

## Effects of Water-Potassium Coupling on Physiological Traits and Yield of Peanut (Postprint)

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**Date:** 2017-11-07T00:00:00+00:00

### Abstract

To clarify the effects of different water-potassium coupling on peanut physiological traits and reproductive growth, a two-factor four-level randomized block design was adopted using 'Huayu 25' as the experimental material, with water [soil water content at 35% (water stress, W1), 50% (mild water stress, W2), 65% (moderate water, W3), 80% (excessive water, W4) of field capacity] and potassium fertilizer [0 g(K<sub>2</sub>O) · kg<sup>-1</sup>(soil) (potassium deficiency, K0), 0.15 g(K<sub>2</sub>O) · kg<sup>-1</sup>(soil) (low potassium, K1), 0.30 g(K<sub>2</sub>O) · kg<sup>-1</sup>(soil) (moderate potassium, K2), 0.45 g(K<sub>2</sub>O) · kg<sup>-1</sup>(soil) (high potassium, K3)]. Through a rain-shelter pot experiment, the differences in protective enzyme activities in peanut leaves at the late podding stage and differences in reproductive growth under different water-potassium coupling conditions were investigated, providing a theoretical basis for efficient water and fertilizer management techniques for peanuts in arid and semi-arid regions. The results showed that water had extremely significant effects on leaf relative water content and chlorophyll content in peanuts, and leaf water content had a significant dilution effect on chlorophyll. With increasing irrigation amount, leaf relative water content (RWC) and chlorophyll content showed opposite trends, and the two were extremely significantly negatively correlated. Water and potassium fertilizer had significant or extremely significant positive interactive effects on the activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). The three enzymes responded differently to different stress conditions: SOD activity increased significantly under potassium deficiency (K0) or high potassium (K3) conditions; POD activity increased extremely significantly under water stress (W1) or K3; CAT activity increased significantly under W1 or K0. With increasing soil water content, leaf CAT activity decreased rapidly and was extremely significantly positively correlated with chlorophyll content, indicating that CAT could slow chlorophyll degradation and extend the functional period of leaves at the late podding stage of peanuts. Potassium fertilizer and irrigation had significant and extremely sig-

nificant effects on total flowers per plant, respectively. Potassium application could significantly delay initial flowering time, while reducing irrigation amount could advance final flowering time. Under moderate potassium (K2), effective flower number and effective flower rate of all water treatments were at relatively high levels. Under moderate water (W3), potassium fertilizer promoted single kernel weight, and mild water stress (W2) also favored the increase in single kernel weight. Significant increase in pods per plant and improvement in double-kernel fruit rate were important reasons for yield increase through water effects. The moderate water and moderate potassium W3K2 treatment had the shortest flowering period (25 d), maximum effective flower rate reaching 51.0%, and highest kernel yield.

## Full Text

### Abstract

This study clarified the combined effects of different water and potassium supply levels on the physiological characteristics and reproductive growth of peanut (*Arachis hypogaea* L.). A pot experiment was conducted under a rainproof shelter to investigate differences in leaf protective enzyme activities at the late podding stage and reproductive growth under various water-potassium coupling conditions. The experiment employed a two-factor randomized block design with four levels for each factor: water supply at 35% (water stress, W1), 50% (mild water stress, W2), 65% (moderate water, W3), and 80% (excess water, W4) of field capacity; and potassium fertilizer at 0 g(K O) · kg<sup>-1</sup> soil (K0, potassium deficiency), 0.15 g(K O) · kg<sup>-1</sup> soil (K1, low potassium), 0.30 g(K O) · kg<sup>-1</sup> soil (K2, moderate potassium), and 0.45 g(K O) · kg<sup>-1</sup> soil (K3, high potassium). The tested peanut cultivar was 'Huayu 25'. The results showed that irrigation had an extremely significant effect on leaf relative water content (RWC) and chlorophyll content. Leaf water content exhibited a clear dilution effect on chlorophyll, with RWC and chlorophyll content showing opposite trends as irrigation increased, displaying an extremely significant negative correlation. Water and potassium showed significant or extremely significant positive interactive effects on superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) activities. The three enzymes responded differently to various stress conditions: SOD activity increased notably under potassium deficiency (K0) or high potassium (K3) conditions; POD activity increased extremely significantly under water stress (W1) or K3 conditions; and CAT activity increased significantly under W1 or K0 conditions. As soil water content increased, leaf CAT activity decreased rapidly and showed an extremely significant positive correlation with chlorophyll content, indicating that CAT could slow chlorophyll degradation and extend leaf functional duration at the late podding stage. Potassium fertilizer and irrigation had significant and extremely significant effects on total flowers per plant, respectively. Potassium application significantly delayed initial flowering, while reduced irrigation advanced flowering termination. Under moderate potassium (K2), both fertile flower number and fertile flower rate were relatively high across

