

Article

Effects of Boron and Zinc Micro-Fertilizer on Growth and Quality of Jujube Trees (*Ziziphus jujuba*) in the Desert Area

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Abstract: Jujubes (*Ziziphus jujuba*) are a crucial industry in the arid region of Xinjiang, facing challenges such as water scarcity and low water use efficiency. This study focuses on jujube orchards located at the edge of the Taklimakan Desert to investigate whether applying trace elements can effectively enhance jujube growth, development, and fruit quality. By foliar spraying boron and zinc micro-fertilizers onto jujube leaves, we analyzed the effects of different doses on growth parameters, photosynthetic activity, crop yield, water use efficiency, and fruit quality. The results revealed that the length of the fruit branch, leaf area index, and fruit longitudinal/transverse diameter increased by 19.35%, 25.72%, and 32.9%/2.28%, respectively; net photosynthetic rate, transpiration rate, and stomatal conductance increased by 105.51%, 91.43%, and 75.3%, respectively, while intercellular CO₂ concentration decreased by 13.09%; yield and water use efficiency improved by 16.95% and 12.68%, respectively; soluble sugar content, titratable acid content, and flavonoid content increased by 13.56%, 51.63%, and 86.12%, respectively. Based on these findings, the optimal application rate for boron micro-fertilizer was determined to be 3.51~3.59 kg/hm², and for zinc micro-fertilizer, it was 3.16~3.32 kg/hm². This study provides practical methods along with theoretical support for applying micro-fertilizers in arid regions.

Keywords: arid area; water use efficiency; photoresponse curve; plant nutrient



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1. Introduction

Jujube tree (*Ziziphus jujuba*) is a unique economic fruit tree in China, accounting for approximately 98% of the global jujube cultivation area [1]. The jujube tree, a prominent species in arid desert regions of China, exhibits exceptional drought and cold tolerance traits along with robust adaptability. It plays a pivotal role in combatting land desertification and enhancing the ecological environment. Jujube trees generate substantial economic benefits when cultivated on a large scale in regions affected by water scarcity, saline-alkali soils, or sandy lands [2]. Xinjiang has emerged as a prominent contributor to the overall jujube output in China, accounting for approximately half of the nation's total yield [3,4]. Given the scarcity of water resources in arid regions like Xinjiang, effectively increasing production levels while maximizing income through innovative technical means under stringent water constraints poses a significant challenge for agricultural development in these dry areas.

Trace elements play a crucial role as constituents of enzymes or coenzymes in plants, exhibiting high specificity and indispensability [5]. Adequate availability of trace elements enhances the physiological functions of plants, facilitating the absorption and utilization of macronutrients by crops while improving the colloidal chemistry of cell protoplasm [6].

This increase in protoplasm concentration enhances crop resistance to adverse environmental conditions. Especially, boron and zinc, essential trace elements, enhance fruit quality significantly and substantially increase fruit setting rates in fruit trees [7].

Boron is an essential trace element for higher plants because its concentration in plants can have detrimental effects if it exceeds or falls below optimal levels [8]. Most of the boron in plants is insoluble, which makes it challenging to transfer and recycle to new plant parts [9]. Therefore, a continuous supply of boron throughout the growth period is necessary. Boron primarily accumulates in the cell wall and intercellular space, constituting more than 50% of the total boron content in plants [10]. Parts with vigorous growth and reproductive organs generally exhibit higher concentrations of boron than other plant tissues [11]. Zinc deficiency in plants inhibits photosynthetic physiological characteristics within leaves, consequently impairing overall photosynthesis [12]. Additionally, zinc is crucial for promoting pollen germination and elongation of pollen tubes, thereby enhancing fertilization rates [13]. Furthermore, zinc facilitates auxin synthesis and assimilate transport within plants by acting as a cofactor for four functional enzymes: acetic deoxyase, carbonase, copper-zinc superoxide dismutase (SOD), and RNA polymerase. These enzymes rely on zinc's participation to fulfill their normal physiological functions [14,15].

Zinc (Zn) promotes the formation of chlorophyll in plants, enhances photosynthesis, and supports protein synthesis. Boron can promote the synthesis and transportation of sugars in plants, providing energy for plant photosynthesis. Therefore, when these two elements act simultaneously, the impact of promoting growth and enhancing quality becomes more obvious. While boron and Zn offer numerous benefits for plant growth, excessive application can have detrimental effects. An excess of boron can hinder cell differentiation and the elongation of root meristem, leading to lignification and root necrosis. Similarly, excess Zn can hinder the elongation of plant roots, obstruct the absorption of other nutrients by plant roots from the soil, disrupt cell membrane permeability, and inhibit plant respiration. Therefore, the optimal application of trace elements must be carefully considered.

In arid and water-scarce desert regions, the soil lacks essential nutrients, including trace elements, making it challenging for plants to absorb these crucial components necessary for photosynthesis and physiological metabolism [16]. To address this issue, this research hypothesized that the application of boron and zinc on jujube trees could effectively enhance growth and development and improve fruit quality, while also establishing a critical threshold for optimal application. This investigation examines the influence of micro-fertilizers containing boron and zinc on various aspects, including growth characteristics, photosynthesis, yield, and quality of jujube trees in arid regions. Moreover, a recommended application scheme for these two micronutrients is proposed to optimize the yield and quality of jujube trees. These research findings have significant theoretical implications for cultivating high-quality and high-yielding jujube trees in arid areas.

2. Materials and Methods

2.1. Site Description

The experimental site is situated in the 224th regiment of the 14th division of Xinjiang Construction Corps (37°12'14" N, 72°22'01" E) within the Eurasian hinterland, at the southern edge of the Taklimakan Desert and the northern region of the junction between Pishan County and Moyu County in Hotan Prefecture along the 315 national highway. It has an elevation ranging from 1304 to 1379 m, representing a typical continental extreme arid desert climate type (Figure 1). The annual average temperature stands at 12.2 °C, with extreme maximum and minimum temperatures recorded as 40.6 °C and −21.6 °C, respectively. The cumulative temperature ≥ 10 °C ranges from 4100 to 4700 °C·d annually, while sunshine hours amount to approximately 2610.6 h per year, with a frost-free period lasting 244 days on average [17]. Annual precipitation averages around 33.4 mm, potential evaporation reaches 2602 mm annually, gales occur 11.5 times yearly, and sandstorms are experienced for 19–52 days yearly [18,19].

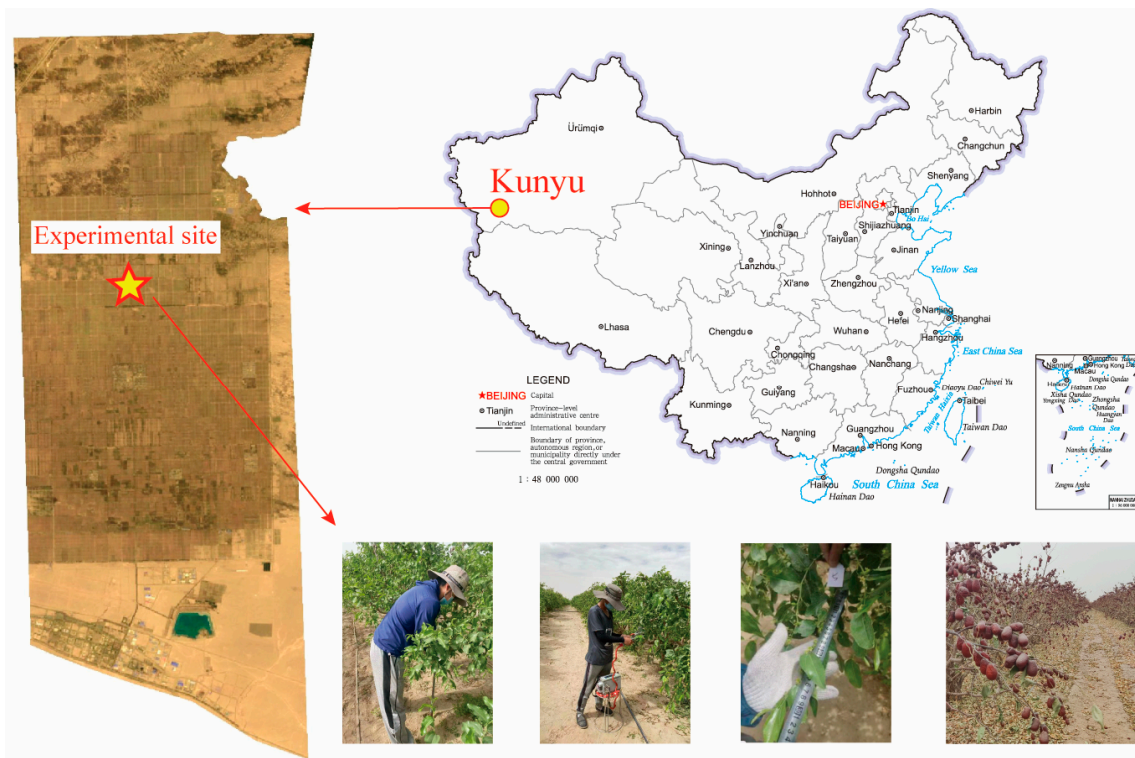


Figure 1. Experimental site.

