Effects of Water Deficit on Mineral Element Uptake, Distribution, and Water Use in Different Wheat Cultivars: Postprint

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Abstract

Against the backdrop of limiting wheat irrigation areas, this study investigated the effects of water deficit on mineral element absorption and distribution characteristics and their relationships with plant water use and yield in different wheat varieties in North China. Three ecotypic winter wheat varieties were selected (drought-resistant variety ‘Cangmai 6001’ , high-yield variety under well-watered conditions ‘Hanmai 9’, and multi-resistant super high-yield variety ‘Jimai 22’), and controlled environment chamber box cultivation experiments were conducted under two water levels (normal and water deficit). The study primarily examined changes in mineral element content, accumulation, and distribution ratios in different wheat organs, as well as the effects of mineral element variations on water use efficiency and yield. The results demonstrated that mineral element content and distribution exhibited organ specificity, with the highest content and distribution ratios observed for Ca in leaves, Cu and Zn in grains, and Na in stems. Fe content, accumulation, and distribution ratios varied depending on variety, organ, and water conditions: under normal water conditions, ‘Cangmai 6001’ showed the highest Fe content and distribution ratio in stems, ‘Hanmai 9’ in leaves, while ‘Jimai 22’ exhibited higher Fe content in stems and glumes, and higher Fe distribution ratios in leaves and glumes. Under water deficit conditions, Fe content was highest in grains for ‘Cangmai 6001’ and ‘Hanmai 9’ , and highest in leaves for ‘Jimai 22’ ; all three varieties showed the highest Fe distribution ratio in grains. Additionally, water deficit increased grain Cu and Zn content and distribution ratios, as well as grain Zn, Na, and Ca accumulation, and significantly enhanced water use efficiency and yield in ‘Cangmai 6001’ and yield water use efficiency in ‘Jimai 22’ . Conversely, it reduced grain Mn accumulation in ‘Cangmai 6001’ , grain Cu and Mn accumulation in ‘Hanmai 9’ , grain Cu and Fe accumulation in ‘Jimai 22’ , as well as water use efficiency, dry matter weight, and yield in ‘Hanmai 9’ .

In summary, under water deficit conditions, ‘Cangmai 6001’ was more likely to achieve high yield and high efficiency, with increased grain Fe content, but required Mn supplementation; ‘Jimai 22’ showed increased water use efficiency with no significant yield reduction, but needed Fe supplementation to ensure quality; ‘Hanmai 9’ experienced significant declines in both yield and water use efficiency, with notable reductions in grain Cu and Mn accumulation. Correlation analysis indicated that Cu, Zn, Ca, and Mn contents exhibited certain mutual regulatory effects with dry matter weight changes, but did not directly affect yield and water use efficiency, which may be related to inter-varietal differences and variety-water interaction effects. However, a trend exists whereby mineral elements may indirectly regulate water use efficiency through their effects on dry matter weight, which requires further investigation and validation.

Full Text

Effect of Water Deficit on Mineral Element Absorption, Distribution, and Water Utilization by Different Wheat Varieties

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Abstract: In the context of limiting wheat irrigation area, it is necessary to promote resource use efficiency, increase yield, and improve wheat quality by exploring nutrient absorption and utilization patterns and water use efficiency under water deficit conditions. Pot experiments were conducted in phytotrons with three wheat varieties under two water conditions (normal and deficit). The three wheat varieties included ‘Cangmai-6001’ (drought-resistant), ‘Hanmai-9’ (high-yielding under adequate water), and ‘Jimai-22’ (multi-resistant and super high-yielding). The content, accumulation, and distribution of mineral elements in different plant organs were measured, and the relationships between these indices and water use efficiency and yield were analyzed. The results showed that mineral element contents and accumulation were organ-specific. The highest content and distribution ratio of Ca were observed in leaves, those of Cu and Zn in grains, and Na in stems. Fe accumulation in different organs was influenced by water conditions and variety. Under normal water conditions, the highest Fe content and distribution ratio were in the stem of ‘Cangmai-6001’ and in the leaf of ‘Hanmai-9’ . For ‘Jimai-22’ , Fe content was higher in stems and glumes, while Fe distribution ratio was higher in leaves and glumes. Under water deficit conditions, Fe content was highest in grains for ‘Cangmai-6001’ and ‘Hanmai-9’ , but highest in leaves for ‘Jimai-22’ . For all investigated varieties, the highest Fe distribution was in grains. Water deficit increased the distribution of Cu and Zn, and the accumulation of Zn, Na, and Ca in grains, as well as water use efficiency and yield for ‘Cangmai-6001’ , and WUEyield for ‘Jimai-22’ . However, water deficit decreased Mn accumulation in grains of ‘Cangmai-6001’ , Cu and Mn accumulation in grains of ‘Hanmai-9’ , Cu and Fe accumulation in grains of ‘Jimai-22’ , and water use efficiency, dry matter weight, and yield of ‘Hanmai-9’ . Overall, ‘Cangmai-6001’ was more beneficial in terms of yield increase with higher WUE, higher Fe accumulation in grain, and supplemented Mn element under water deficit condition. ‘Jimai-22’ had stable yield with increasing WUE and supplemented Fe element in grain under water deficit condition. For ‘Hanmai-9’ variety, yield, WUE, Cu and Mn accumulation in grain decreased obviously under water deficit condition. Correlation analysis indicated that Cu, Zn, Ca, and Mn had significant interactions with dry matter, with no direct effect on yield and WUE. This was related to differences in variety and interaction effects of variety and water. There was still the tendency for mineral elements to regulate water utilization by influencing wheat dry matter formation, which needed further research and verification.

