

Effects of Alternate Irrigation on Physio-ecological Characteristics of Crops in Wheat/Broad Bean Intercropping System (Postprint)

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Abstract

To investigate the effects of alternating irrigation on crop physiological status and growth and development in wheat/faba bean intercropping systems and to elucidate the water-saving mechanism of alternating irrigation, a rhizobox experiment was conducted using wheat and faba bean as experimental materials. Two irrigation methods—alternating irrigation (A) and conventional irrigation (T)—and three planting patterns—monoculture wheat (SW), monoculture faba bean (SF), and wheat intercropped with faba bean (IWF)—were established. From March to November 2008, the effects of alternating irrigation on leaf water physiology and biomass allocation in wheat/faba bean intercropping were systematically investigated in a greenhouse at Gansu Agricultural University. The results demonstrated that: 1) Compared with conventional irrigation, alternating irrigation increased chlorophyll content in leaves of intercropped wheat and intercropped faba bean, while decreasing water physiological indicators such as leaf relative water content and leaf water potential; no significant differences in physiological characteristics of wheat/faba bean intercropping were observed between different irrigation methods. Among different planting patterns, intercropping significantly increased chlorophyll content, leaf relative water content, and leaf water potential in wheat and faba bean leaves. 2) Wheat/faba bean intercropping under alternating irrigation maintained essentially unchanged photosynthetic rate while reducing transpiration rate and stomatal conductance. Compared with conventional irrigation, alternating irrigation reduced transpiration rate and stomatal conductance of intercropped wheat by 10.99% and 20.99%, respectively, and those of intercropped faba bean by 6.66% and 11.63%, respectively. 3) Compared with conventional irrigation, alternating irrigation decreased aboveground dry matter accumulation in crops and increased root-to-shoot ratio, with the root-to-shoot ratio of intercropped wheat and intercropped faba bean under alternating irrigation increasing by 14.47% and 18.18% compared with conventional irrigation, respectively. 4) Intercropping was beneficial

for crop yield improvement; the harvest index of intercropped wheat under alternating irrigation and conventional irrigation increased by 8.68% and 2.72% compared with corresponding monoculture, respectively, while that of intercropped faba bean increased by 4.78% and 5.23% compared with corresponding monoculture treatments, respectively. It is evident that implementing alternating irrigation in wheat/faba bean intercropping can regulate photosynthate allocation between root and shoot, optimize root-to-shoot ratio, and represents a practical and feasible irrigation approach.

Full Text

Preamble

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Effects of Alternative Irrigation on Eco-Physiological Characteristics of Wheat/Faba-Bean Intercropping*

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Abstract

Wheat/faba-bean strip intercropping is a common intercropping system in Northwest China that has significantly contributed to food security and poverty alleviation. However, the traditional net irrigation quota for wheat/faba-bean intercropping is relatively high, deepening the conflict between water resource supply and demand in agriculture. Alternative irrigation is a biological water-saving technique extensively used in agricultural production in arid and semi-arid areas, which is assumed to increase water use efficiency (WUE) and maintain high yield in wheat/faba-bean intercropping systems. In order to determine the effects of alternative irrigation on physiological response and yield of wheat/faba-bean intercropping, a root box experiment was conducted under glass greenhouse conditions at Gansu Agricultural University in 2008. The experiment included two irrigation methods [alternative irrigation (A) and conventional irrigation (T)] and three planting patterns [sole wheat (SW), sole faba-bean (SF), and intercropped wheat/faba-bean (IWF)]. The results showed that leaf chlorophyll content of intercropped wheat and faba-bean increased under alternative irrigation conditions, while leaf relative water content and leaf water potential decreased compared with conventional irrigation treatment. However, there were no significant differences between the two irrigation methods for wheat intercropped with faba-bean. Leaf chlorophyll content and leaf water potential of intercropped wheat were higher than those of sole cropping, and leaf chlorophyll content, leaf relative water content, and