This region's jujube cultivation area covers nearly 10,700 hm^2 predominantly, representing economically significant fruit trees in this area. Drip irrigation is employed as the method for jujube irrigation, using two rows of pipes laid out accordingly. The drip irrigation belt is positioned 1 m away from each jujube tree, with a spacing of 4 m between jujube rows. The physicochemical parameters of the test site (0–20, 20–40, 40–60, and 60–80 cm) were determined through laboratory analysis. Soil sand content ranged from 85.29% to 86.77%, soil organic matter content varied between 0.03 and 2.24 g/cm^3 , soil bulk density was within the range of 1.59 to 1.62 g/cm^3 , and pH values ranged from 8.2 to 8.4. Available potassium content was found to be in the range of 15.18 to 25.31 mg/kg , whereas available phosphorus content was observed at levels ranging from 4.87 to 12.31 mg/kg . In addition, the soil's available boron and zinc content was 1.2 and 0.7 mg/kg , respectively.

2.2. Experimental Design

A jujube orchard that had undergone 12 years of cultivation was selected as the subject of study. The test plot covered an area of 120 m^2 (4 m $\times$ 30 m), with a planting spacing of 1 $\times$ 4 m^2 for the red jujube trees while keeping a distance of 1 m from the drip irrigation belt to the jujubes. Two repeated test plots were set up for each treatment. The study was conducted over two periods, from April to November 2022 and April to November 2023.

To conduct a systematic study on the impact of boron and zinc micro-fertilizers on Jujube trees in sandy land, this research aims to compare and analyze the effects of applying a single micro-fertilizer versus combining two micro-fertilizers. The treatments for single applications of boron micro-fertilizer are as follows: B0Z0, B1Z0, B2Z0, B3Z0, and B4Z0, while the treatments for single applications of zinc micro-fertilizer are as follows: B0Z0, B0Z1, B0Z2, B0Z3, and B0Z4. Additionally, the combined application of boron and zinc micro-fertilizers will be examined through an interaction combination involving B1~B4 and Z1~Z4 (totaling 12 processing variations). The application rates for boron are as follows: B0: 0 kg/hm^2 , B1: 1.5 kg/hm^2 , B2: 3.0 kg/hm^2 , B3: 4.5 kg/hm^2 , and B4: 6.0 kg/hm^2 . Similarly, the five gradient application rates for zinc micro-fertilizer are as follows: Z0: 0 kg/hm^2 , Z1: 1.5 kg/hm^2 , Z2: 3.0 kg/hm^2 , Z3: 4.5 kg/hm^2 , and Z4: 6.0 kg/hm^2 . The specific plan for

applying the micro-fertilizers is presented in Table S1. Two repeated tests were set for each boron and zinc micro-fertilizer application treatment.

According to local irrigation practices, the total irrigation quota was 300 mm, and the entire growth period underwent 10 irrigations, with a 14-day interval between each irrigation event. Nitrogen and potassium fertilizers were applied with the water droplets during each irrigation event, with a nitrogen fertilizer dose of 300 kg/hm², potassium fertilizer dose of 45 kg/hm², and phosphorus fertilizer dose of 100 kg/hm². The potassium fertilizer dose was increased to 180 kg/hm² during fruit enlargement, while the phosphorus fertilizer dose was increased to 150 kg/hm² during flowering.

The specific methods of spraying micro-fertilizers according to the manufacturer's recommendations are as follows: (1) Dissolve the determined dose of boron and zinc fertilizers in magnetoelectric water, ensuring thorough shaking until no precipitation is observed while maintaining a concentration not exceeding 0.1%. (2) Opt for spraying before 9:00 am or after 6:00 pm to minimize the impact of high temperatures on micro-fertilizer absorption. (3) When applying fertilizer, ensuring the uniform distribution of tiny droplets is crucial, with particular attention given to spraying leaves' upper and dorsal surfaces. Newer leaves exhibit a higher nutrient absorption rate than older ones. At the same time, the dorsal surface demonstrates a greater capacity for nutrient uptake than the ventral surface, thereby enhancing overall absorption efficiency.

2.3. Measurement Indicators

2.3.1. Growth Index of Jujube Tree

The leaf area index was determined by selecting four leaves from different directions for each tree (three sample trees) and measuring their length and width to calculate the leaf area. This process was repeated every 15 days, and the total leaf area was divided by the land area. The longitudinal and transverse diameters of eight jujubes were measured using vernier calipers, and each fruit was selected from a different position on the tree. The measurements were taken every 15 days. The experiment randomly selected three trees for each treatment, with four fruit branches securely fixed in four directions on each tree. The length of the fruit branches was recorded and measured using a soft ruler every 15 days. This study focused on analysis of individual plant yield and overall production. Specifically, individual plant yield refers to the average weight of each jujube multiplied by the number of jujubes per tree. Total production, on the other hand, was calculated by multiplying the average yield per jujube tree by the total number of jujube trees.

2.3.2. Physiological Index of Jujube Tree

The LI-6400 portable photosynthesis measurement system, manufactured by LI-COR, was utilized to measure the diurnal variation in the photosynthetic rate in jujube trees. One leaf from each tree in every experimental group was measured in three directions: southeast, northeast, and northwest. Five data points were recorded for each leaf during each measurement session, and the average value was calculated. Finally, the mean value of five trees was calculated. The measured parameters included net photosynthetic rate, transpiration rate, stomatal conductance, and intercellular CO₂ concentration.

2.3.3. Quality Indexes of Jujubes

To assess the impact of boron-zinc micro-fertilizer on the quality of red jujube, the flavonoid content was determined using aluminum nitrate-sodium nitrite colorimetry, titratable acid was measured through acid–base neutralization titration, and soluble sugar levels were analyzed via anthrone colorimetry [20].

2.3.4. Water Use Efficiency

The water use efficiency of jujube trees is defined as the ratio of yield to water consumption. Real-time monitoring of soil water content at a depth of 0~2 m using water

sensors allows for the determination of changes in water storage in the root zone, enabling the calculation of water consumption [21]. The specific calculation formula is as follows.

$$W = \theta h \quad (1)$$

$$ET = 0.001(P + \Delta W)S\rho \quad (2)$$

$$WUE = Y/ET \quad (3)$$

where θ is soil water content (cm^3/cm^3); h is soil depth (mm); W is soil water storage (mm); ΔW is soil water storage change (mm); S is the average area of each tree (m^2/tree); ρ is planting density of jujube tree (tree/hm^2); ET is water consumption of jujube tree (m^3/hm^2); Y is the yield of jujube tree per unit area (kg/hm^2); and WUE is the water use efficiency of jujube tree (kg/m^3).

2.3.5. Physical and Chemical Properties of Soil

The soil texture was determined using the advanced Malvern Laser Particle Size analyzer (Mastersize 2000, Malvern Instruments Ltd., Enigma Business Park, Malvern, UK). Soil bulk density was accurately measured using the ring knife method. The content of soil organic matter was precisely determined through the potassium dichromate oxidation-volumetric method [22]. Soil pH was meticulously assessed using the potential method, with a soil–water ratio set at 1:5, and each soil sample was measured three times to ensure accuracy, ultimately taking an average value [23]. Regarding soil nutrients, available nitrogen levels were carefully evaluated utilizing the alkali hydrolysis diffusion method. The available phosphorus content was accurately determined using the sodium bicarbonate extraction–molybdenum–antimony resistance colorimetric technique. Lastly, potassium levels were rapidly and efficiently assessed using ammonium acetate and analyzed via flame spectrophotometry [24].

