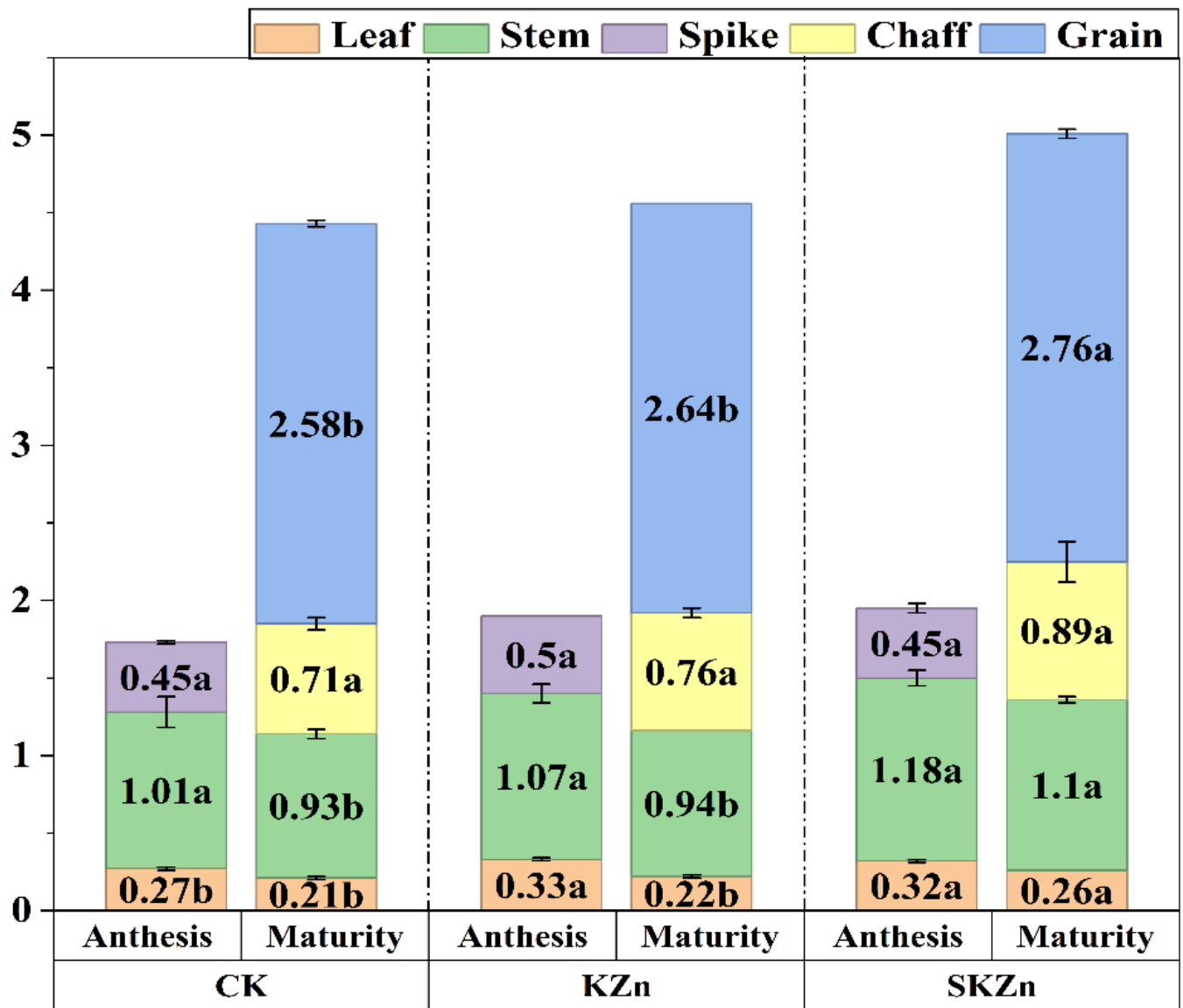


Figure 2

Dry matter weight accumulation and partitioning of various plant organs in wheat (2024)