leaf water potential of intercropped faba-bean were significantly higher than those of sole faba-bean. Compared with conventional irrigation treatment, transpiration rate and stomatal conductance reduced by 10.99% and 6.66%, respectively, in intercropped wheat leaves, and by 6.78% and 5.32%, respectively, in intercropped faba-bean leaves under alternative irrigation conditions. Thus, leaf water use efficiency of wheat/faba-bean intercropping under alternative irrigation improved. Compared with conventional irrigation, shoot dry weight of sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean decreased, while root/shoot ratio significantly increased under alternative irrigation. The root/shoot ratio of sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean in alternative irrigation treatments were 14.47%, 7.56%, 36.36%, and 19.63% higher than those of conventional irrigation, respectively. Compared with sole cropping, yield of intercropping treatments generally increased. The harvest indexes of intercropped wheat under alternative and conventional irrigation increased by 8.68% and 2.72% over those of corresponding sole wheat treatment, respectively. Also, harvest index of intercropped faba-bean under alternative and conventional irrigation increased by 4.78% and 5.23% over those of the corresponding sole faba-bean treatment, respectively. In conclusion, wheat/faba-bean intercropping under alternative irrigation maintained high leaf water use efficiency of wheat and faba-bean by increasing root growth and root/shoot ratio. It significantly reduced excessive transpiration without much reduction in photosynthetic rate. The research suggested that wheat/faba-bean intercropping under alternative irrigation had the potential for the realization of high-quality and efficient irrigation.

Keywords: Alternative irrigation; Wheat/faba-bean strip intercropping; Water use efficiency; Biomass; Yield; Harvest index

Introduction

The constraint of water and soil resource shortages on agricultural production is intensifying, making research on efficient irrigation techniques crucial for improving resource utilization efficiency and promoting agricultural development. As the critical system for material and information exchange between aboveground and underground parts of crops, roots significantly influence crop growth, development, and yield formation. Alternative partial root-zone irrigation actively controls the alternating wetting and drying of root zones, subjecting partial roots to moderate water stress and stimulating compensatory absorption functions [1]. When part of the root system experiences water stress, the root-sourced signal abscisic acid (ABA) is transported to leaves, regulating stomata to maintain optimal opening and achieving water savings without sacrificing photosynthate accumulation [2]. The water-saving mechanism is based on the relationship between photosynthesis, transpiration, and stomatal opening, as well as the regulation of stomatal aperture by crop water stress signals gen-

erated from soil water deficits [3]. Numerous studies have demonstrated that alternative partial root-zone irrigation technology can effectively control crop growth redundancy, regulate the proportion and distribution of photosynthates between roots and shoots, optimize root/shoot ratio, substantially reduce leaf transpiration losses while maintaining similar photosynthetic rates, and improve leaf water use efficiency [1, 4-8].

Intercropping is an essential component of China's traditional intensive cultivation agriculture and plays a vital role in promoting sustainable agricultural development. Current intercropping research has primarily focused on crop combinations in mixed populations [9], pest and disease control [10], nutrient utilization [11-13], and light energy utilization [14], while studies on efficient water management mechanisms in mixed populations remain relatively weak. Moreover, previous research on water utilization in mixed populations has been established under relatively high water supply levels, making it difficult to serve as a technical basis for efficient water management in water-limited areas. In intercropping systems composed of two or more crops with different water requirements, traditional intercropping irrigation regimes are formulated based on the water requirements of only one crop, easily causing a mismatch between water supply and demand for paired crops and increasing ineffective water loss. Therefore, designing intercropping irrigation regimes that simultaneously consider the water requirements of different crops and interspecific complementary water-use mechanisms, while providing separate water supply for different crops, can improve the match between water supply and crop demand in intercropping systems and create an alternating water supply pattern among different crops, forming a model similar to alternative irrigation technology. From 2006 to 2009, we studied the water-saving effects of implementing alternative partial root-zone irrigation in wheat (*Triticum aestivum*) intercropped with maize (*Zea mays*) in the arid desert oasis region of the Shiyang River Basin in Gansu Province, confirming the substantial water-saving and yield-increasing potential of this technique for wheat/maize intercropping in arid desert oasis areas. However, due to limitations of field experimental conditions, systematic and in-depth research on the growth and physiological-ecological regulation mechanisms of wheat/faba-bean (*Vicia faba*) intercropping under root-zone irrigation patterns has been lacking. Therefore, this study employed a root box water control experiment with alternative irrigation in wheat/faba-bean intercropping to investigate the effects of alternative irrigation on growth regulation and water physiology of wheat/faba-bean intercropping, providing theoretical and practical support for constructing intercropping water-saving techniques based on alternative irrigation theory.