2.4. Photosynthetic Light Response Model

The non-rectangular hyperbolic model is another commonly used light response model applied to many plants [25]. The model equation (Equation (3)) has advantages and disadvantages, similarly to the rectangular hyperbolic model. However, it introduces a parameter that reflects the degree of curvature of the photosynthetic curve, which makes the fit more physiologically meaningful.

$$P_n = \frac{\alpha \times I + P_{n\max} - \sqrt{(\alpha \times I + P_{n\max})^2 - 4I\alpha k P_{n\max}}}{2k} - R_d \quad (4)$$

where P_n is the net photosynthetic rate ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$); α is the apparent quantum efficiency; I is the photosynthetically active radiation or PAR; k is the curve angle of the non-rectangular hyperbola and has a value between 0~1; and $P_{n\max}$ is the maximum net photosynthetic rate.

The light compensation point (LCP) can be calculated as follows:

$$LCP = \frac{R_d \times P_{n\max} - kR_d^2}{\alpha(P_{n\max} - R_d)} \quad (5)$$

where R_d is the dark respiration rate ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). The line $y = P_{n\max}$ intersects the line $y = \alpha I - R_d$, and the value on the x -axis corresponding to the intersection point is the light saturation point (LSP).

2.5. Statistical Analysis

A statistical significance analysis is necessary to compare the disparities among various methods of micro-fertilizer application. Multi-way analysis of variance (ANOVA) was performed using the SciPy Python library (1.12.0 version). The Kruskal–Wallis H-test

and Mann–Whitney test were used to conduct multiple comparisons after the ANOVA to evaluate the significance of observed differences. Differences were considered statistically significant when $p < 0.05$. The Nash efficiency coefficient (R^2) was defined to assess the consistency of the calculated and observed solutions.

3. Results

3.1. Effects of Boron and Zinc on the Growth Index of Jujube Tree

The changing characteristics of average growth indicators of jujube trees in 2022 and 2023 under different treatments are illustrated in Figure 2. The corresponding data for these two years can be found in Table S2. The cumulative changes in the length of fruit branches under different growth periods with boron-zinc micro-fertilizer treatments are presented in Figure 2a. Results indicate that the length of the fruit branch was significantly ($p = 0.0164$) more considerable in treatments containing trace elements compared to the control group (B0Z0), with B3Z2 showing the most significant effect, increasing by 19.35%. Figure 2b shows the LAI values for jujube trees under different treatments, which were significantly ($p = 0.0135$) higher than those of the control group when treated with boron-zinc micro-fertilizers, and B3Z2 treatment showed the best effect, increasing the LAI by 25.72%. Transverse and longitudinal diameters of jujubes under different treatments are shown in Figure 2c,d, indicating that the application of boron and zinc also increased these dimensions ($p = 0.0188$ and $p = 0.0172$). Among them, B2Z4 treatment had the best effect compared to the control group, with an increase of 24.28% and 32.9%, respectively.

3.2. Effects of Boron and Zinc on Photosynthesis of Jujube Tree

3.2.1. Photoresponse Curve

Figure 3a illustrates the photoresponse curves of jujube trees under different boron application levels with fixed zinc fertilizer application. At the same time, Table 1 presents the corresponding critical parameters for different concentrations of sprayed boron fertilizer. Amongst the treatments with fixed zinc fertilizer application Z2, it is evident that boron fertilizer significantly enhanced photosynthesis in jujube trees ($p = 0.0386$), with the following treatment trends observed: B2Z2 > B3Z2 > B4Z2 > B1Z2 > B0Z2 > B0Z0. As the application of boron fertilizer increased, there was an initial increase followed by a subsequent decrease in net photosynthetic rate. The highest net photosynthetic rate was achieved under treatment B2Z2, which exhibited a 105.51% improvement compared to treatment B0Z0 without micro-fertilizer spraying. However, when considering only zinc fertilizer application (B0Z2), photosynthesis showed a 35.56% enhancement compared to treatment B0Z0 alone. The maximum net photosynthetic rate of the B2Z2 treatment exhibited a 90.45% increase compared to that of the B0Z0 treatment. In contrast, the maximum dark respiration rate was observed in the B2Z2 treatment, showing a 19.6% enhancement over the B0Z0 treatment. Conversely, the B0Z2 treatment displayed a slight decrease of 3.5% compared to the B0Z0 treatment's dark respiration rate. Additionally, it was found that the minimum light compensation point occurred in the B4Z2 treatment, demonstrating a significant reduction of 53.29% when compared to that of the B0Z0 treatment, whereas, conversely, the maximum light saturation point was observed in the B0Z2 treatment, with an increment of 30.00% relative to that of the B0Z0 control.

The photoresponse curves and critical parameters of jujube under different zinc application levels with fixed boron are presented in Figure 3b and Table 1. The results demonstrate that zinc fertilizer significantly enhanced the net photosynthetic rate of jujube trees ($p = 0.0312$), following the trend of B2Z2 > B2Z3 > B2Z4 > B2Z1 > B2Z0 > B0Z0. With increasing zinc fertilizer application, the net photosynthetic rate initially increased and then decreased. Under the B2Z2 treatment, the leaf net photosynthetic rate reached its peak, showing a remarkable increase of 105.51% compared to the treatment without micro-fertilizer application (B0Z0). Moreover, when boron fertilizer was applied alone (B2Z0), the net photosynthetic rate was still elevated by 36.14% compared to B0Z0 treatment. Notably, under the B2Z2 treatment, the maximum net photosynthetic rate was observed, with an

increase of 90.67% over B0Z0 treatment; meanwhile, B2Z3 exhibited a maximum light saturation point that surpassed that of B0Z0 by 35.7%. Additionally, it is worth mentioning that B20 showed a minimum light compensation point that was lower by 44.39% compared to B0Z0. The results of ANOVA showed that Pmax reached a significant difference with a *p* value of 0.032. The statistical table of variance analysis is shown in Table S3.