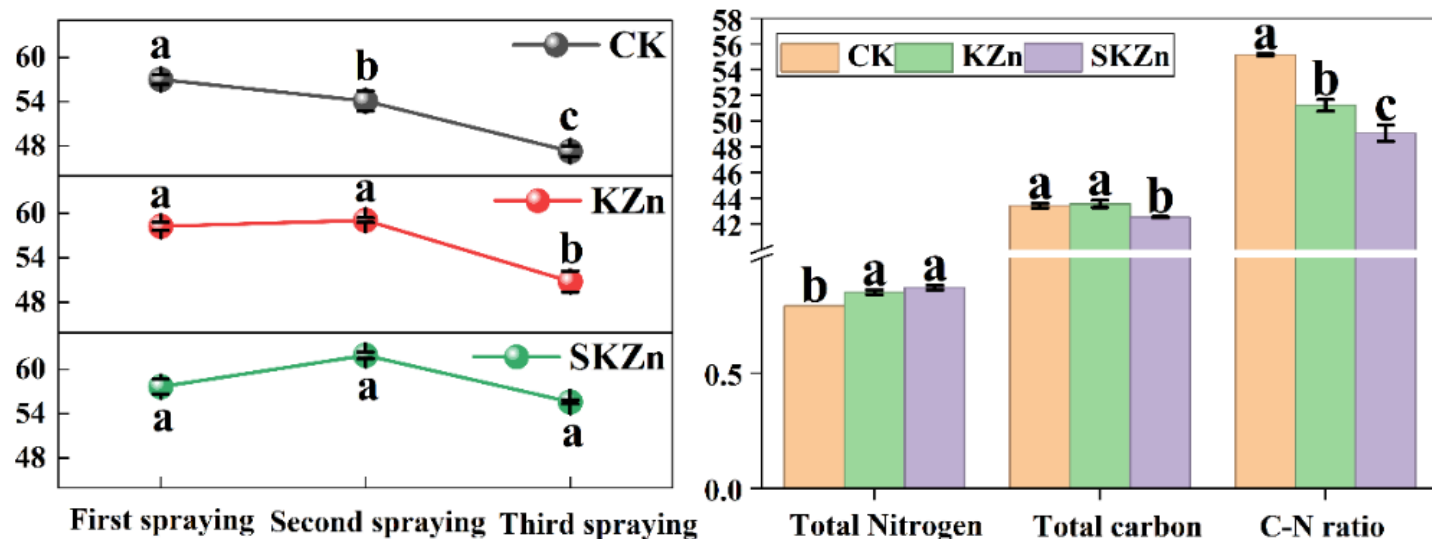


Figure 3
 Flag leaf SPAD value recorded one week after each of the three foliar applications (left), and total carbon and nitrogen contents in flag leaves at maturity (right)