Materials and Methods

1.1 Experimental Materials

The experiment was conducted from March to November 2008 in a net room at Gansu Agricultural University. The tested soil was alkaline irrigation silt soil collected from the university's practice base, with a field capacity of 24.24%, total nitrogen and phosphorus contents of $1.73 \text{ g} \cdot \text{kg}^{-1}$ and $0.75 \text{ g} \cdot \text{kg}^{-1}$, respectively, available nitrogen of $190.6 \text{ mg} \cdot \text{kg}^{-1}$, available phosphorus of $30.18 \text{ mg} \cdot \text{kg}^{-1}$, and pH 7.95. The spring wheat variety was 'Yongliang 4' provided by Gansu Academy of Agricultural Sciences, and the faba-bean variety was 'Linxian 5' provided by Linxia Institute of Agricultural Sciences. Root boxes were made of PVC (polyvinyl chloride) with dimensions of $90 \text{ cm} \times 30 \text{ cm} \times 60 \text{ cm}$, surrounded by wooden boards. For monoculture treatments, PVC plates divided each box into two chambers to separate the root growth zones of wheat and faba-bean, while intercropping treatments used no partition, allowing free root intermingling between the two crops.

1.2 Experimental Design and Management

The experiment comprised two irrigation methods [traditional irrigation (T), where the entire box soil was uniformly watered each time, and alternative irrigation (A), where each furrow underwent wet-dry alternation between two irrigations, with the initially irrigated furrow not receiving water next time, repeating alternately] and three planting patterns [sole wheat (SW), sole faba-bean (SF), and wheat/faba-bean intercropping (W/F)], forming six treatments with three replications each. The field structures of wheat/faba-bean intercropping, sole wheat, and sole faba-bean are shown in [Figure 1: see original paper]. Both sole wheat and sole faba-bean were planted with three rows per box at 15 cm row spacing. Wheat/faba-bean intercropping used single-row planting with 15 cm row spacing and a 1:1 land occupation ratio. Pre-sowing fertilization levels were consistent across all boxes at $200 \text{ mg} \cdot \text{kg}^{-1}$ soil for nitrogen (pure N) and $200 \text{ mg} \cdot \text{kg}^{-1}$ soil for phosphorus (pure P O). The tested soil was air-dried, passed through a 2 mm sieve, mixed uniformly with fertilizer, and loaded into root boxes. Water was added to reach 60% of field capacity, ensuring uniform moisture content across treatments. After the surface soil dried slightly, seeds were sown following germination pretreatment, and seedlings were thinned after emergence.

The root boxes were placed outdoors with a plastic shed overhead to exclude rainwater interference. After lining the box walls with plastic film, 150 kg of soil mixed with fertilizer was loaded. During soil loading, two PVC pipes (2.5 cm diameter) were inserted in the center of each row for irrigation, with three rows of 5 mm diameter holes (15 holes per row, 2.5 cm spacing) drilled on the pipes for water seepage. The pipes were filled with gravel and wrapped with two layers of gauze at the bottom and around to prevent soil compaction from irrigation. Micro-ridges were formed along the box width direction for crop sowing,

creating 10 cm irrigation furrows between ridges. When wheat and faba-bean seedlings emerged, the irrigation amount was determined using the weighing method with sole wheat and sole faba-bean as controls, maintaining soil moisture at 60% of field capacity throughout the growth period with irrigation every 5 days. Traditional irrigation distributed water evenly across furrows, while alternative irrigation alternated between irrigated and non-irrigated adjacent furrows. Wheat was sown on March 15, faba-bean on March 25. After seedling emergence, plants were thinned to 15 wheat plants per row and 3 faba-bean plants per row. Wheat was harvested on July 8, and faba-bean on July 10. All other field management measures were consistent across treatments.