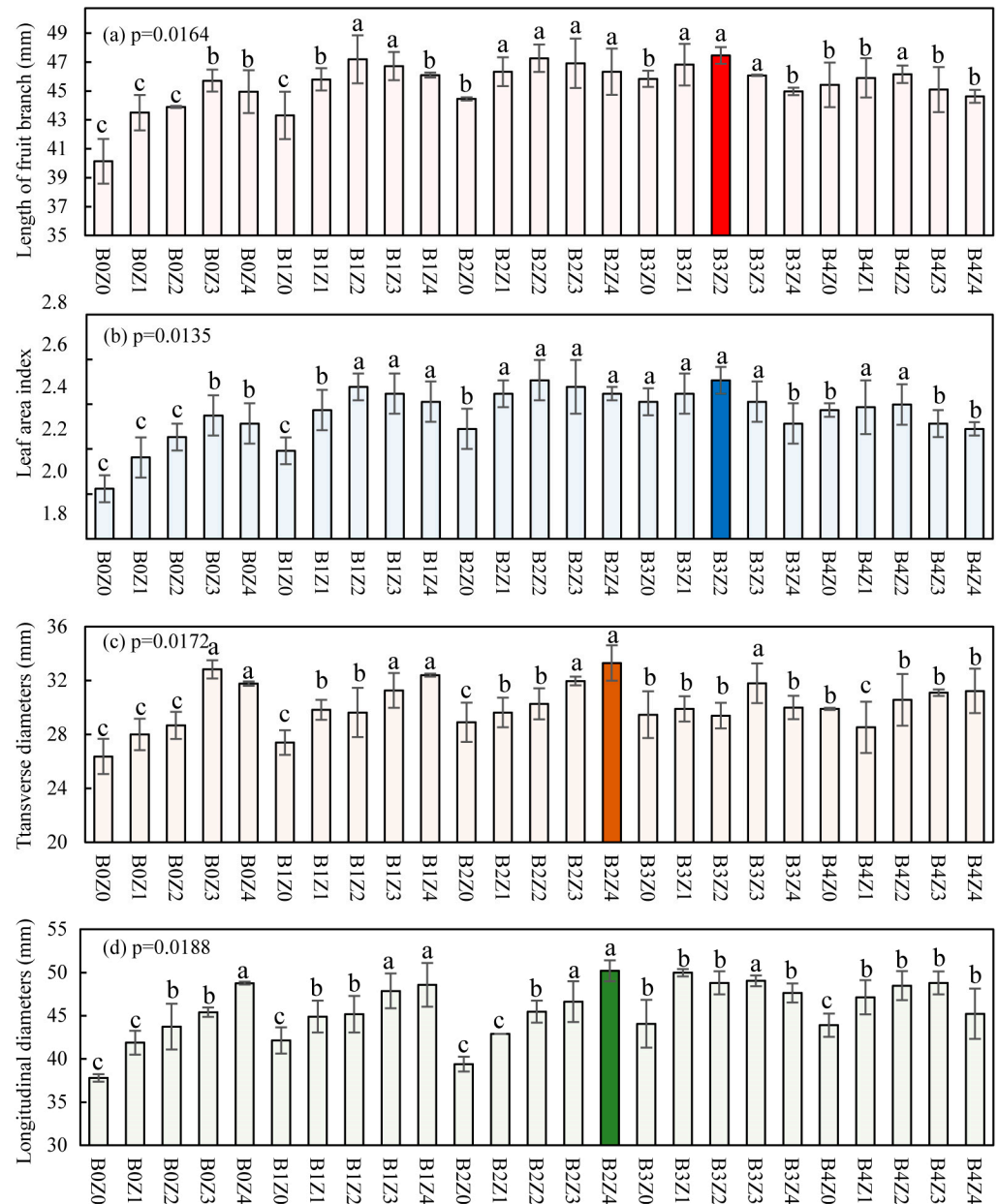


Figure 2. Effect of boron-zinc micro-fertilizer on growth parameters of jujube tree. B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively. (a–d) represent length of branch, leaf area index, transverse diameters, and longitudinal diameters, respectively. Different letters in the same column indicate significant differences at the 0.05 level. The deepened color indicates the maximum value.

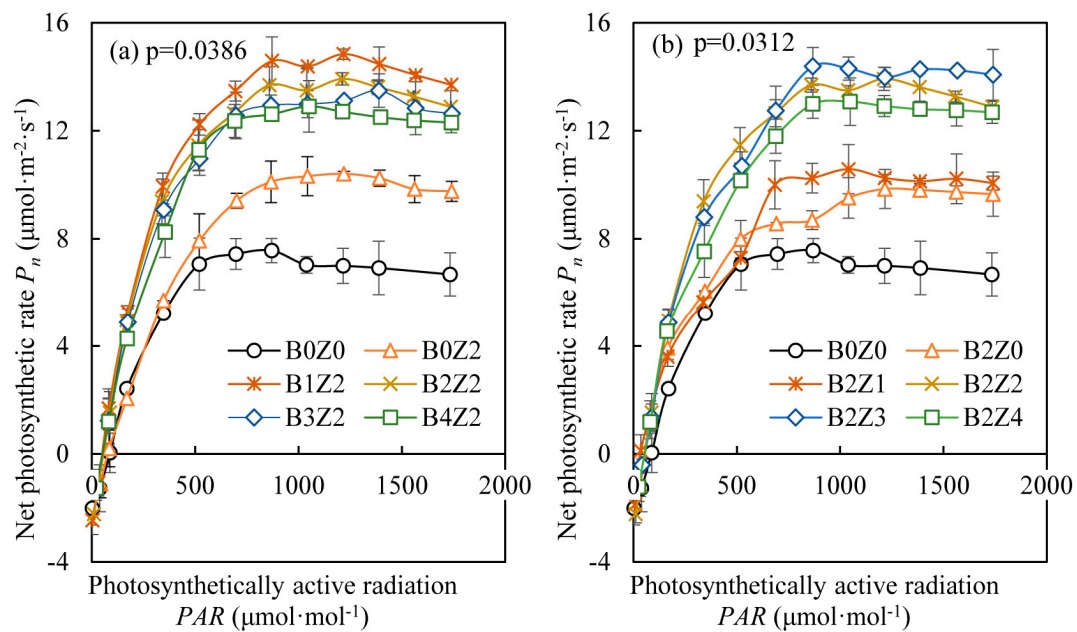


Figure 3. The impact of trace elements boron and zinc on the photoresponse curve of jujube tree. B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively. (a,b) represent the different boron with fixed zinc conditions and different zinc with fixed boron, respectively.

Table 1. Effect of boron application on the parameters of photoresponse curve of jujube tree.

Treatment		α	$P_{nmax}/$ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	R_d $/\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$LCP/$ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$LST/$ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	R^2
Fixed zinc	B0Z0	0.0231 ± 0.0025	9.11 ± 0.34 a	1.99 ± 0.26	86.32 ± 4.91	480.11 ± 14.29	0.99
	B0Z2	0.0228 ± 0.0017	12.30 ± 0.34 a	1.92 ± 0.21	84.95 ± 4.87	624.04 ± 14.29	0.996
	B1Z2	0.0279 ± 0.0036	14.40 ± 0.69 a	1.38 ± 0.30	50.15 ± 2.58	564.54 ± 18.33	0.994
	B2Z2	0.0459 ± 0.0051	17.35 ± 0.61 a	2.38 ± 0.38	52.81 ± 1.19	430.21 ± 12.42	0.994
	B3Z2	0.0365 ± 0.0036	14.98 ± 0.49 b	1.49 ± 0.30	41.35 ± 4.20	451.97 ± 17.04	0.995
	B4Z2	0.0292 ± 0.0018	13.91 ± 0.32 b	1.17 ± 0.22	40.32 ± 4.39	517.04 ± 16.36	0.996
Fixed boron	B2Z0	0.0435 ± 0.0058	12.87 ± 0.46 a	1.93 ± 0.24	48.00 ± 2.38	340.29 ± 14.23	0.99
	B2Z1	0.0294 ± 0.0071	12.76 ± 1.02 a	1.50 ± 0.51	52.07 ± 4.46	484.30 ± 16.16	0.98
	B2Z2	0.0459 ± 0.0051	17.35 ± 0.61 a	2.38 ± 0.38	52.81 ± 3.33	430.21 ± 18.96	0.99
	B2Z3	0.0251 ± 0.0029	14.79 ± 0.70 b	1.59 ± 0.43	63.37 ± 4.95	651.49 ± 15.02	0.98
	B2Z4	0.0404 ± 0.0056	17.37 ± 0.80 b	1.94 ± 0.40	49.16 ± 2.67	477.95 ± 13.36	0.99

Note: B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively. Different letters in the same column indicate significant differences at the 0.05 level.

3.2.2. Intercellular CO₂ Concentration

The variation in intercellular CO₂ concentration with PAR under different boron doses and zinc fixation is illustrated in Figure 4a. The results demonstrate a consistent pattern of decreasing and increasing intercellular CO₂ concentration with effective light intensity for each treatment, but $p = 0.0545$, which did not reach the level of significant difference. Overall, the average intercellular CO₂ concentration ranked as B0Z2 > B0Z0 > B1Z2 > B2Z2 > B4Z2 > B3Z2. Notably, the intercellular CO₂ concentration under the B3Z2 treatment was significantly lower, exhibiting a decrease of 13.09% compared to that under B0Z0. Figure 4b illustrates the variation characteristics of intercellular CO₂ with PAR under fixed boron and different zinc doses ($p = 0.0349$). Like boron treatments, each treatment exhibited a trend of initially decreasing and then increasing intercellular CO₂ concentration. On average, the

highest intercellular CO_2 concentrations were observed for $\text{B2Z1} > \text{B2Z0} > \text{B0Z0} > \text{B2Z2} > \text{B2Z3} > \text{B2Z4}$. Remarkably, the lowest level of intercellular CO_2 concentration was found in the case of the combined application of boron (B2Z0) and zinc (B0Z2), which showed an 11.38% reduction compared to that under B0Z0 alone. Compared to the individual applications of either boron (B2Z0) or zinc (B0Z2), the combined application demonstrated superior efficacy in reducing intercellular CO_2 levels.