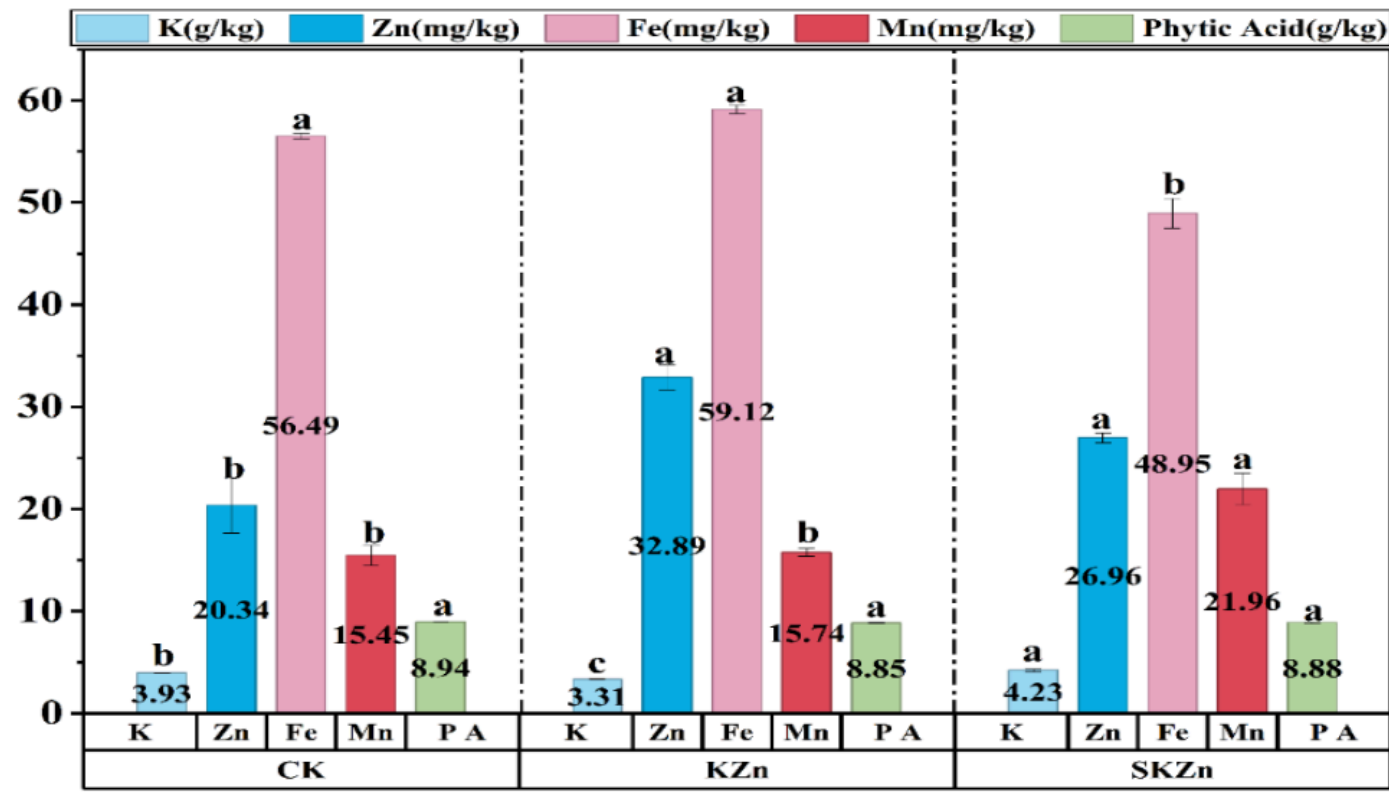


Figure 4
 Mineral element contents in grains in the 2024 growing season

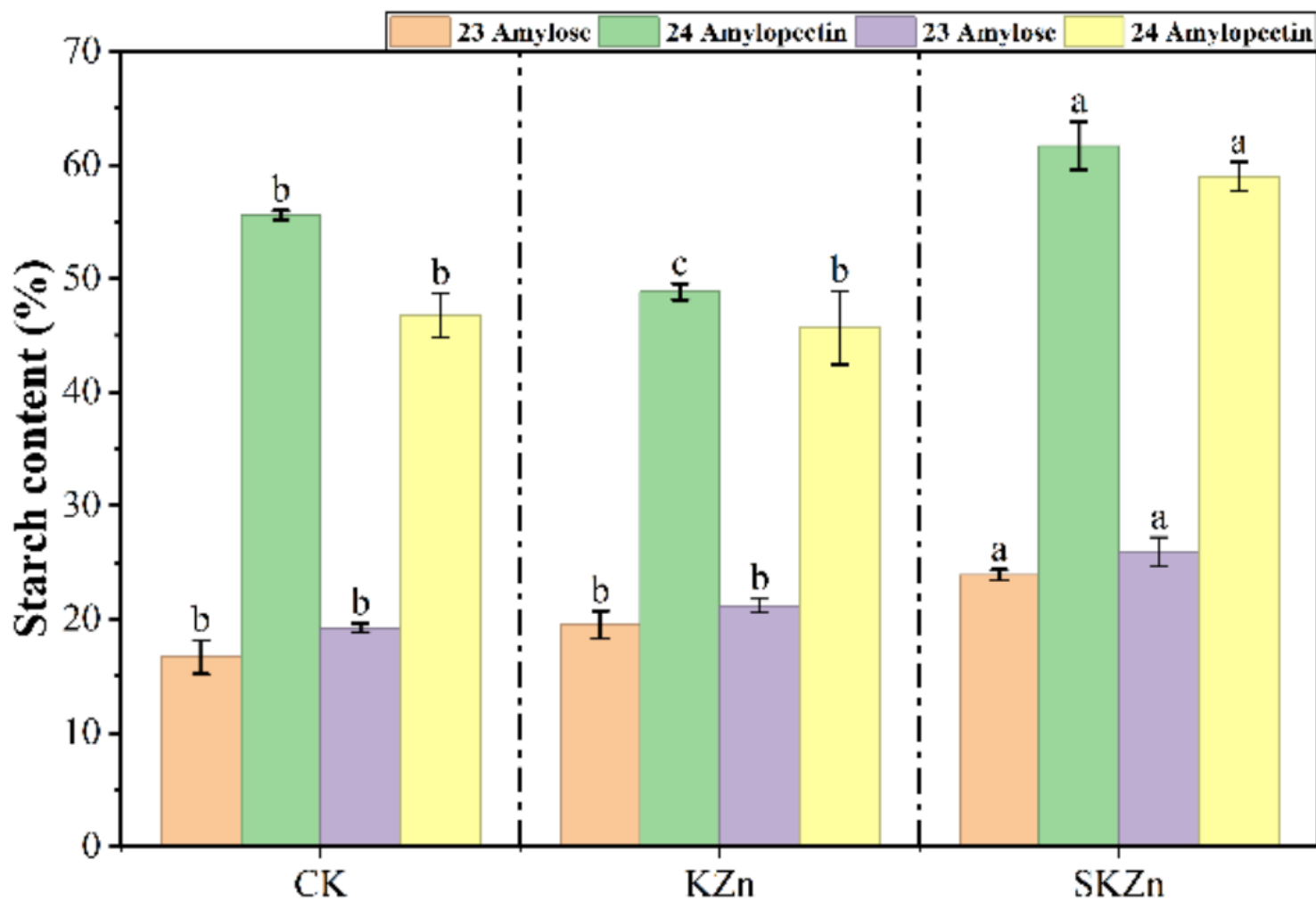


Figure 5

Starch component contents of grains across the two growing seasons

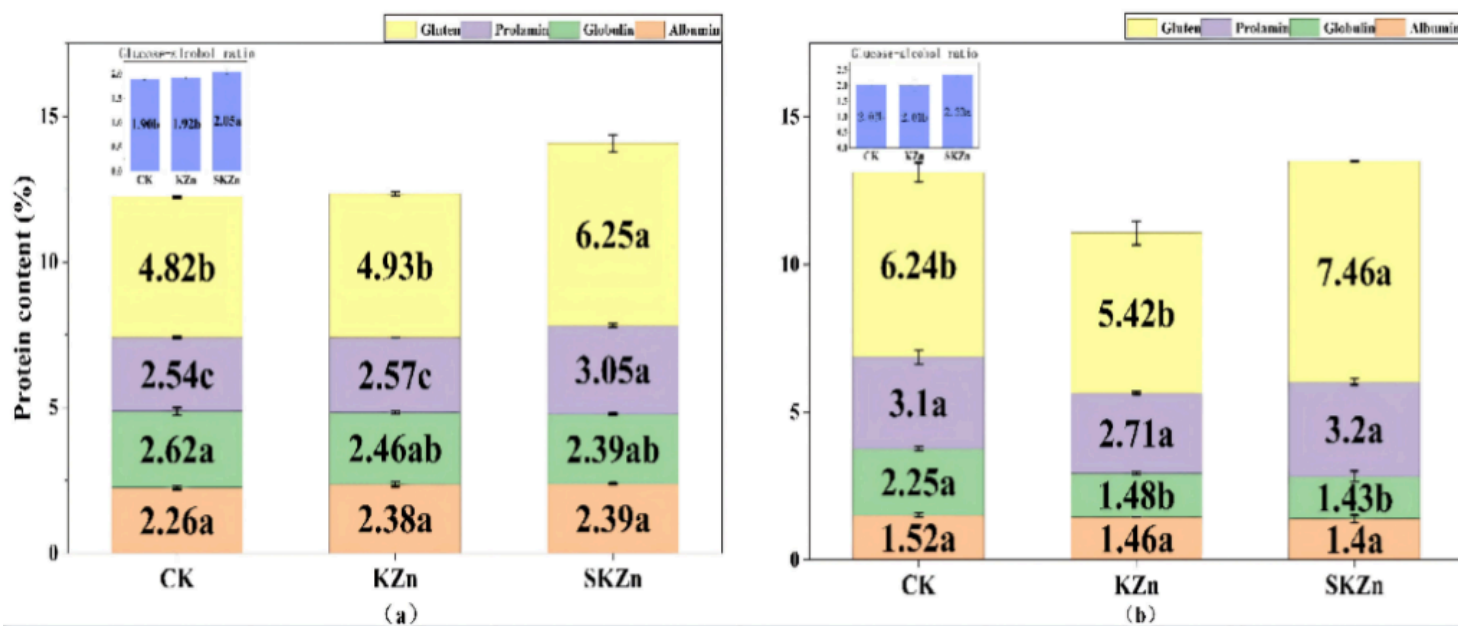


Figure 6