Keywords: Wheat; Ecological type; Water deficit; Mineral element; Yield; Distribution ratio of organ; Water use efficiency

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Introduction

Water scarcity is a key factor limiting wheat (Triticum aestivum L.) production and yield improvement in North China. Soil mineral elements must dissolve in water to be absorbed by crops in ionic form, participating in various metabolic and physiological-biochemical processes and playing a regulatory role in plant water balance [1-2]. Understanding the content of different nutrient elements in wheat plants, their absorption and utilization patterns in different organs, and their effects on plant water use under different water conditions is crucial for promoting efficient resource utilization, ensuring wheat yield, and improving wheat quality [3].

Previous studies have shown that insufficient external water can alter ion distribution in soil, affect ion transport, and induce crops to accumulate large amounts of Na, Ca, and other ions to reduce intracellular water potential [4-5]. Supplementing certain mineral elements (K and Ca) can alleviate the adverse effects of stress on plant growth and enhance plant tolerance [6]. Similarly, changes in mineral elements under drought stress can affect plant water balance and drought resistance regulation to a certain extent [7-9]. Na salt ions in desert soils can improve plant water retention and increase water use efficiency [9]. Of course, different drought severity leads to different degrees of plant impact: moderate drought can increase Cu, Mn, Fe, Zn, and Ca contents in wheat seedlings, thereby regulating plant drought resistance; however, excessive drought reduces the content of each element and disrupts water balance [9-12].

Currently, in response to long-term water scarcity in the North China wheat region and against the backdrop of limiting wheat irrigation water, maintaining high wheat productivity in Hebei Province requires comprehensive consideration of improving water use efficiency and pursuing a development path of water-saving, stable yield, and high quality. However, systematic reports on the characteristics of mineral element absorption and utilization by different ecological types of wheat varieties in this region and their relationship with water use efficiency are scarce. This study used a large phytotron to simulate natural climate conditions and established two water conditions (normal and deficit) to investigate the regionalized distribution and accumulation of major mineral elements involved in water regulation in three different wheat varieties, and to conduct correlation analysis with dry matter weight, yield, and water use efficiency. The objective was to provide theoretical references for further regulating nutrient fertilizer application, increasing beneficial elements for human health, reducing harmful elements, and improving resource use efficiency in water-saving wheat cultivation in North China.

Materials and Methods

1.1 Experimental Design

Three ecologically adapted winter wheat varieties were selected: 'Cangmai-6001' (Cangmai-6001), a winter-type, drought-resistant variety bred by Cangzhou Academy of Agricultural Sciences, Hebei Province, and approved by the Hebei Provincial Variety Approval Committee in 1998; 'Hanmai-9' (Hanmai-9), a high-yielding variety under adequate water conditions bred by Handan Academy of Agricultural Sciences, Hebei Province, and approved in 2003; and 'Jimai-22' (Jimai-22), a super high-yielding, multi-resistant variety bred by Shandong Academy of Agricultural Sciences and approved for the North Yellow-Huai River region in 2007.