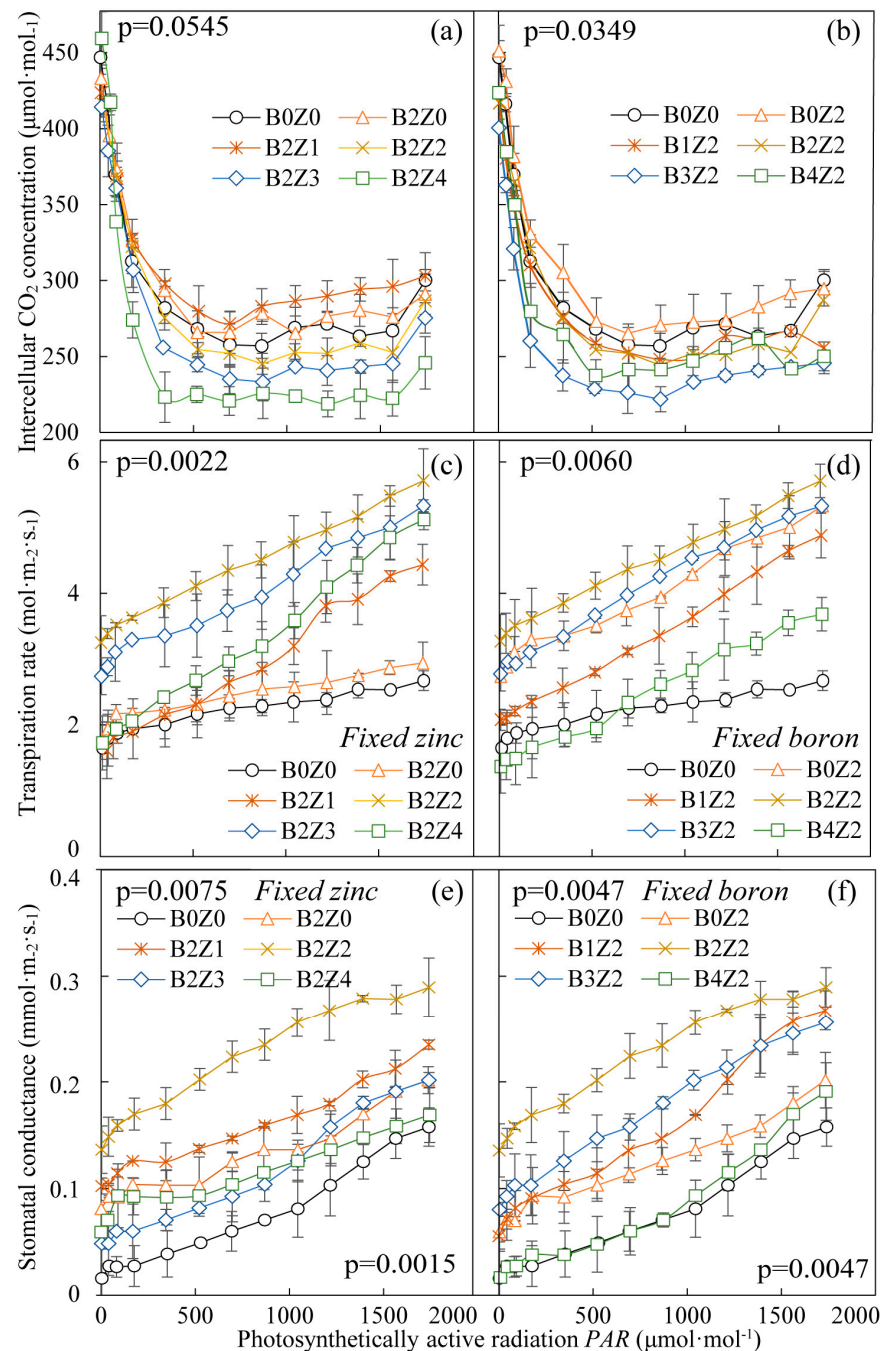


Figure 4. Effects of boron and zinc micro-fertilizer on critical parameters of the photoresponse curve of jujube tree. B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm^2 , respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm^2 , respectively. (a,c,e) were conducted under fixed zinc conditions; (b,d,f) were conducted under fixed boron conditions.

3.2.3. Transpiration Rate

Figure 4c shows the variation in leaf transpiration rate with PAR under different boron doses with fixed zinc ($p = 0.0022$). The results showed that the leaf transpiration rate increased with PAR under each treatment. The size relationship for the average transpiration rate under each treatment was $B2Z2 > B3Z2 > B4Z2 > B1Z2 > B0Z2 > B0Z0$. The maximum transpiration rate was observed under the B2Z2 treatment, which was 91.43% higher than that under the B0Z0 treatment. Figure 4d shows the variation characteristics for the leaf transpiration rate with PAR under different zinc doses with fixed boron. Similarly to other boron treatments, the transpiration rate increased with the increase in PAR ($p = 0.0060$). The size relationship for the average transpiration rate under each treatment was $B2Z2 > B2Z3 > B2Z1 > B2Z0 > B2Z4 > B0Z0$. The maximum transpiration rate was observed under the B2Z2 treatment, which was 91.43% higher than that under the B0Z0 treatment. Compared with the application of zinc (B0Z2) or boron (B2Z0) alone, the combined application of zinc and boron improved the crop transpiration rate.

3.2.4. Stomatal Conductance

Figure 4e depicts the response of stomatal conductance in leaves to varying levels of boron fertilizer under a fixed zinc fertilizer application influenced by PAR ($p = 0.0075$). The results demonstrate that stomatal conductance increased proportionally with PAR increment across all treatments. The relative order of stomatal conductance among different treatments was $B2Z2 > B1Z2 > B0Z2 > B3Z2 > B4Z2 > B0Z0$, with the highest observed in the B2Z2 treatment, exhibiting a remarkable increase of 75.30% compared to the control treatment (B0Z0). Similarly, Figure 4f illustrates the impact of increasing PAR on leaf stomatal conductance with varying levels of zinc fertilizer under a fixed boron fertilizer application ($p = 0.0047$). Consistent with boron-treated plants, leaf stomatal conductance also exhibited an upward trend for all treatments as PAR increased. The relative order of stomatal conductance among different treatments was $B2Z2 > B2Z3 > B2Z1 > B2Z0 > B2Z4 > B0Z0$, with the highest observed in the B2Z2 treatment, exhibiting a significant increase of 75.30% compared to the control treatment (B0Z0). Notably, the synergistic effects of combining boron and zinc fertilizers were found to offer considerable benefits compared to their separate applications.

3.3. Effects of Boron and Zinc on Water Use Efficiency of Jujube Tree

3.3.1. Water Consumption Process of Jujubes

Water consumption by jujube trees is influenced by various factors, including irrigation quota, air temperature, and soil moisture; however, the most significant factor is the irrigation quota. Equation (2) was used to calculate the water consumption during each growth period. The average values for 2022 and 2023 are presented in Figure 5a, and the data for the two years are shown in Table S3. The water consumption during different growth stages of jujube trees can be ranked as follows: fruit expansion stage > flowering stage > germination and leaf spreading period > maturity stage. Throughout the growth period, the trend of increasing followed by decreasing consumption was consistent with the basic temperature fluctuation pattern. The effects of different micro-fertilizer treatments on total water consumption were significant ($p = 0.0164$). Under each treatment condition, water consumption during the germination and leaf spreading stage ranged from 19.48% to 20.49%, the flowering stage ranged from 23.27% to 24.95%, the fruit expansion stage ranged from 45.16% to 46.21%, and the ripening stage ranged from 9.54% to 10.92%. Applying boron alone led to a certain increase in the jujube tree's water consumption; specifically, B4Z0 treatment exhibited the highest water consumption, which was approximately 3.15% higher than that of B0Z0 treatment, while B0Z4 treatment had a maximum water consumption about 3.56% higher than that of B0Z0 treatment when zinc was applied solely without boron supplementation. When boron and zinc were combined, the maximum recorded water consumption for jujube trees reached 279.05 mm under the B2Z4 treatment, representing an actual increment of approximately 6.07% compared to that under the B0Z0 treatment.