Protein component contents of wheat grains across the two growing seasons

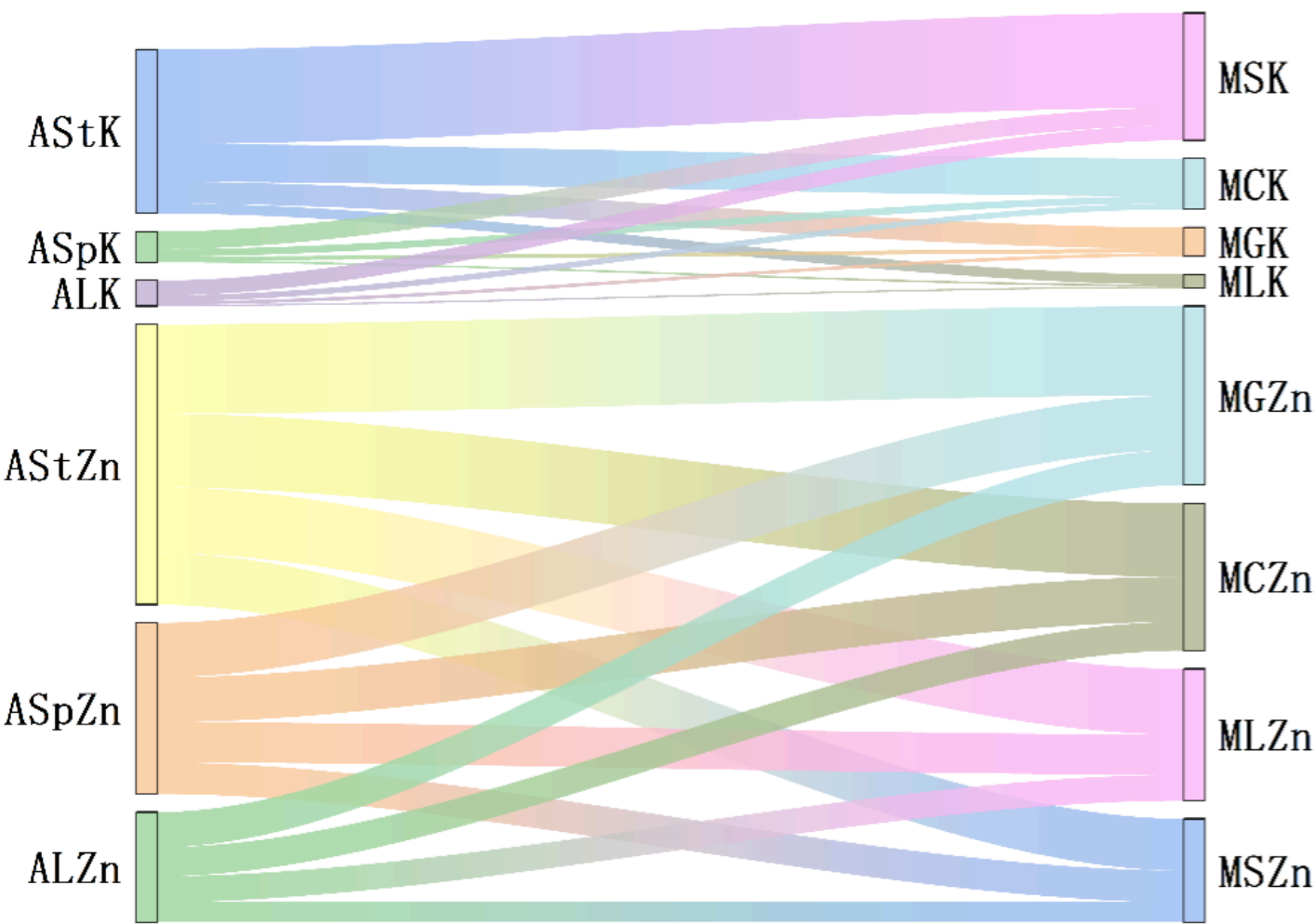


Figure 7

Sankey diagram of K and Zn contents in various organs at different growth stages

Note: Anthesis stem potassium (AS_tK), Anthesis spike potassium (AS_pK), Anthesis leaf potassium (AL_K), Anthesis stem zinc (AS_tZn), Anthesis spike zinc (AS_pZn), Anthesis leaf zinc (AL_{Zn}), Maturity stem potassium (MSK), Maturity chaff potassium (MCK), Maturity grain potassium (MGK), Maturity leaf potassium (MLK), Maturity stem zinc (MSZ_n), Maturity chaff zinc (MCZ_n), Maturity grain zinc (MGZ_n), Maturity leaf zinc (MLZ_n)