all water treatments. Under moderate water conditions (W3), potassium fertilizer promoted single seed weight, which was also enhanced under mild water stress (W2). The significant increase in pods per plant and dual-kernel fruit rate were important reasons for the yield-increasing effect of water. The W3K2 treatment (moderate water and moderate potassium) had the shortest flowering period (25 days), the highest fertile flower rate (51.0%), and the highest seed kernel yield.

**Keywords:** peanut; water-potassium coupling effect; reproductive growth; antioxidant enzyme activity; fertile flower; yield

## Introduction

Water resources are severely scarce in northern China, with water availability per unit cultivated land area being only half of the world average, and agricultural irrigation water use efficiency ranging from 40% to 50%, compared to 70% to 80% in developed countries [1]. China also suffers from scarce potassium mineral resources, with current-season utilization efficiency of only 35% to 50%, far below that of developed countries [2]. Peanut (*Arachis hypogaea* Linn.) is an important oil crop in China, primarily distributed in arid and semi-arid regions, where the contradiction between insufficient water-fertilizer resources and their low utilization efficiency severely constrains sustainable peanut production.

Under normal conditions, plants effectively scavenge excess reactive oxygen species (ROS) through enzymatic and non-enzymatic systems. However, when plants suffer severe drought stress, the balance between ROS production and scavenging is disrupted [3]. Foreign studies have shown that gene expression levels of CAT1 and CAT2 in wheat (*Triticum* spp.) change with drought severity and diurnal patterns, with expression significantly enhanced under severe drought [4]. Research on crop stress physiology indicates that potassium fertilizer application can significantly increase SOD, POD, and CAT activities during various growth stages of maize (*Zea mays* L.) under water stress, reducing MDA content, while the effect is not prominent under normal water supply [5]. Lu et al. [6] suggested that potassium nutrition is closely related to POD, CAT, and SOD activities and could even serve as auxiliary indicators for potassium nutrition diagnosis in rapeseed (*Brassica* spp.). Further research has recognized the important role of potassium fertilizer in promoting chloroplast development, enhancing photosynthesis, and delaying senescence [7].

Peanut exhibits indeterminate flowering habits, with effective flowering period length varying under different environmental conditions [8]. Studies show that low-yielding peanuts have large flower numbers and long flowering periods but mostly fail to set pods, while high-yielding peanuts have moderate and concentrated flowering. Lao et al. [9] proposed that total flowers per peanut plant should be 75-100, with effective flowers accounting for no less than 60% of the total as a basic standard for breeding high-yield peanut varieties. Among the many factors affecting peanut pod yield, rational water-fertilizer regulation is key to

high yield [10]. Appropriate water control during the seedling stage can increase the dual-kernel fruit rate [11], while moderate water control during the podding stage benefits kernel number, pod weight, and full pod rate [12]. Peanut has symbiotic nitrogen fixation capability, so its nitrogen demand is not substantial; excessive nitrogen application reduces pods per plant and kernel rate, whereas potassium fertilizer can significantly increase peanut yield [13]. In recent years, numerous scholars have conducted in-depth research on crop water-fertilizer coupling technology [14], but studies on the effects of water-potassium coupling on peanut leaf protective enzyme activities and reproductive growth remain scarce. Therefore, this study investigated differences in peanut SOD, POD, CAT, flowering phenology, and yield under various water-potassium coupling conditions to provide a theoretical basis for efficient water-fertilizer management of peanut in China's arid and semi-arid regions.