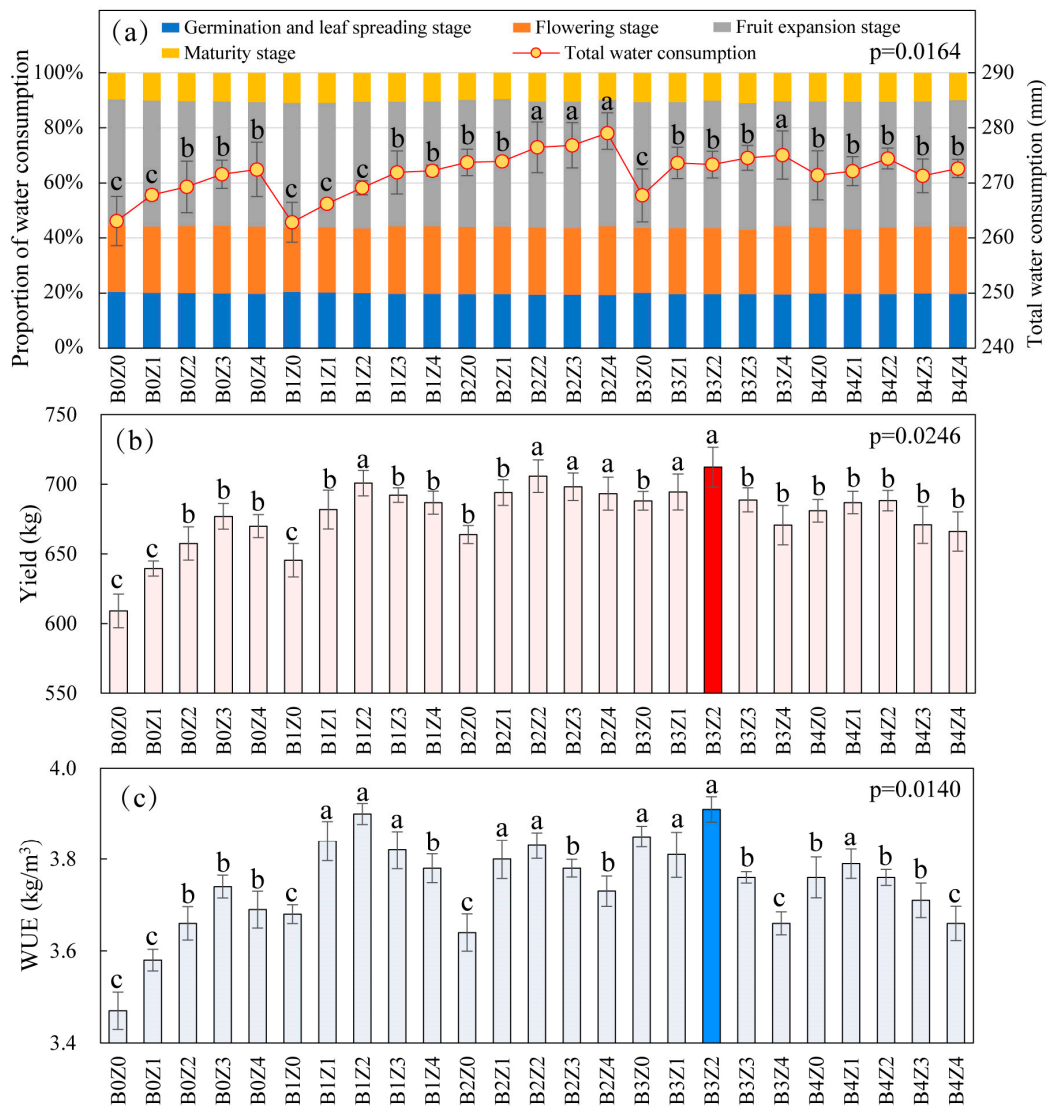


Figure 5. Water consumption, yield, and water use efficiency of jujube trees treated with boron and zinc micro-fertilizer. B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively. (a–c) represent the water consumption, yield, and water use efficiency, respectively. Different letters in the same column indicate significant differences at the 0.05 level. The deepened color indicates the maximum value.

3.3.2. Yield

The average jujube yields of 2022 and 2023 are presented in Figure 5b, and the data for the two years are listed in Table S4. The results showed that the yield of jujubes increased significantly ($p = 0.0246$). The treatments B1Z0, B2Z0, B3Z0, and B4Z0, which received boron micro-fertilizer alone, exhibited significantly higher yields than the B0Z0 treatment. Their yields were 9681.56, 9957.96, 10,321.00, and 10,213.22 kg/hm² respectively, representing an increase of 5.99%, 9.01%, 14.13%, and 11.81% over the B0Z0 treatment. The treatments with zinc micro-fertilizer alone (B0Z1, B0Z2, B0Z3, and B0Z4) resulted in yields of 9591.39, 9860.75, 10,153.52, and 10,048.12 kg/hm², respectively, which were higher than the yield of the B0Z0 treatment by 5.00%, 7.95%, 11.15%, and 10.00%. Among the treatments where both boron and zinc micro-fertilizers were applied together, B3Z2 exhibited the highest jujube yield at 10,684.05 kg/hm², 16.95% higher than the B0Z0 treatment. The application rates for boron and zinc micro-fertilizers were 4.5 and 3.0 kg/hm² respectively. The red

date yield will decrease when excessive boron or zinc fertilizers are sprayed. Therefore, selecting appropriate application rates when utilizing these fertilizers is crucial.

3.3.3. Water Use Efficiency (WUE)

The average water use efficiency in 2022 and 2023 is illustrated in Figure 5c, and the data for the two years are listed in Table S4. The results showed that the *WUE* of jujube trees increased significantly ($p = 0.0140$). The findings demonstrated that both trace elements, boron and zinc, enhance water use efficiency in jujube trees. Specifically, the treatments solely supplemented with boron fertilizer (B1Z0, B2Z0, B3Z0, and B4Z0) exhibited water use efficiencies of 3.68, 3.64, 3.85, and 3.76 kg/m³, respectively. These values increased by 6.05%, 4.90%, 10.95%, and 8.36%, respectively, compared to the treatment without boron fertilizer (B0Z0), with the highest increase observed in the B3Z0 treatment. The treatments exclusively supplied with zinc fertilizer (B0Z1, B0Z2, B0Z3, and B0Z4) demonstrated water use efficiencies of 3.58, 3.66, 3.74, and 3.69 kg/m³, respectively. These values increased by 3.17%, 5.48%, 7.78%, and 6.34%, respectively, compared to the treatment without zinc fertilizer (B0Z0), with the maximum increase observed in the B0Z3 treatment. When boron and zinc were applied together as a combined treatment (B3Z2), a significant improvement was observed in *WUE* at 3.91 kg/m³, representing an increase of 12.68% compared to the control group without any fertilizers (B0Z0).

3.4. Effect of Boron and Zinc on Quality of Red Jujube

3.4.1. Soluble Sugar

The average soluble sugar content of jujubes in 2022 and 2023 is depicted in Figure 6, and the data for the two years are listed in Table S5. The findings demonstrated that applying boron and zinc micro-fertilizer can significantly enhance the soluble sugar content of jujubes ($p = 0.0367$). Among the treatments involving boron micro-fertilizer (B1Z0, B2Z0, B3Z0, and B4Z0), the soluble sugar content was recorded as 737.47, 741.94, 778.43, and 774.43 g/kg, respectively, representing a respective increase of 1.84%, 2.45%, 7.49%, and 6.94% compared to B0Z0 treatment, with the highest increment observed in the B3Z0 treatment group. Similarly, for treatments involving zinc micro-fertilizer (B0Z1, B0Z2, B0Z3, and B0Z4), the soluble sugar content was measured as follows: 729.59, 737.59, 766.81, and 755.89 g/kg, respectively, indicating an increase of approximately 0.75%, 1.85%, 5.89% and 4.38% when compared to that of the control group (B0Z0), with maximum enhancement observed in the B0Z3 treatment group. Boron-zinc combined application resulted in a remarkable elevation in soluble sugar content, with a maximum value of 822.38 g/kg in the B2Z3 treatment group, a 13.56% increase compared to the B0Z0 treatment.

3.4.2. Titratable Acid

The average titratable acid content of jujubes in 2022 and 2023 is presented in Figure 6, and the data for the two years are listed in Table S5. The results demonstrate that the application of boron and zinc significantly increased the titratable acid content of jujube ($p = 0.0104$). Under boron treatment (B1Z0, B2Z0, B3Z0, and B4Z0), the titratable acid contents were 7.86, 8.41, 9.59, and 8.95 g/kg, respectively, representing a remarkable increase of 10.03%, 16.28%, 29.72%, and 20.36% compared to the B0Z0 treatment, with the B3Z0 treatment showing the highest enhancement effect. Similarly, when applying zinc alone (B0Z1, B0Z2, B0Z3, and B0Z4), the titratable acid content reached levels of 7.77, 8.24, 8.91, and 8.66 g/kg, respectively, exhibiting significant increases by 8.85%, 15.35%, 24.82%, and 21.27% compared to B0Z0, with the B0Z3 treatment showing the maximum improvement among all treatments. Notably, the combination of both boron and zinc micro-fertilizers resulted in a substantial elevation in titratable acid content, with the maximum value observed under the B2Z0 treatment, reaching up to 10.83 g/kg, a striking increment by 51.63% as compared to that obtained with B0Z0.