The experiment was conducted at Hebei Agricultural University in 2015. Independent, self-controlled phytotrons capable of regulating light, temperature, air humidity, and CO2 concentration were used, with environmental data automatically controlled and recorded by a computer system. During the vernalization stage, day/night temperatures were set at 20°C with a 12 h/12 h cycle (6:00-18:00). During the regreening and later growth stages, day/night duration was set at 14 h/10 h, with light intensity of 28,000-30,000 lx, day/night temperatures of 25°C/16°C, and relative humidity of 60%.

Soil culture was conducted in storage boxes (55 cm × 41 cm × 36 cm, length × width × height). Soil was collected from the 0–20 cm surface layer of farmland, air-dried, crushed, mixed, and packed into boxes. Each box contained 73.5 kg of dry soil, to which 18 L of tap water was added. Basal fertilizer application consisted of 5.86 g diammonium phosphate, 7.5 g urea, and 11.8 g potassium sulfate (50%). After reaching 75% relative water content, the soil layer was manually broken and turned to a depth of 15 cm using a small shovel. Sowing was conducted on March 28, with three rows per box and row spacing of 10 cm.

From the wheat spike differentiation stage to maturity harvest, two water treatments were established: normal water (CK) and water deficit (D), controlled using the weighing method. For the normal water treatment, each box was watered to 91.5 kg, with a lower limit of 86.0 kg, corresponding to a relative water content range of 60%-80%. For the deficit treatment, boxes were watered to 86.0 kg (relative water content of 40%-60%), with a deficit irrigation amount of 24.39 mm. Each treatment had three replicates. The dynamic water consumption during the wheat growth period is shown in [Figure 1: see original paper]. Total water consumption (mm) and water use efficiency were calculated following Liu et al. [13] as:

Total water consumption (mm) = Σwater replenishment + (initial weight - final weight) (1)

Yield water use efficiency (WUEyield, kg · m ^{3}) = Yield (g · m ^{2}) / Total water consumption (mm) (2)

Biomass water use efficiency (WUEbiomass, kg · m ^{3}) = Aboveground total dry weight (g · m ^{2}) / Total water consumption (mm) (3)

1.2 Sampling and Measurements

1.2.1 Dry Matter and Yield At wheat maturity, 10 plants were harvested from each treatment, threshed after drying, and average grain yield was calculated based on box area. Another approximately 10 plants were randomly selected, roots were cut off, and aboveground parts were retained. Samples were killed at 105°C for 30 min, then dried at 65°C to constant weight, separated into four parts (leaf, stem, glume, and grain), weighed, ground with a wheat grinder (Retsch MM400, Verder Shanghai Instrument Equipment Co., Ltd., Germany), sieved through a 100-mesh screen, and sealed for mineral element content determination.

1.2.2 Mineral Element Content The nitric acid-perchloric acid digestion method was used. A 0.5 g sample was weighed into a digestion tube, 5 mL HNO -HClO (4:1 volume ratio) was added, left overnight, digested on a digestion furnace until clear, cooled, diluted to 50 mL, filtered with microporous filter paper, and Cu, Fe, Mn, Zn, Ca, and Na contents were determined using an atomic absorption analyzer (Z-5300, Hitachi, Japan).

1.2.3 Mineral Element Distribution Ratio The aboveground biomass was divided into four parts: glume, grain, stem, and leaf. The distribution ratio of mineral elements in each organ was calculated as the ratio of element accumulation in that organ to the total element accumulation in the aboveground part.

1.2.4 Mineral Element Accumulation Mineral element accumulation in an organ = Mineral element content in the organ × Dry weight of the organ per plant (4)

1.3 Data Analysis

This study employed a two-factor design with interaction between two water levels and three varieties, arranged in a completely randomized block design. Two-way ANOVA was used to analyze the effects of different water and variety treatments on mineral element content, accumulation, dry matter weight, yield, and water use efficiency in different organs. Duncan’ s multiple comparison method was used for comparisons among water, variety, and organ factors.

Results

2.1 Changes in Mineral Element Content in Different Organs Under Different Water Conditions

As shown in , significant differences in Mn content existed among organs of the three wheat varieties. Leaf Mn content was significantly higher than in other organs, while stem Mn content was significantly lower, with differences ranging from 98.47 to 139.74 g • g ^{1} between leaf and stem. Under water deficit conditions, stem Mn content in ‘Cangmai-6001’ and leaf, stem, and glume Mn content in ‘Hanmai-9’ decreased by 31.70%, 27.89%, 9.12%, and 39.80%, respectively, while Mn content changes in ‘Jimai-22’ were not significant.