## Materials and Methods

### 1.1 Experimental Materials

The experiment was conducted from May to October 2014 under a rainproof shelter at the Shenyang Agricultural University experimental station. A pot culture method was employed using ordinary plastic buckets (30 cm height, 25 cm diameter) with four ventilation holes at the bottom. The test soil was cinnamon soil collected from Laohetu Township, Fumeng County, Liaoning Province, with the following properties: organic matter  $19.21 \text{ g} \cdot \text{kg}^{-1}$ , total nitrogen  $1.15 \text{ g} \cdot \text{kg}^{-1}$ , total phosphorus  $0.41 \text{ g} \cdot \text{kg}^{-1}$ , total potassium  $24.97 \text{ g} \cdot \text{kg}^{-1}$ , alkali-hydrolyzable nitrogen  $69.60 \text{ mg} \cdot \text{kg}^{-1}$ , available phosphorus  $15.56 \text{ mg} \cdot \text{kg}^{-1}$ , available potassium  $100.07 \text{ mg} \cdot \text{kg}^{-1}$ , and field capacity (FC) 25.25%. The soil was air-dried, crushed, and passed through a 5 mm sieve. Air-dried soil (15 kg per bucket) was mixed with basal fertilizer and placed in buckets. Tap water was used for irrigation, and the tested peanut cultivar was 'Huayu 25'.

### 1.2 Experimental Design

The experiment employed a two-factor randomized block design with four levels each for water and potassium, totaling 16 treatments with three replicates (three buckets per treatment). The four soil relative water content levels were: water stress (W1, 35% FC), mild stress (W2, 50% FC), moderate water (W3, 65% FC), and excess water (W4, 80% FC). Potassium fertilizer (potassium sulfate) was applied at four levels based on K<sub>2</sub>O content: no potassium (K0,  $0 \text{ kg} \cdot \text{hm}^{-2}$ ), low potassium (K1,  $135 \text{ kg} \cdot \text{hm}^{-2}$ ), moderate potassium (K2,  $270 \text{ kg} \cdot \text{hm}^{-2}$ ), and high potassium (K3,  $405 \text{ kg} \cdot \text{hm}^{-2}$ ). Nitrogen fertilizer (urea) was applied at  $60 \text{ kg N} \cdot \text{hm}^{-2}$ , with both potassium and nitrogen split into two applications: half as basal fertilizer and half as topdressing at the podding stage. Phosphorus fertilizer (calcium superphosphate) was applied as basal fertilizer at  $150 \text{ kg P O} \cdot \text{hm}^{-2}$  in one application.

Three days before sowing, soil moisture in each bucket was adjusted to field

capacity using the weighing method. The calculated water amount was divided into three equal portions: the first portion was applied to the surface, the second was applied at 10 cm depth using a plastic tube, and the third at 20 cm depth to ensure uniform fertilizer distribution. Before water treatment initiation, all treatments were maintained at 70% FC to ensure normal seedling growth. Water treatments began 21 days after sowing, with irrigation amounts determined by weighing. Throughout the growing season, soil moisture in each treatment was maintained at the designed level, with supplemental irrigation applied every 1-3 days depending on temperature. Sowing occurred on May 23, with two holes per bucket and two seeds per hole. Seedlings were thinned 10 days after emergence, leaving one plant per hole.