1.3 Measurement Items and Methods

Chlorophyll content: Fresh leaves of wheat and faba-bean were collected at the jointing, heading, and filling stages of wheat, washed with deionized water in the laboratory, and 0.05 g of mixed fresh leaves was weighed and measured using the acetone-anhydrous ethanol mixed extraction method.

Photosynthetic diurnal variation: Uniform and robust wheat and faba-bean plants were selected for measurement. For faba-bean, the third fully expanded mature leaf from the top was chosen, while for wheat, the flag leaf was used. A CI-301 portable photosynthesis system (CID, USA) was employed to measure leaf photosynthetic rate, transpiration rate, and stomatal conductance. Measurements were taken every 2 hours from 6:00 to 18:00 on June 10, 2008, with three replicates per measurement.

Leaf relative water content (RWC): At the jointing, heading, and filling stages of wheat, six functional leaves per box were collected and cut into approximately 1 cm segments. After mixing, they were divided into three portions, weighed, and placed in petri dishes with distilled water to saturate for 24 hours before reweighing and oven-drying at 80°C to constant weight. RWC was calculated as:

$$\text{RWC (\%)} = \frac{(\text{fresh weight} - \text{dry weight})}{(\text{saturated weight after imbibition} - \text{dry weight})} \times 100\% \quad (1)$$

Leaf water potential: Measured using a WP4 dew point soil/plant water potential meter (USA) based on the principle that an object's water potential has a functional relationship with the water vapor pressure when the object reaches equilibrium in space. At temperature equilibrium, WP4 calculates object water potential by measuring the relative humidity of a sealed sample chamber. The device enables internal temperature control between 15-40°C with $\pm 0.2^\circ\text{C}$ precision. Fresh leaves of wheat and faba-bean were randomly collected at jointing, heading, and filling stages between 9:00-11:00 AM and placed in the sample chamber for measurement.

Root/shoot ratio: After harvest, roots and aboveground parts were collected from each treatment, killed at 105°C for 30 minutes, and oven-dried at 60°C to constant weight. Root/shoot ratio was calculated as:

$$\text{Root/shoot ratio (\%)} = \frac{\text{root dry weight}}{\text{aboveground dry weight}} \times 100\% \quad (2)$$

Yield: Twenty wheat plants and five faba-bean plants were sampled after harvest to determine air-dried mass and calculate yield.

1.4 Data Processing

Data processing and graphing were performed using Microsoft Excel 2007. One-way ANOVA and LSD ($\alpha = 0.05$) in SPSS 16.0 statistical software were used for variance analysis and multiple comparisons.

Results

2.1 Changes in Leaf Photosynthetic Physiological Characteristics of Wheat/Faba-Bean Intercropping System Under Different Irrigation Methods

2.1.1 Changes in Chlorophyll Content Measurement results of leaf chlorophyll content in wheat and faba-bean at different growth stages under alternative irrigation conditions (Table 1) showed similar trends across treatments. Wheat chlorophyll content at the milky stage was significantly lower than at the heading stage, while faba-bean chlorophyll content at the pod-setting stage was significantly lower than at the flowering/squaring stage. Compared with sole wheat, intercropped wheat chlorophyll content increased by 1.89%-26.66%, with significant differences at the milky stage under alternative irrigation treatment. Compared with sole faba-bean, intercropped faba-bean chlorophyll content increased by 13.93%-29.79%, with all differences reaching significance. Alternative irrigation increased chlorophyll content in upper leaves of wheat/faba-bean intercropping, particularly at wheat milky stage and faba-bean pod-setting stage, where intercropped wheat chlorophyll content under alternative irrigation increased by 1.56%-8.14% compared with conventional irrigation, and intercropped faba-bean chlorophyll content increased by 6.47%-10.03%, though differences were not significant. Chlorophyll content of sole wheat and sole faba-bean under alternative irrigation decreased slightly compared with conventional irrigation by 0.15%-5.09% and 0.28%-1.88%, respectively, but differences were not significant. ANOVA results indicated that planting pattern significantly affected leaf chlorophyll content at all growth stages except wheat heading stage ($P < 0.05$), while irrigation method had no significant effect on chlorophyll content across treatments ($P > 0.05$). Therefore, alternative irrigation did not

reduce crop adaptability to drought environments or affect the sensitivity of chlorophyll to stress-induced damage.