Significant differences in Zn content were also observed among organs of the three varieties, with grain Zn content significantly higher than in other organs. Under water deficit conditions, stem Zn content in ‘Cangmai-6001’ significantly decreased by 17.07%, while stem Zn content in ‘Hanmai-9’ and grain Zn content in ‘Jimai-22’ significantly increased by 82.20% and 32.21%, respectively, with no significant changes in other organs.

Under water deficit conditions, leaf and glume Cu content in ‘Cangmai-6001’ significantly decreased by 42.92% and 39.30%, respectively. In ‘Hanmai-9’ , Cu content in stem, grain, and glume significantly decreased by 31.47%, 65.02%, and 48.11%, respectively. In ‘Jimai-22’ , grain and glume Cu content significantly decreased by 47.81% and 42.05%, respectively, while stem Cu content significantly increased by 77.59%, with no significant change in leaves.

Under different water conditions, all three varieties showed significantly higher leaf Ca content than other organs. Under water deficit conditions, glume Ca content in ‘Jimai-22’ significantly decreased by 43.43%, while glume Ca content in ‘Cangmai-6001’ and grain Ca content in ‘Hanmai-9’ and ‘Jimai-22’ significantly increased by 107.00%, 36.61%, and 9.70%, respectively.

Grain Na content was the lowest among organs in all three varieties, significantly lower than in other organs. Under water deficit conditions, leaf and stem Na content in ‘Cangmai-6001’ and stem Na content in ‘Jimai-22’ significantly decreased by 49.47%, 60.76%, and 25.87%, respectively, while Na content changes in ‘Hanmai-9’ were not significant.

Fe content varied greatly among organs of different varieties. Under water deficit conditions, Fe content in leaf, stem, and glume of 'Cangmai-6001' significantly decreased by 36.50%, 84.68%, and 43.61%, respectively. In 'Hanmai-9' , leaf Fe content significantly decreased by 45.68%. In 'Jimai-22' , Fe content in stem, grain, and glume significantly decreased by 56.37%, 52.27%, and 74.37%, respectively. However, grain Fe content in 'Cangmai-6001' and 'Hanmai-9' significantly increased by 239.00% and 136.00%, respectively. These results indicate that water condition changes simultaneously alter Fe absorption and utilization in wheat organs.

Furthermore, water and variety interaction had significant effects on Ca content and highly significant effects on Zn, Cu, Na, and Fe contents. Water and organ interaction had significant effects on Mn content and highly significant effects on Cu, Na, and Fe contents. Variety and organ interaction, as well as three-factor interaction, had significant or highly significant effects on all element contents.

2.2 Distribution Ratio of Aboveground Mineral Elements Under Different Water Conditions

[Figure 2: see original paper] shows the distribution ratios of mineral element accumulation in different organs of wheat varieties. Cu and Zn had the highest distribution ratios in grains of all three varieties. Na had the highest distribution ratio in stems. Ca had the highest distribution ratio in leaves. Mn had relatively high distribution ratios in both leaves and grains. Fe distribution in major organs differed among varieties and water conditions.

Compared with normal water conditions, water deficit significantly increased the distribution ratios of Cu, Zn, and Fe accumulation in grains of 'Cangmai-6001'by 58.89%, 16.05%, and 380.00%, respectively. Meanwhile, the distribution ratios of Mn in leaves and Na in glumes increased by 50.58% and 80.96%, respectively. Correspondingly, Fe distribution ratios in leaves, stems, and glumes decreased by 40.07%, 81.23%, and 54.14%, respectively ([Figure 2: see original paper]A).

Under water deficit conditions, 'Hanmai-9' showed increased distribution ratios of Cu, Zn, and Ca in stems by 46.64%, 49.50%, and 44.98%, respectively. Grain Mn and Fe distribution ratios increased by 15.48% and 151.00%, respectively, while leaf Cu distribution ratio increased by 197.00% ([Figure 2: see original paper]B).

Water deficit increased grain Mn, Zn, Fe, Na, and Ca distribution ratios in 'Jimai-22' by 20.18%, 26.52%, 35.17%, 63.14%, and 72.59%, respectively, and increased stem Cu and Ca distribution ratios by 131.00% and 13.09%, respectively ([Figure 2: see original paper]C).