### 1.3 Measurement Items and Methods

**Flowering, pegging, and podding:** Observations were made on fixed plants. Starting from June 23 when the first flower opened, newly opened flowers were recorded daily at 4:00 PM, along with the opening time of the first flower (initial flowering) and last flower (final flowering) for each observation plant. After harvest on October 8, all pegs were cut and counted per pot, and yield components were investigated to calculate pods per plant and dual-kernel fruit rate.

**Leaf relative water content, chlorophyll content, and enzyme activities:** Leaf relative water content (RWC) was measured using the saturated weighing method. On August 27 at 10:30 AM, the third leaf from the top of uniformly growing peanut plants was selected for chlorophyll measurement using a SPAD-502 chlorophyll meter (SPAD values represented relative chlorophyll content). Samples were then collected, temporarily stored in an ice box, and kept in a -80°C freezer for later analysis. CAT activity was determined using the ultraviolet absorption method, with one enzyme activity unit (U) defined as the amount causing a 0.1 decrease in A per minute. SOD activity was measured using the NBT method, with one U defined as the amount inhibiting NBT photochemical reduction by 50%. POD activity was determined using the guaiacol method [15], with one U defined as the amount causing a 0.01 change in A per minute.

### 1.4 Data Processing and Analysis

Data were organized and plotted using Microsoft Excel 2013, and statistically analyzed using DPS 7.5 software. All data in figures and tables represent the mean of three replicates. The critical period for effective flowers was defined as 15 days after initial flowering [9].

$$\text{Effective flower rate} = \frac{\text{Effective flowers per plant}}{\text{Total flowers per plant}} \quad (1)$$
$$\text{Flowering duration (days)} = \text{Final flowering time (days)} - \text{Initial flowering time (days)} \quad (2)$$

$$\text{Leaf relative water content} = (\text{Fresh weight} - \text{Dry weight}) / (\text{Turgid weight} - \text{Dry weight}) \times 100\% \quad (3)$$

## Results

### 2.1 Effects of Water-Potassium Coupling on Peanut Leaf Relative Water Content and Chlorophyll Content

**2.1.1 Effects on Leaf Relative Water Content** Leaf relative water content (RWC) is an important indicator reflecting leaf water status. Two-way ANOVA showed that irrigation had an extremely significant effect on RWC ( $P < 0.01$ ). As shown in [Figure 1: see original paper]A, under the same potassium application, RWC generally exhibited a “low-high-low” trend with changing water levels. Except for K3, the maximum RWC values under the other three potassium conditions all appeared at W3, with W3K0 showing the highest value of 88.54%. This was extremely significantly higher ( $P < 0.01$ ) than W1K0, W2K0, and W4K0 under the same no-potassium condition, indicating that soil moisture content above or below 65% FC was unfavorable for RWC improvement. Under the same soil moisture condition, RWC showed no obvious change with increasing potassium application.

**2.1.2 Effects on Leaf Chlorophyll Content** Chlorophyll is one of the first components degraded during leaf senescence. As shown in [Figure 1: see original paper]B, under the same potassium treatment, chlorophyll content generally decreased with increasing water levels. Statistical analysis indicated that under K0 and K2 conditions, the difference in chlorophyll content between W1 and the other three water treatments was extremely significant ( $P < 0.01$ ); under K1 and K3 conditions, the difference was significant ( $P < 0.05$ ). This may be due to the dilution effect of adequate long-term water supply on chlorophyll content.

### 2.2 Effects of Water-Potassium Coupling on Peanut Leaf Antioxidant Enzymes

Different water-potassium coupling treatments had varying effects on leaf protective enzyme activities. Two-way ANOVA revealed that water-potassium interaction effects on the three enzyme activities were significant ( $P < 0.05$ ) or extremely significant ( $P < 0.01$ ). As shown in [Figure 2: see original paper]A, the average potassium effect on SOD activity showed high values at both ends and low in the middle, indicating that both potassium deficiency and high potassium increased SOD activity. [Figure 2: see original paper]B shows that water and potassium had opposite effects on POD: the average water and potassium effects demonstrated that POD activity decreased with increasing water but increased with increasing potassium. Under water stress (W1), CAT activity decreased with increasing potassium application, reaching its minimum at K1, after which potassium had little effect. CAT activity under this water condition

was higher than in other treatments, with CAT activities at K0, K2, and K3 all being extremely significantly higher than other treatments, indicating that water stress (W1) induced increased CAT activity for environmental adaptation ([Figure 2: see original paper]C). In summary, leaf protective enzyme activities in peanut were stimulated and enhanced under water stress, potassium deficiency, or high potassium conditions.