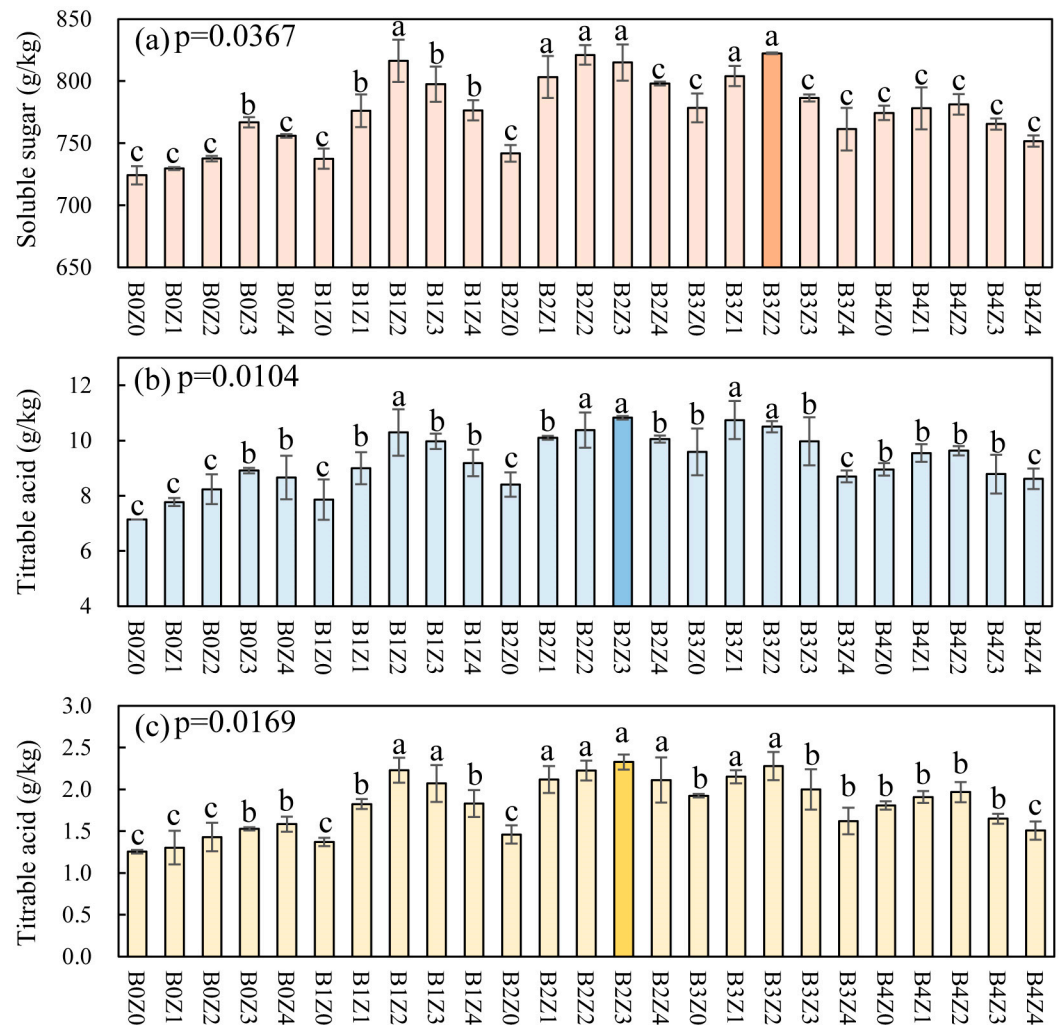


Figure 6. Effects of boron and zinc micro-fertilizer on soluble sugar, titratable acid, and flavone of jujubes. B0, B1, B2, B3, and B4 represent boron fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively, while Z0, Z1, Z2, Z3, and Z4 represent zinc fertilizer application rates of 0, 1.5, 3, 4.5, and 6 kg/hm², respectively. (a–c) represent soluble sugar, titratable acid, and flavone, respectively. Different letters in the same column indicate significant differences at the 0.05 level. The deepened color indicates the maximum value.

3.4.3. Flavone

The average flavone content in jujubes in 2022 and 2023 is illustrated in Figure 6, and the data for the two years are listed in Table S5. The results demonstrate that applying these two trace elements increased flavone content in jujubes ($p = 0.0169$). When boron was applied individually (B1Z0, B2Z0, B3Z0, and B4Z0), the flavone content increased by 9.59%, 16.13%, 47.14%, and 36.46%, respectively, compared to B0Z0, with the maximum treatment being B3Z0 at a content of 1.92 g/kg. Similarly, when zinc was applied alone (B0Z1, B0Z2, B0Z3, and B0Z4), the flavone contents were elevated by 0.75%, 2.50%, 3.90%, and 4.68%, respectively, compared to B0Z0, with the highest content observed with B4Z0, at 1.58 g/kg. In terms of combined application of boron and zinc, under the treatment of B2Z3, the highest flavone content reached up to 2.33 g/kg, significantly higher than that obtained from solely applying or not applying either element.

3.5. Quantitative Relationship

Figure 7 shows the quantitative relationship between boron and zinc micro-fertilizer and red jujube's yield and quality indexes. The functional relationship obtained through

data fitting (25 observations) is shown in Equations (6)–(9), and the fitting accuracy R^2 values were 0.83, 0.77, 0.84 and 0.78, respectively. The results demonstrated that the optimal application rates for boron and zinc were 3.59 and 3.32 kg/hm², respectively, resulting in a 10,581.87 kg/hm² yield. Similarly, the recommended application rates for achieving a soluble sugar content of 814.16 g/kg were 3.43 and 3.16 kg/hm² for boron and zinc, respectively. Furthermore, to attain a titratable acid content of 10.53 g/kg and flavonoid content of 2.24 g/kg, the ideal application rates were found to be 3.52/3.26 kg/hm² and 3.51/3.17 kg/hm² for boron/zinc. To determine the precise optimal application amounts of boron and zinc micro-fertilizers, we used the entropy weight method with yield, soluble sugar content, titratable acid content, and flavonol content assigned weight coefficients of 0.2557, 0.2469, 0.2516, and 0.2459, respectively. Calculating the application amounts based on these coefficients to achieve maximum yield and quality resulted in a boron micro-fertilizer rate of 3.51 kg/hm² and zinc micro-fertilizer rate of 3.23 kg/hm².

$$Y = -45.72B^2 - 38.50Z^2 - 36.27B \times Z + 448.58B + 385.51Z + 9137.57 \quad (6)$$

$$S = -4.35B^2 - 3.69Z^2 - 2.08B \times Z + 36.66B + 31.20Z + 699.70 \quad (7)$$

$$T = -0.14B^2 - 0.12Z^2 - 0.08B \times Z + 1.27B + 1.07Z + 6.54 \quad (8)$$

$$F = -0.50B^2 - 0.04Z^2 - 0.02B \times Z + 0.43B + 0.33Z + 0.96 \quad (9)$$

where Y is the jujube yield (kg/hm²); S is the soluble sugar content of jujubes (g/kg); T is the titratable acid (kg/hm²); F is the flavone (kg/hm²); B is the boron micro-fertilizer rate (kg/hm²); and Z is the zinc micro-fertilizer rate (kg/hm²).