2.3 Changes in Mineral Element Accumulation Under Different Water Conditions

As shown in , under different water conditions, Cu, Mn, and Zn mainly accumulated in grains of the three wheat varieties, significantly higher than in other organs except for ‘Cangmai-6001’ . Na mainly accumulated in stems, and Ca accumulated in leaves, both significantly higher than in other organs. Fe accumulation varied greatly among organs of different varieties.

Under water deficit, grain Zn, Na, and Ca accumulation increased, while the effects on grain Cu, Fe, and Mn accumulation showed genotypic differences. Grain Cu accumulation in ‘Cangmai-6001’ increased by 52.82%, while it decreased by 70.85% and 32.06% in ‘Hanmai-9’ and ‘Jimai-22’ , respectively. For Fe, water deficit substantially increased grain Fe accumulation in ‘Cangmai-6001’ and ‘Hanmai-9’ by 314.00% and 127.00%, respectively, but decreased it in ‘Jimai-22’ by 39.00%. The effect on Mn showed the opposite pattern.

Further comparison of mineral element accumulation changes in leaves, stems, and glumes revealed that under water deficit, leaf and glume Cu accumulation in ‘Cangmai-6001’ significantly decreased by 53.00% and 58.00%, respectively. Fe accumulation in leaves, stems, and glumes of all three varieties decreased, with significant differences except for stems and glumes of ‘Hanmai-9’ and leaves of ‘Jimai-22’ . Mn accumulation in glumes of ‘Cangmai-6001’ and in leaves and glumes of ‘Hanmai-9’ significantly decreased by 40.00%, 34.00%, and 48.00%, respectively. Zn accumulation in glumes, and Na accumulation in leaves and stems of ‘Cangmai-6001’ significantly decreased by 41.00%, 55.00%, and 60.00%, respectively, while glume Ca accumulation significantly increased by 47.00%. In ‘Jimai-22’ , stem Na and leaf Ca accumulation significantly decreased by 29.00% and 20.00%, respectively. In ‘Hanmai-9’ , leaf Ca accumulation significantly decreased by 24.00%, with no significant changes in other organs. Additionally, interactions among water, variety, and organ factors had significant or highly significant effects on mineral element accumulation.

2.4 Changes in Water Use Efficiency

As shown in , under normal water conditions, ‘Hanmai-9’ had significantly higher total water consumption, aboveground dry matter weight, yield, biomass water use efficiency (WUEbiomass), and yield water use efficiency (WUEyield) than the other two varieties. ‘Jimai-22’ had significantly higher aboveground dry matter weight, yield, WUEbiomass, and WUEyield than ‘Cangmai-6001’ .

Under water deficit conditions, ‘Cangmai-6001’ had significantly higher total water consumption and aboveground dry matter weight than the other two varieties, and significantly higher yield and WUEbiomass than ‘Hanmai-9’ . ‘Hanmai-9’ had significantly higher total water consumption than ‘Jimai-22’ , but significantly lower WUEyield.

Compared with normal water conditions, water deficit significantly decreased total water consumption, aboveground dry matter weight, yield, WUEbiomass, and WUEyield of ‘Hanmai-9’ by 18.77%, 33.51%, 39.42%, 18.26%, and 25.70%, respectively. For ‘Jimai-22’ , water consumption and aboveground dry matter weight significantly decreased by 21.01% and 22.45%, respectively, while yield and WUEbiomass did not change significantly, and WUEyield significantly increased by 22.14%. Notably, under water deficit conditions, ‘Cangmai-6001’ showed no significant change in water consumption, but aboveground dry matter weight, yield, WUEbiomass, and WUEyield significantly increased by 78.49%, 142%, 83.06%, and 148%, respectively. These results indicate that moderate water deficit substantially improved water use efficiency of ‘Jimai-22’and ‘Cangmai-6001’ , and significantly increased yield of ‘Cangmai-6001’ .

Furthermore, water factor had highly significant effects on total water consumption and WUEyield, and significant effects on WUEbiomass. Variety factor and variety × water interaction had highly significant effects on total water consumption, aboveground dry matter weight, yield, WUEyield, and WUEbiomass.