### 2.3 Correlation Analysis of Stress Enzyme Activities, Relative Water Content, and Chlorophyll Content

As shown in , chlorophyll content was extremely significantly ( $P < 0.01$ ) positively correlated with CAT activity, suggesting that CAT may be a key enzyme in chloroplasts during the late podding stage, effectively eliminating hydrogen peroxide produced by photorespiration and thereby slowing chlorophyll degradation. As shown in [Figure 1: see original paper], RWC tended to increase with irrigation amount while chlorophyll content decreased, with correlation analysis revealing an extremely significant negative correlation ( $P < 0.01$ ) between them.

### 2.4 Effects of Water-Potassium Coupling on Peanut Flowering Dynamics

**2.4.1 Effects on Flowering Dynamics** Two-way ANOVA showed that potassium and water effects on total flowers per plant were significant ( $P < 0.05$ ) and extremely significant ( $P < 0.01$ ), respectively. As shown in [Figure 3: see original paper], the cumulative flowering amount per plant generally increased with soil water content across all treatments. After 45-60 days after sowing, the slope of the flowering dynamic curve was significantly greater than in other periods, with flowering during this period accounting for 68.2%-77.5% of the total. As shown in [Figure 3: see original paper]C, the slope of W3 treatment exceeded that of W4 starting from day 45. Comparing [Figure 3: see original paper]A-D shows that, except for W1, total flowers per plant under each water condition exhibited a “low-high-low” trend with increasing potassium, reaching maximum values at K1, indicating that low potassium was beneficial for increasing total flower number per plant.

**2.4.2 Effects on Flowering Period and Flower Number** Flowering period length is determined by initial and final flowering times, which responded differently to water and potassium effects. Potassium had an extremely significant effect ( $P < 0.01$ ) on initial flowering time, with a significant water-potassium interaction ( $P < 0.05$ ), while water had an extremely significant effect ( $P < 0.01$ ) on final flowering time. Under no-potassium conditions (K0), the difference in first flower opening time among water treatments was within 0.7 days. Compared with the earliest flowering treatment (K1W3), other treatments were delayed by 1.7-6 days. Under low potassium (K1), the average initial flowering time across water treatments was earlier than other potassium treatments, suggesting that no or excessive potassium application may delay flowering. Final

flowering time was determined by water level, showing a delayed trend with increasing water across all potassium conditions. Under moderate potassium, final flowering time showed a “U-shaped” change with increasing potassium, shortening the flowering period. The W3K2 treatment had the shortest flowering period at only 25 days.

The pattern of effective flower number was relatively consistent with total flower number per plant. With constant potassium application, effective flower number showed significant ( $P < 0.05$ ) or extremely significant ( $P < 0.01$ ) increasing trends with irrigation amount, with effective flower numbers at all water treatments reaching relatively high levels under K2. This indicates that flowering concentration differed across growth stages. Therefore, large total flower number did not necessarily mean proportional increases in effective flowers. For example, under K1, W3 and W4 total flower numbers were 125.8 and 139.5, respectively, higher than any other treatment, but under K2, W3 and W4 effective flower numbers reached 61.8 and 63.3, respectively, exceeding all other treatments. Effective flower rate is an important indicator reflecting flowering concentration during the effective period. In this study, average effective flower rates under K2 and K3 were higher than under K0 and K1. In summary, moderate potassium application not only ensured relatively high total flower number but also improved flowering concentration during the effective period.