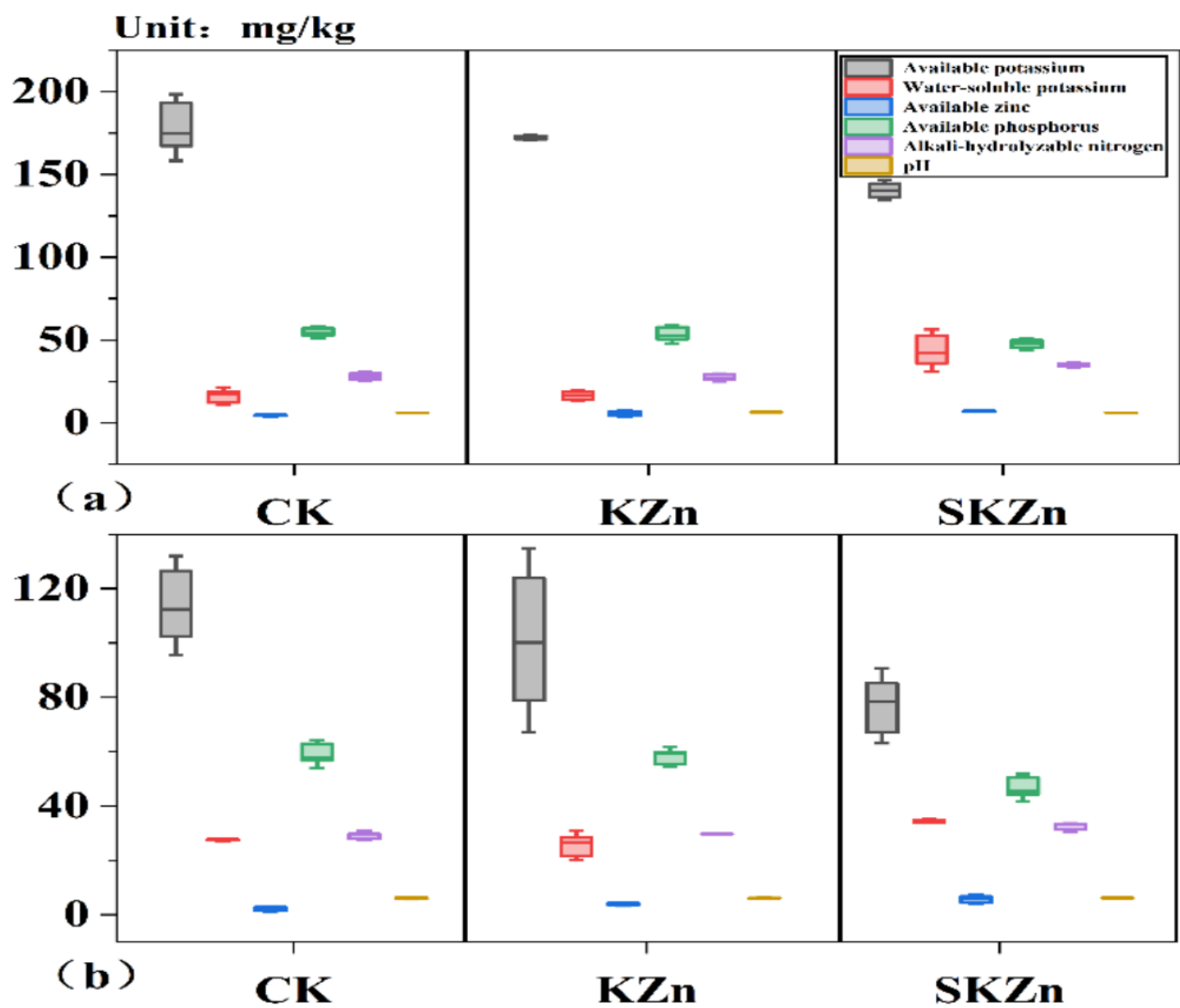


Figure 8

Soil physicochemical properties across two growing seasons

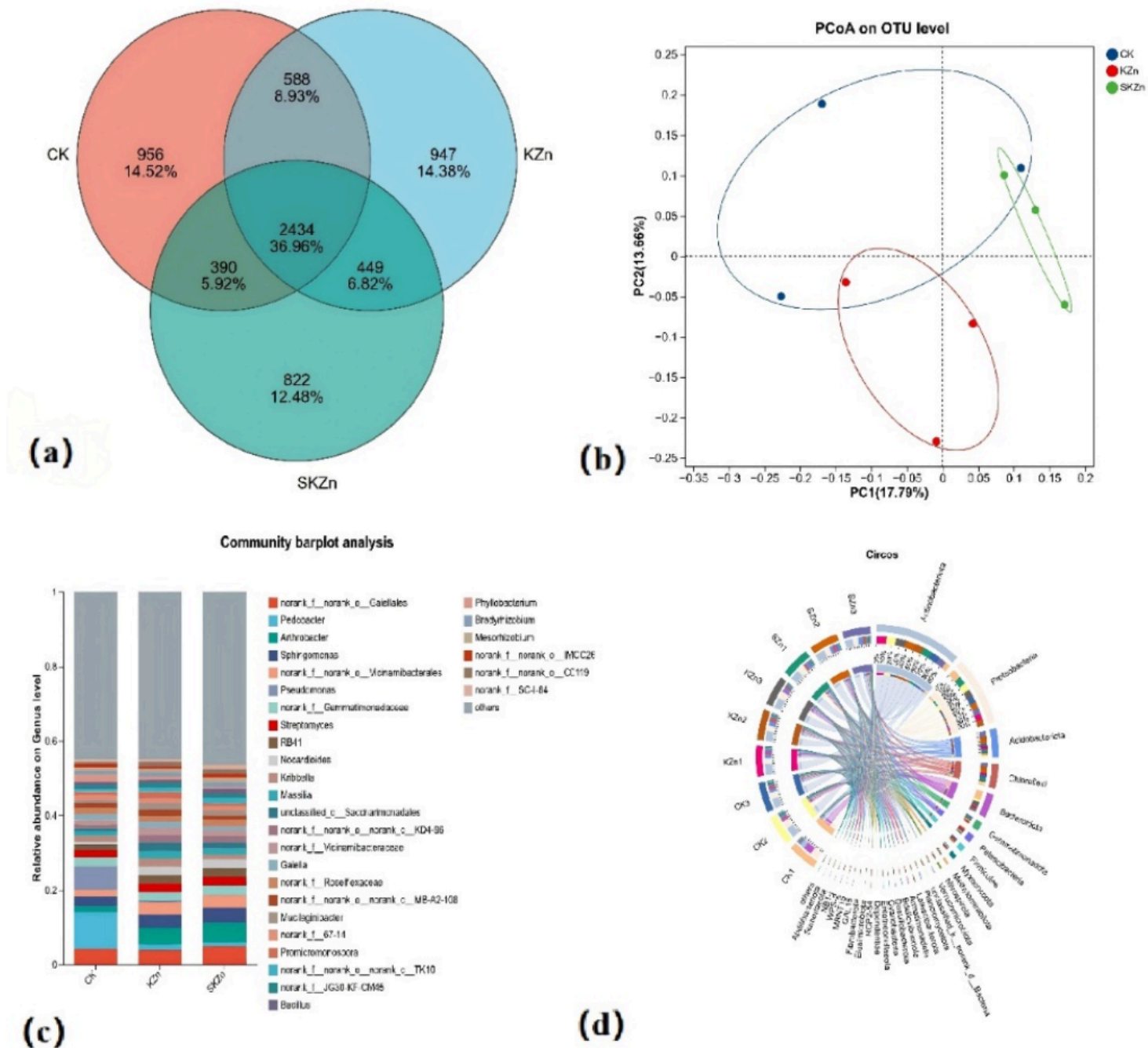


Figure 9

Venn diagram of shared and unique OTUs (a), principal coordinates analysis (PCoA) scatterplot of microbial communities (b), bacterial community composition at the genus level (c), and Circos diagram illustrating sample-species associations (d)