2.1.2 Diurnal Photosynthetic Variation Figure 2 [Figure 2: see original paper] compares the full-day photosynthetic characteristics of crops at key growth stages (wheat filling stage, faba-bean pod-setting stage) under different irrigation conditions in June (weather conditions: daily maximum temperature 31.7°C, minimum temperature 13.9°C, average air humidity 32.6%, sunny). All treatments showed synchronized “double-peak” curves for net photosynthetic rate (P_n) diurnal variation, with the first peak around 12:00 and the second peak delayed to around 16:00, with a noticeable photosynthetic “midday depression” at 14:00. Comparison between irrigation methods revealed that P_n peaks under conventional irrigation were higher than those under alternative irrigation, with insignificant differences in the morning but significant differences in the afternoon. Compared with conventional irrigation, alternative irrigation reduced average P_n by 8.00%, 1.59%, 9.91%, and 1.48% for sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean, respectively, with no significant differences between the two irrigation methods ($P > 0.05$). Among planting patterns, intercropped wheat/faba-bean under alternative irrigation increased P_n by 1.10%–25.69% and 1.60%–19.79% compared with sole wheat and sole faba-bean, respectively.

Irrigation methods affected transpiration rate (Tr) differently across planting patterns. Under conventional irrigation, Tr diurnal variation of sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean showed consistent “double-peak” curves with peaks at 12:00 and 16:00. Under alternative irrigation, Tr diurnal variation showed single-peak curves with decreased values at all time periods, peaking at 14:00 in the afternoon—a relative lag compared with photosynthesis. This occurred because under alternative irrigation, leaf water deficit reduced water vapor saturation in mesophyll cell interspaces, keeping crop transpiration relatively low. Compared with conventional irrigation, alternative irrigation reduced average Tr by 6.45%, 13.16%, 10.99%, and 6.66% for sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean, respectively. Among planting patterns, intercropped wheat and faba-bean increased leaf Tr by 9.17% and 7.66% on average compared with corresponding sole crops. ANOVA results showed that planting pattern had significant effects on leaf Tr across treatments ($P < 0.05$), while irrigation method significantly affected Tr in intercropped wheat and sole faba-bean treatments ($P < 0.05$).

Higher stomatal conductance (G_s) facilitates water-gas exchange, while lower G_s inhibits water loss. Figure 2 [Figure 2: see original paper] shows that under conventional irrigation, G_s diurnal variation of sole wheat, sole faba-bean, and wheat/faba-bean intercropping exhibited “double-peak” curves. Under alternative irrigation, no “double-peak” characteristics were observed, and G_s values decreased across all time periods and planting patterns. Alternative irrigation reduced G_s by 19.32%, 18.71%, 20.99%, and 11.63% for sole wheat, sole faba-

bean, intercropped wheat, and intercropped faba-bean, respectively, compared with conventional irrigation. Compared with corresponding sole crops, the reduction amplitude of Gs in intercropped wheat and faba-bean under alternative irrigation was 2.01% and -0.29%, respectively, while under conventional irrigation it was -0.06% and 7.75%, respectively.