## 2.5 Effects of Water-Potassium Coupling on Peg Number and Yield Components

Both water and potassium effects on peg number were extremely significant ( $P < 0.01$ ), with a significant water-potassium interaction ( $P < 0.05$ ). Under the same potassium condition, peg number increased with irrigation, with only K0 showing the same trend for pegging rate; water-potassium effects on pegging rate were not obvious under other potassium conditions (). As shown in and , the variation patterns of pod number and seed yield with water-potassium treatments were highly consistent with effective flower number, indicating that effective flower number is a key factor determining peanut yield. Analysis of yield components showed that the main reason for water-induced yield increase under each potassium treatment was significant ( $P < 0.05$ ) increase in pods per plant. Additionally, water significantly ( $P < 0.05$ ) increased the dual-kernel fruit rate, which was also an important reason for yield increase. Water had a significant effect ( $P < 0.05$ ) on single seed weight. Under no-potassium conditions, W2 was second only to W4; under other potassium conditions, W2 was higher than other water treatments, indicating that mild water stress was beneficial for photosynthate translocation to pods, compensating to some extent for yield loss from reduced pod number. Under moderate water conditions, potassium fertilizer also promoted single seed weight.

## Discussion

### 3.1 Effects of Water-Potassium Coupling on Peanut Leaf Protective Enzymes

SOD is the first line of defense in the plant antioxidant enzyme system, rapidly dismutating superoxide anion radicals ( $O_2^-$ ) into hydrogen peroxide ( $H_2O_2$ ) and oxygen molecules ( $O_2$ ), and is a major protective enzyme against cell membrane lipid peroxidation [16]. Under water stress, the drought-tolerant alfalfa (*Medicago sativa* L.) cultivar ‘Xinmu No.1’ showed higher SOD activity than the non-tolerant ‘Northstar’, indicating stronger superoxide radical scavenging capacity in drought-tolerant varieties, which has been verified in drought-tolerant common bean (*Phaseolus vulgaris* L.) and maize varieties [17]. This study showed that during the late podding stage under mild water stress (W2), application of a small amount of potassium fertilizer (K1) stimulated increased leaf SOD activity. Higher protective enzyme activity at this stage could timely scavenge ROS, thereby reducing membrane damage. However, SOD activity decreased when potassium application was above or below  $135\text{ kg} \cdot \text{hm}^{-2}$ .

CAT is the primary enzyme for scavenging  $H_2O_2$  [18], completely degrading  $H_2O_2$  in plants into water and oxygen, and working synergistically with SOD and POD to remove excess ROS [19]. Sorghum [*Sorghum bicolor* (L.) Moench] relies primarily on CAT as an antioxidant enzyme, with CAT activity increasing significantly under water stress, conferring strong drought resistance [20]. Zhao et al. [21] found that leaf CAT activity in ‘Qianjin No.1’ buckwheat (*Fagopyrum esculentum* Moench.) increased significantly under mild drought, with significant differences among water gradients, reaching maximum activity of  $405.45\text{ U} \cdot \text{g}^{-1}$  under severe drought. Consistent results were obtained in this experiment: under all potassium treatments, CAT activity under water stress (W1) was higher than under W2, W3, and W4, with W1K0, W1K2, and W1K3 treatments showing extremely significant differences ( $P < 0.01$ ) compared with other treatments under the same potassium conditions, indicating that water stress (W1) could induce increased CAT activity.

In addition to metabolizing hydrogen peroxide and organic peroxides, POD participates in lignin and suberin synthesis and can repair damaged cell walls [22]. Kang et al. [23] suggested that appropriate potassium application helps increase SOD, CAT, and POD activities, maintaining ROS metabolism balance for longer periods and delaying senescence, which is similar to our results. This experiment showed that under water stress or mild stress, appropriate potassium application helped increase peanut leaf POD activity. Most studies indicate that protective enzyme activities show an initial increase followed by a decrease during water stress, suggesting that the early stage of water stress induces increased enzyme activity [23-25]. In summary, all three enzymes in this experiment maintained high activity under long-term water stress.