2.5 Correlation Analysis Between Mineral Element Content and Wheat Dry Matter, Yield, and Water Use Efficiency

As shown in , different mineral element contents showed certain correlations with wheat dry matter weight, yield, and water use efficiency. Cu and Zn showed significant positive correlation, while Mn and Ca showed highly significant positive correlation. Na showed significant and highly significant negative correlations with Cu and Zn, respectively, indicating that mineral elements had certain synergistic and antagonistic relationships. Yield showed highly significant positive correlations with both WUEbiomass and WUEyield, and WUEbiomass and WUEyield were also highly significantly positively correlated, indicating that yield could be further increased by promoting water use efficiency at maturity. Additionally, dry matter weight was highly significantly positively correlated with Cu and Zn, and highly significantly negatively correlated with Mn and Ca. However, mineral elements and dry matter weight were not significantly directly correlated with yield, possibly due to effects of variety differences and variety × water interactions. Nevertheless, the tendency for mineral elements to indirectly regulate water use efficiency by affecting dry matter weight existed, as mineral elements participated in drought resistance under water deficit, indirectly affecting plant water balance and dry matter accumulation, thereby reducing transport efficiency to grains and not directly affecting yield and water use efficiency. This requires further research and verification.

Discussion and Conclusion

Mineral elements constitute important organic compounds in plants. Different elements have mutual inhibition or promotion relationships and are affected by other ions in soil, thereby promoting or inhibiting wheat growth [14]. The content and accumulation of different mineral elements vary significantly depending on drought stress severity and duration. This study showed that under water deficit, Fe content and accumulation in grains of ‘Cangmai-6001’ and ‘Hanmai-9’ significantly increased, while significantly decreasing in other organs. In ‘Jimai-22’ , grain Fe content and accumulation significantly decreased, while stem Fe accumulation increased, possibly because water deficit prevented Fe transport from stems to grains in this variety. Zn has high mobility in plants, and during wheat grain filling, 36.64% of grain Zn comes from transfer from vegetative organs, with stems contributing the most [15]. This study showed that under water deficit, grain Zn content and accumulation in 'Cangmai-6001' did not change significantly, while stem Zn content and accumulation significantly decreased. In 'Hanmai-9' , grain and stem Zn content and accumulation significantly increased. In 'Jimai-22' , grain Zn content and accumulation significantly increased, while stem Zn content and accumulation showed no significant changes, due to genotypic differences in grain Zn content [16]. Dai et al. [10] reported that Fe and Zn contents and absorption in wheat seedlings increased with increasing drought severity, attributing this to increased leaf transpiration pull and enhanced root absorption capacity during seedling water loss. Additionally, genotypic differences of the varieties themselves should be considered [17].

Zhang et al. [18] reported that under certain water deficit conditions, some wheat lines had high grain Mn content but low Cu content. Cu and Mn contents in other organs are mainly related to regulating photosynthesis and antioxidant enzyme activity [19-20]. Tan et al. [11] noted that Cu and Mn contents in wheat seedlings could increase under moderate drought but decreased under severe drought. This study showed that under water deficit, grain Cu content and accumulation in 'Hanmai-9'and 'Jimai-22'significantly decreased, while grain Cu content in 'Cangmai-6001' did not change significantly, but Cu accumulation substantially increased. Cu content and accumulation in whole plants of all three varieties decreased. Grain Mn content showed no significant changes among the three varieties, while whole plant Mn content and accumulation decreased in 'Cangmai-6001' and 'Hanmai-9' , but increased in 'Jimai-22' . These results indicate that differences in grain Cu and Mn contents are affected not only by water conditions but also possibly by chromosome group types of different varieties [17].

Studying Na and Ca contents and accumulation helps understand plant regulation of osmotic stress [9,21-22]. This study showed that grain Na and Ca contents were the lowest among organs in all three varieties, with the highest leaf Ca content and highest stem Na content. Under water deficit, grain Ca in 'Hanmai-9' and 'Jimai-22' significantly increased, and Na and Ca accumulation in all three varieties increased, indicating that moderate drought could improve grain quality of different wheat varieties. Increased mineral element content under drought may result from enhanced transpiration pull during wheat water loss, increasing transport rates of mineral elements in xylem vessels and thus increasing element contents in plants [23]. This study showed that under water deficit, leaf and stem Na content in 'Cangmai-6001' and stem Na and glume Ca content in 'Jimai-22' significantly decreased. Sun [24] reported that root and leaf Ca contents decreased with increasing drought severity. Decreased mineral element absorption under drought may be due to reduced root vigor or partial root death with increasing stress severity, weakening ion absorption capacity or reducing absorption area [23].