At the single-leaf level, water use efficiency (WUE) under alternative irrigation increased by -0.40%, 3.84%, 8.88%, and 10.76% for sole wheat, sole faba-bean, intercropped wheat, and intercropped faba-bean, respectively, compared with conventional irrigation. ANOVA results indicated that planting pattern had no significant effect on leaf WUE across treatments ($P > 0.05$), while irrigation method significantly affected leaf WUE in sole and intercropped faba-bean treatments ($P < 0.05$). These results demonstrate that alternative irrigation can reduce transpiration rate and stomatal conductance while maintaining essentially unchanged photosynthetic rate, thereby improving crop water use efficiency. The underlying mechanism may be that alternative irrigation in wheat/faba-bean intercropping subjects wheat and faba-bean to moderate drought stress, inducing roots to synthesize more ABA, which regulates stomatal opening in aboveground leaves, reduces luxury transpiration, and improves single-leaf water use efficiency. Therefore, implementing alternative irrigation in wheat/faba-bean intercropping is feasible for improving single-leaf water use efficiency.

2.2 Changes in Water Characteristics of Wheat/Faba-Bean Intercropping System Under Different Irrigation Methods

2.2.1 Leaf Relative Water Content Leaf relative water content is an accurate indicator for evaluating leaf water status and reflects tissue resistance to dehydration. The results (Table 2) showed that wheat and faba-bean responded differently to planting patterns in terms of leaf relative water content. Under alternative irrigation, intercropped wheat leaf relative water content decreased by 0.51%, 3.22%, and 1.66% at jointing, heading, and filling stages, respectively, compared with corresponding sole crops. Under conventional irrigation, intercropped wheat leaf relative water content decreased by 3.96%, 2.64%, and 1.64% at jointing, heading, and filling stages, respectively. In contrast, intercropped faba-bean leaf relative water content under alternative irrigation increased by 0.66%, 2.22%, and 2.54% at jointing, squaring, and pod-setting stages, respectively, compared with sole faba-bean, while under conventional irrigation it increased by 2.84%, 3.13%, and 2.87%, respectively. Between irrigation methods, alternative irrigation reduced leaf relative water content across treatments by 0.26%–4.29%. Alternative irrigation reduced leaf relative water content of sole wheat and intercropped wheat by 2.35% and 1.35% on average compared with conventional irrigation, with sole wheat showing significant differences at the jointing stage. Alternative irrigation reduced leaf relative water content of intercropped and sole faba-bean by 0.87% and 2.06%, respectively, with no significant differences ($P > 0.05$). These results indicate that alternative irrigation did not significantly affect leaf relative water content in either intercropping

or sole cropping. However, during the experiment, wheat and faba-bean under alternative irrigation showed obvious leaf shedding at maturity, exhibiting water deficit symptoms. Since upper leaves have stronger water absorption capacity than lower leaves, water deficit in lower leaves caused shedding. As leaf relative water content is generally measured using middle newly developed leaves, differences between irrigation treatments were not significant. The trend of leaf relative water content remained basically unchanged with crop growth progression but gradually decreased during later growth stages, reflecting leaf senescence patterns in wheat and faba-bean.

2.2.2 Leaf Water Potential Leaf water potential is an important physiological indicator reflecting plant water deficit. Table 3 shows that throughout the experiment, leaf water potential of intercropped wheat was generally higher than that of sole wheat, increasing by 4.71%, 1.61%, and 0.72% at jointing, heading, and filling stages, respectively, though differences were not significant ($P > 0.05$). Intercropped faba-bean leaf water potential was higher than that of sole faba-bean, increasing by 7.63%, 4.93%, and 4.38% at jointing, squaring, and pod-setting stages, respectively, with significant differences at the jointing stage ($P < 0.05$). Between irrigation methods, alternative irrigation reduced water potential, with intercropped and sole wheat water potential decreasing by 7.79% and 8.54% on average compared with conventional irrigation, and intercropped and sole faba-bean decreasing by 9.78% and 9.10%, respectively. No significant differences were observed except at the jointing stage of wheat and faba-bean ($P > 0.05$). These results demonstrate that wheat/faba-bean intercropping under alternative irrigation can meet the normal growth requirements of crops at different growth stages while reducing irrigation amounts.