In mechanistic studies, leaf relative water content effectively reflects plant water status, generally showing a linear correlation with soil water content [26]. In

this experiment, leaf relative water content first increased then decreased with irrigation amount, possibly because excessive water affected root respiration, limiting water absorption. Chlorophyll, as the material basis for photosynthesis, plays a role in light harvesting and conversion. Its content can reflect photosynthetic capacity and leaf senescence to some extent [27-28]. In this experiment, chlorophyll content decreased with increasing soil water content, possibly because higher SOD, POD, and CAT activities under water stress or mild stress more effectively scavenged ROS, thereby greatly slowing chlorophyll degradation. The extremely significant positive correlation ( $P < 0.01$ ) between CAT and chlorophyll content supports this conclusion.

### 3.2 Effects of Water-Potassium Coupling on Peanut Reproductive Growth

High-yielding peanuts produce 63.16%-76.36% of their total flowers during the 15-day effective flowering period, with daily flower number dropping sharply after the effective period and almost no flowers 25 days after initial flowering, showing concentrated flowering [9]. Flowering periods in this experiment were short, ranging from 25.0 to 31.3 days, consistent with high-yielding peanut characteristics. Guo et al. [29] reported that effective flower number determines peanut yield, so a longer peak flowering period benefits effective flower and peg formation. In this study, the W3K2 treatment had the shortest flowering period at only 25 days but achieved the highest effective flower rate (51%) and highest yield, consistent with Guo et al. [29], possibly because a shortened flowering period allowed plants to shift their growth center to pod development earlier, saving nutrients that would have been spent on ineffective flowers. Previous research suggests that early flowering produces more pods, late flowering produces none, and intermediate timing produces partial pods [30]. This study showed that no or excessive potassium application may delay initial flowering, while final flowering time tended to be delayed with increasing water. Therefore, applying moderate potassium during the seedling stage can extend the seedling period, building nutritional reserves for concentrated flowering after initial bloom. After the effective flowering period, appropriate water control should be applied to advance flowering termination, which not only ensures relatively high total flower number per plant but also improves effective flower rate.

Peanut flowering proceeds from bottom to top. During the effective flowering period, lower flowering nodes produce pegs closer to the ground that enter soil earlier and have stronger pod-setting ability, while higher node pegs are mostly ineffective [30], consistent with our results. Liu et al. [11] suggested that drought significantly reduces pods per plant, the main cause of yield reduction; however, appropriate water control during the seedling stage promotes pod development, increasing full pod rate and dual-kernel fruit rate, also benefiting 100-pod weight, 100-kernel weight, and kernel rate, compensating to some extent for yield loss from reduced pod number. Our results are similar in that drought reduced pod number but single seed weight was higher than other treatments, yet contradic-

tory in that water significantly promoted dual-kernel fruit rate, which increased with irrigation across all potassium treatments. In normal field production, moderate water conditions allow potassium fertilizer to promote kernel development and increase single seed weight.

Under our experimental conditions, SOD, CAT, and POD all maintained high activity under water stress or mild stress, enhancing peanut drought resistance to some extent. During the late podding stage, chlorophyll content changed consistently with CAT activity, indicating that CAT played a leading role in the leaf protective enzyme system. Peanut produces large numbers of flowers throughout its life cycle, and rational water-fertilizer regulation can beneficially alter flowering rhythm and ultimately increase yield. Therefore, moderate potassium application during the seedling stage can extend the seedling period, and appropriate water control after the effective flowering period can advance flowering termination, ensuring both high total flower number and effective flower rate. Irrigation should be restored after flowering to guarantee dual-kernel fruit rate. Overall, maintaining soil moisture at 65% FC with potassium application at 270 kg · hm<sup>-2</sup> throughout the growing period was most beneficial for increasing pod number and kernel yield.

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