Under drought conditions, Mn fertilizer application can significantly improve net photosynthetic rate and short-term water use efficiency of maize leaves [25]. Li et al. [26] noted that foliar Zn application had a trend of increasing wheat yield but did not significantly affect it. Quota irrigation (120 mm) was more conducive to mineral element absorption and utilization than traditional irrigation (200 mm), but yield significantly decreased [27]. This study showed that water deficit significantly decreased biomass, yield, and water use efficiency of 'Hanmai-9' , significantly decreased biomass of 'Jimai-22' , but significantly increased WUEyield, with no significant changes in yield and WUEbiomass. Notably, under water deficit, 'Cangmai-6001' showed significant increases in dry matter weight, yield, WUEbiomass, and WUEyield. This may be because this variety is a drought-resistant and water-saving type, but with average lodging resistance [28]. Under normal water conditions in this experiment, this variety had excessive vegetative growth with a long duration and late heading. Additionally, lodging occurred before heading to some extent, causing population shading, which was unfavorable for photosynthate transport to grains and increased ineffective spikes, resulting in lower yield. Appropriate water deficit could promote the transition from vegetative to reproductive growth, enable timely heading, and avoid disadvantages and losses from prolonged vegetative growth. Second, under water deficit, grain Cu accumulation in 'Cangmai-6001' increased, while whole plant Cu accumulation in 'Hanmai-9' and 'Jimai-22' decreased by 64.45% and 26.49%, respectively, possibly affecting photosynthesis and antioxidant enzyme activity [20-21]. Under water stress, whole plant Cu accumulation in 'Cangmai-6001' decreased by only 3.82%, mainly due to decreased Cu accumulation and content in leaves and glumes rather than reduced Cu absorption from soil. This suggests that coordinated balance of Cu distribution among different organs in 'Cangmai-6001' may be another important reason for improved yield under drought stress. This study also showed that under water deficit, Fe content and accumulation in leaves, grains, stems, and glumes of 'Jimai-22' and Mn content and accumulation in leaves, grains, stems, and glumes of 'Hanmai-9' significantly decreased, thereby affecting chlorophyll regulation of photosynthesis and antioxidant enzyme activity [18], which may be another factor reducing grain yield of these two varieties under water deficit.

Correlation analysis showed that dry matter weight was significantly positively correlated with Cu and Zn contents and highly significantly negatively correlated with Mn and Ca contents. However, element contents and dry matter weight were not significantly correlated with yield and water use efficiency, possibly because dry matter was more affected by water factor or water × variety interaction. Nevertheless, the tendency for mineral elements to indirectly regulate water use efficiency by affecting dry matter weight existed. Since mineral elements participate in drought resistance under water deficit, they indirectly affect plant water balance and dry matter accumulation, reducing transport efficiency to grains and thus not directly affecting yield and water use efficiency. This requires further research and verification. Yield was highly significantly positively correlated with both WUEbiomass and WUEyield, indicating synchronization of high yield and efficient water use [29]. Increased Fe in soil reduces wheat grain absorption of Zn, Cu, and Mn, Zn promotes Fe absorption, while Mn has no significant effect on absorption of other cationic micronutrients [30-31]. This study showed significant positive correlations between Cu and Zn and between Mn and Ca in wheat plants, and significant negative correlations between Na and Cu and Zn. However, Fe showed no significant correlation with other elements, indicating that mutual promotion or inhibition relationships among external Fe, Zn, Cu, and Mn may change after plant absorption and utilization, re-establishing complex synergistic and antagonistic relationships within plants to regulate growth and stress resistance.

In conclusion, from the perspective of water-saving, efficiency improvement, and quality promotion, 'Cangmai-6001' is more suitable for high yield and high efficiency under water deficit, with increased grain Fe content but requiring Mn supplementation, making it suitable for planting in water-scarce areas. 'Jimai-22' can improve water use efficiency without significant yield reduction under water deficit and requires Fe supplementation to ensure quality, making it suitable for both water-deficit and normal areas. 'Hanmai-9' shows significant decreases in yield and water use efficiency under water deficit, with obvious decreases in grain Cu and Mn accumulation, making it more suitable for areas with better water conditions. In practical production, water and micronutrient fertilizer should be reasonably controlled according to local resource conditions and dietary structure, and wheat varieties conducive to high yield and quality should be selected.

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