2.3 Effects of Different Irrigation Methods on Biomass Distribution in Wheat/Faba-Bean Intercropping System

Table 4 shows that wheat/faba-bean intercropping significantly promoted wheat root growth, with root dry weight of intercropped wheat under alternative and conventional irrigation increasing by 20.95% and 36.97% on average compared with corresponding sole wheat, respectively ($P < 0.01$). Compared with conventional irrigation, alternative irrigation treatments had greater root dry weight, with sole and intercropped wheat root dry weight increasing by 27.27% and 12.39%, respectively, and sole and intercropped faba-bean root dry weight increasing by 19.63% and 7.56%, respectively. Aboveground dry matter weight of wheat/faba-bean intercropping was higher than that of sole cropping, while conventional irrigation treatments had higher aboveground dry matter weight than alternative irrigation treatments, though no significant differences were observed ($P > 0.05$). Among planting patterns, only the root/shoot ratio of intercropped wheat under conventional irrigation was significantly higher than that of sole wheat, with no significant differences among other treatments. Compared with conventional irrigation, alternative irrigation increased root/shoot ratio of sole and intercropped wheat by 36.36% and 14.47%, respectively, and

that of sole and intercropped faba-bean by 16.67% and 18.18%, respectively. These results may be explained by the fact that under alternative irrigation conditions, wheat and faba-bean in intercropping adapted to soil water stress by self-regulating photosynthate distribution, enhancing root development, increasing root absorption capacity, and preferentially allocating photosynthates to roots to maintain their functional performance, though this increase was constrained by aboveground parts. Root/shoot ratio is an important indicator reflecting aboveground and underground growth. Increased photosynthate supply to roots affects aboveground growth, making root/shoot ratio a key measure of crop environmental adaptation. The increased root/shoot ratio under alternative irrigation enhances crop drought resistance and creates conditions for enhanced later-stage regulation and compensatory growth.

2.4 Effects of Different Irrigation Methods on Yield of Wheat/Faba-Bean Intercropping System

Planting pattern and irrigation method affected wheat and faba-bean yield differently. Intercropping promoted plant growth and yield increase. Compared with sole wheat, intercropped wheat increased economic yield, biomass yield, and harvest index by 15.64%, 10.61%, and 5.71% on average, respectively. Intercropped faba-bean increased economic yield, biomass yield, and harvest index by 6.71%, 1.77%, and 5.01% on average compared with sole faba-bean. Between irrigation methods under sole cropping, alternative irrigation reduced wheat economic yield, biomass yield, and harvest index by 11.22%, 6.32%, and 5.24%, respectively, compared with conventional irrigation, with significant differences in economic yield but not in biomass yield or harvest index. Alternative irrigation reduced faba-bean economic yield and harvest index by 0.42% and 2.66%, respectively, while increasing biomass yield by 2.31% compared with conventional irrigation, with no significant differences among any yield components. For intercropping, alternative irrigation reduced wheat economic yield and biomass yield by 0.86% and 1.82%, respectively, while increasing harvest index by 0.95% compared with conventional irrigation. Alternative irrigation reduced faba-bean economic yield, biomass yield, and harvest index by 3.45%, 0.35%, and 3.12%, respectively, with no significant differences among any indicators (Table 5).

ANOVA results showed that planting pattern had significant effects on wheat economic yield, biomass yield, and harvest index (F-values of 6.043, 6.798, and 5.774, respectively). Planting pattern also had significant effects on faba-bean economic yield and biomass yield (F-values of 6.943 and 6.051, respectively) but not on harvest index (F = 3.774). Irrigation method had no significant yield effects on any of the three indicators. The interaction between irrigation method and planting pattern had significant effects on wheat biomass yield and faba-bean economic yield, but not on other indicators.