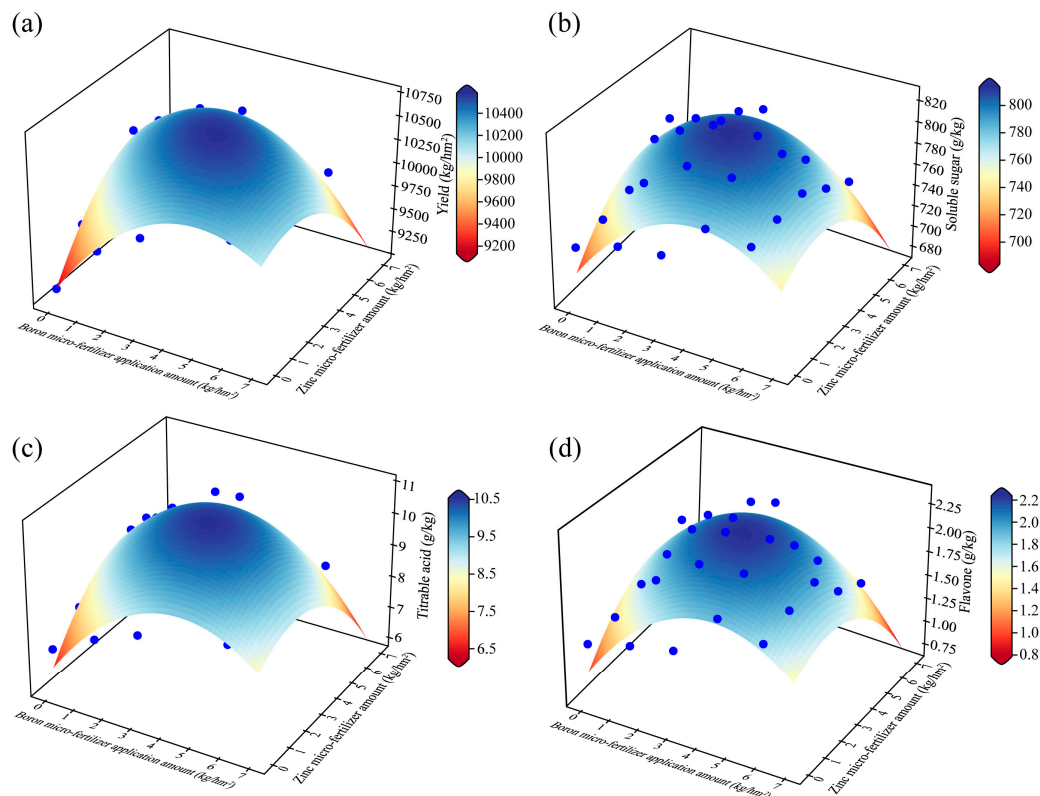


Figure 7. Quantitative relationship between boron and zinc micro-fertilizers and yield and quality. (a–d) represent yield, soluble sugar, titratable acid, and flavone, respectively.

4. Discussion

4.1. Growth Parameters

Boron and zinc are essential micronutrients for higher plants. Deficient or excessive levels of boron/zinc can lead to abnormal plant growth, development, or dysfunction. In citrange (*Poncirus trifoliata* (L.) Raf.), deficiency of boron resulted in significant shortening of internodes and thickening and browning of the root system [26]. Similarly, both deficiency and excess of boron reduced plant height in mulberry (*Morus* L.) [27]. Abd El-wahed et al. also investigated the positive effects of boron and zinc application on pomegranate trees. They revealed that it significantly enhances leaf nutrient content, leaf numbers, leaf area, shoot length, canopy volume, and chlorophyll concentration. Previous studies have documented the significance of zinc and boron as micronutrients in enhancing growth parameters for various tree species [28]. Zinc deficiency in fruit trees often causes stunting of branches, dead shoots, defoliation, or complete yellowing [29,30]. Our study also revealed that jujube trees exhibited decreased fruit branch length, leaf area index, and fruit diameter under conditions with no or excessive application of boron and zinc. These findings indicate that jujube tree growth is adversely affected by either deficient or excessive levels of these micronutrients. However, the appropriate application of boron and zinc promotes growth. For instance, Seraji et al. found that foliar application with 0.5% zinc sulfate +0.3% borax significantly increased branch length, number of leaves per branch, and leaf area in apples [31]. Foliar application of zinc sulfate and boron had significant effects on new shoot growth, plant height, plant spread, stem length, and leaf area in 15-year-old pomegranate (*Psidium guajava* L.) [32]. From the results of this study, the application of boron and zinc micro-fertilizer treatment were better than no application, and the growth of jujube trees was better when boron and zinc were combined than when applied alone. However, excessive application is also not conducive to the growth of jujube trees. Therefore, the appropriate application amount needs to be optimized. Under the conditions of this study, the B3Z2 scheme resulted in the best growth of jujube trees.

4.2. Yield

Using boron and zinc elements to develop novel micro-fertilizers to enhance crop and fruit tree yields has garnered significant attention from scholars both domestically and internationally. For instance, Din et al. observed a 27.8% increase in cotton boll number, a 6.9% increase in boll weight, and a 27.8% increase in seed cotton yield through the application of boron (0.1%) + zinc (0.2%) + urea (2%) treatment [33]. Shahgholi et al., on the other hand, discovered that wheat treated with zinc + boron exhibited a 17% higher yield compared to control treatments under regular irrigation as well as drought stress conditions, suggesting that iron, zinc, and boron micronutrients have a positive effect on wheat agronomic characteristics and potential for wheat cultivation in cold temperate regions with semi-arid climates [34]. Ullah et al. found that the application of boric acid at concentrations of 0.1%, 0.2%, 0.3%, and 0.4% on Kinnow mandarin during the fruit set stage resulted in elevated levels of N, P and K in the leaves when compared to the untreated control group. It is also evident that the presence of more K in the leaves helps to improve the quality of fruits and reduce the incidence of cracking [35]. Guilherme et al.'s findings indicated that appropriate levels of boron can regulate plasma membrane H-ATPase activity and enhance nutrient absorption in citrus trees, thereby increasing citrus yields [36]. Meriño-Gergichevich et al. stated that boron and zinc supplementation may enhance the uptake of macronutrients, thus leading to enhanced yield [37]. Along with these lines of evidence, numerous studies have demonstrated that applying boron and zinc micro-fertilizers can effectively boost crop yields; however, determining the optimal application dose remains crucial for achieving maximum productivity gains. On the other hand, it is worth noting that apricot trees did not exhibit corresponding increases despite these efforts; Berkant et al., for example, found no significant differences in apricot fruit size or yield even with increased doses of boron [38]. While limited research exists regarding using boron and zinc micro-fertilizers on jujube trees, our study's results align with similar

experiments conducted on various crops or fruit trees worldwide. Specifically, we found that neither excessively low nor high applications of boron and zinc yielded optimal results; instead, an increase in yield by 16.95% was achieved under B3Z2 treatment.

4.3. Quality

In addition to the yield from agricultural production, the quality of crops or fruit trees is also a crucial indicator and even more important for economic efficiency. Applying trace elements to improve quality is a hot topic at home and abroad. For example, the oil quality of rape (*Brassica napus* L.) was significantly affected by the lack of boron (B) and zinc (Zn); the combined application of these two elements significantly improved the quality, and the effect was better than that achieved with the application of only a single element [39]. In higher plants, fully developed leaves serve as the main supplier of photoassimilates, with additional green organs like fruit peels also contributing to the quality of the fruit. Michailidis et al. reported the significant role of boron in sweet cherry metabolism, physiological traits, and fruit developmental changes [40]. Panjekar et al. applied 0.2% zinc sulfate and 0.1% boric acid to tomatoes, reducing the fruit cracking rate by 90% [41]. Zhang et al. found through a study of corn that a single application of zinc fertilizer or borax fertilizer or the combined application of both zinc fertilizer and borax fertilizer could increase the protein content of corn kernel, and that zinc element could significantly increase the fat content of corn kernel [42]. Many studies have confirmed that boron and zinc elements positively affect the quality of fruit trees and crops. This study also obtained similar results through the application on jujubes; that is, the contents of soluble sugar, titratable acid, and flavonoids in jujube fruits were increased by 13.56%, 51.63%, and 86.12%, respectively, under B2Z3 treatment. Conversely, Safdar et al. reported that excessive levels of boron and zinc can cause an imbalance in enzymes and this imbalance can lead to a decrease in plant height, seed yield, and yield traits [39]. Our findings unequivocally show that the combined boron and zinc application is an effective method to improve the quality of red jujube. In general, the effect of boron and zinc interaction was synergistic on the growth and yield of red jujube. This increase in productivity can result in economic benefits for agricultural producers.

5. Conclusions

The effects of boron and zinc micro-fertilizer on jujube trees in the arid area of the southern margin of the Taklimakan Desert in Xinjiang were systematically analyzed in this study. By analyzing two years' worth of field test data, it was observed that a moderate application of boron and zinc micro-fertilizer promoted the growth, development, and overall benefits of jujube trees. However, excessive or insufficient amounts had detrimental effects on their health. Consequently, an optimal application scheme for the study area (boron: 3.51 kg/hm², zinc: 3.23 kg/hm²) is proposed.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14040741/s1>, Table S1: Application scheme of boron and zinc micro-fertilizer in jujube trees; Table S2: Growth index of jujube trees in 2022 and 2023; Table S3: Analysis of variance statistical table; Table S4: Water consumption during different growth stages in 2022 and 2023; Table S5: Yield and water use efficiency in 2022 and 2023; Table S6: Jujube water use efficiency in 2022 and 2023.

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

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