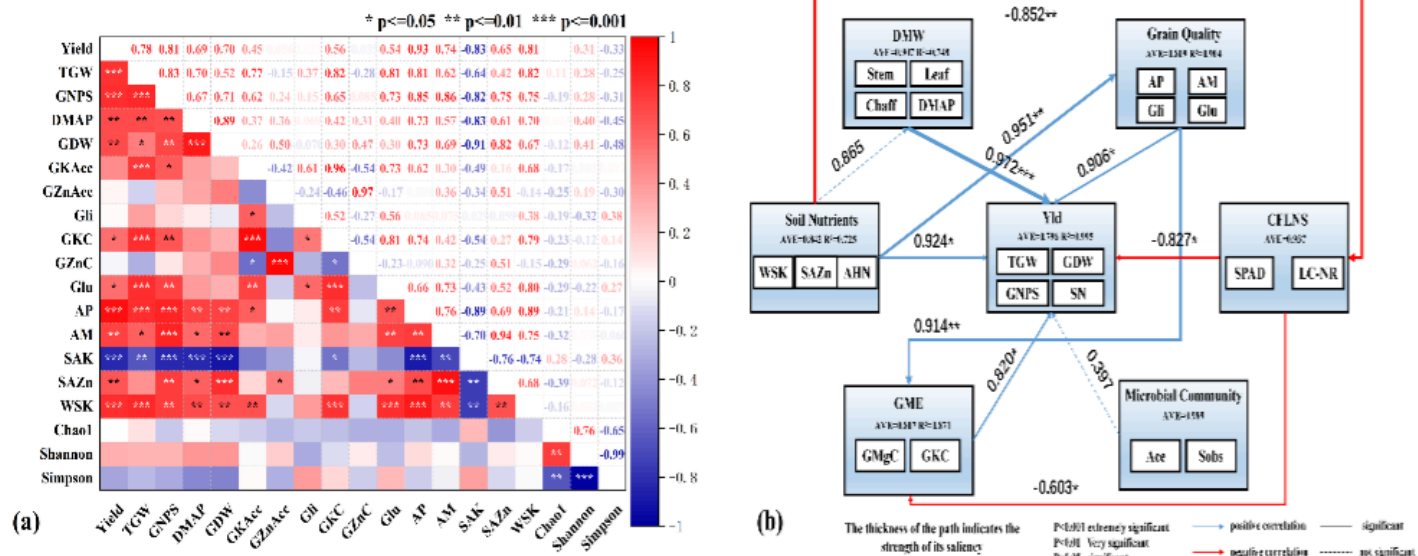


Figure 10

Correlation heatmap of intrinsic mechanism (a) and the partial least squares structural equation modeling (PLS-SEM) framework (b)

Note: Dry matter accumulation post-anthesis (DMAP), Grain dry weight (GDW), Grain potassium accumulation (GKAcc), Grain zinc accumulation (GZnAcc), Gliadin (Gli), Grain potassium concentration (GKC), Grain zinc concentration (GZnC), Grain magnesium concentration (GMgC), Glutenin (Glu), Amylopectin (AP), Amylose (AM), Soil available potassium (SAK), Soil available zinc (SAZn), Water-soluble potassium (WSK), Alkali-hydrolyzable nitrogen (AHN), Spike number (SN), Characteristics of flag leaf nutrition senescence (CFLNS)