Discussion and Conclusion

Chlorophyll, as a photosynthetic pigment, participates in light energy absorption, transfer, and conversion in photosynthesis. Its content determines leaf photosynthetic rate and serves as an important physiological indicator of leaf senescence. Although intercropping has been shown to increase chlorophyll content in functional leaves [15–16], unreasonable crop combinations and water management systems may reduce chlorophyll content. Previous studies have shown that under mild or moderate drought stress, crop chlorophyll and photosynthetic rate decrease [17], while water stress-induced non-hydraulic signals (ABA) transmitted to leaves induce stomatal closure or partial closure [18], reducing transpiration rate. When the reduction in photosynthetic rate (P_n) is relatively small, instantaneous water use efficiency (P_n/Tr) increases. This study demonstrated that alternative irrigation increased chlorophyll content in intercropped wheat and faba-bean leaves. The diurnal variation curves of net photosynthetic rate and transpiration rate for wheat and faba-bean under different treatments were “double-peak” types with photosynthetic “midday depression.” Stomatal conductance under conventional irrigation showed “double-peak” curves, while alternative irrigation showed no “double-peak” characteristics. Under different treatments, alternative irrigation did not significantly change the daily average net photosynthetic rate compared with conventional irrigation, while significantly reducing daily average transpiration rate and stomatal conductance. This may occur through actively reducing stomatal opening to inhibit transpiration and balance plant water use, achieving optimized water distribution under deficit irrigation conditions [19–20]. Compared with sole cropping, wheat/faba-bean intercropping has certain photosynthetic advantages. Under alternative irrigation conditions, compensatory water absorption increased chlorophyll content in intercropped wheat and faba-bean leaves, thereby improving net photosynthetic rate. These results indicate that alternative irrigation in wheat/faba-bean intercropping can regulate crop stomatal movement, maintain partial roots in relatively dry areas, reduce luxury transpiration water consumption, and greatly improve water use efficiency.

Plant water characteristics represent structural responses to environmental conditions [21]. Reduced leaf water potential facilitates water absorption from soil and reduces water loss to the atmosphere, maintaining plant growth under water stress [22]. In this experiment, crop leaf water potential decreased with growth progression, consistent with previous research [23]. Compared with conventional irrigation, alternative irrigation reduced leaf relative water content and leaf water potential, but not significantly, indicating that alternative irrigation crops increased drought tolerance and resistance as soil moisture decreased, consistent with previous conclusions [24]. In the wheat/faba-bean intercropping system, competition for soil water existed between wheat and faba-bean throughout the growth period, but differences were only significant at wheat heading stage, with no obvious differences at other growth stages. This demonstrates that wheat/faba-bean intercropping under alternative irrigation can meet nor-

mal growth requirements at different growth stages while reducing irrigation amounts. Although leaf relative water content and leaf water potential are the best measures of water status, water transport within crops is affected by soil, atmosphere, and water potential gradients in different parts. Therefore, comprehensive analysis of different factors affecting crop water physiology is necessary to fully understand water transport and storage mechanisms in wheat/faba-bean intercropping systems under alternative irrigation.

Crop biomass production and distribution are closely related to environmental conditions. In terms of biomass distribution across treatments, wheat/faba-bean intercropping significantly increased wheat root dry weight, and alternative irrigation significantly affected photosynthate distribution patterns, favoring increased allocation to roots, consistent with previous studies [25-26]. Crop root/shoot ratio is an important indicator of environmental adaptation. Increased root/shoot ratio enhances crop drought resistance and creates conditions for enhanced regulation and compensatory growth. This study showed that under alternative irrigation, leaf water use efficiency and stomatal limitation remained relatively stable in wheat/faba-bean intercropping, with more biomass allocated to roots of intercropped wheat and faba-bean, significantly increasing root/shoot ratio and enabling acquisition of more water and nutrient resources. Thus, the biomass distribution pattern of wheat and faba-bean in intercropping showed strong adaptability to alternative irrigation.

In summary, alternative irrigation can induce water protection mechanisms in wheat/faba-bean intercropping leaves, increase leaf chlorophyll content, delay leaf senescence, reduce luxury transpiration water consumption while maintaining essentially unchanged photosynthetic rate, and improve water use efficiency at the leaf level. Simultaneously, alternative irrigation can reduce redundant growth of intercropped wheat and faba-bean, promote root growth and development, and stimulate root compensatory functions to maintain crop growth and development in arid and semi-arid intercropping systems, providing a reference basis for promoting wheat/faba-bean intercropping under field conditions.

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