

Regulation effects of water and nitrogen on yield, water, and nitrogen use efficiency of wolfberry post-print

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Abstract

Wolfberry (*Lycium barbarum* L.) is important for health care and ecological protection. However, it faces problems of low productivity and resource utilization during planting. Exploring reasonable models for water and nitrogen management is important for solving these problems. Based on field trials in 2021 and 2022, this study analyzed the effects of controlling soil water and nitrogen application levels on wolfberry height, stem diameter, crown width, yield, and water (WUE) and nitrogen use efficiency (NUE). The upper and lower limits of soil water were controlled by the percentage of soil water content to field water capacity (f), and four water levels, i.e., adequate irrigation (W0, 75%-85% f), mild water deficit (W1, 65%-75% f), moderate water deficit (W2, 55%-65% f), and severe water deficit (W3, 45%-55% f) were used, and three nitrogen application levels, i.e., no nitrogen (N0, 0 kg/hm²), low nitrogen (N1, 150 kg/hm²), medium nitrogen (N2, 300 kg/hm²), and high nitrogen (N3, 450 kg/hm²) were implied. The results showed that irrigation and nitrogen application significantly affected plant height, stem diameter, and crown width of wolfberry at different growth stages ($P < 0.01$), and their maximum values were observed in W1N2, W0N2, and W1N3 treatments. Dry weight per plant and yield of wolfberry first increased and then decreased with increasing nitrogen application under the same water treatment. Dry weight per hundred grains and dry weight percentage increased with increasing nitrogen application under W0 treatment. However, under other water treatments, the values first increased and then decreased with increasing nitrogen application. Yield and its component of wolfberry first increased and then decreased as water deficit increased under the same nitrogen treatment. Irrigation water use efficiency (IWUE, 8.46 kg/(hm² • mm)), WUE (6.83 kg/(hm² • mm)), partial factor productivity of nitrogen (PFPN, 2.56 kg/kg), and NUE (14.29 kg/kg) reached their highest values in W2N2, W1N2, W1N2, and W1N1 treatments. Results of principal component analysis (PCA) showed that yield, WUE, and NUE were better in W1N2

treatment, making it a suitable water and nitrogen management mode for the irrigation area of the Yellow River in the Gansu Province, China and similar planting areas.

Full Text

Preamble

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Regulation Effects of Water and Nitrogen on Yield, Water, and Nitrogen Use Efficiency of Wolfberry

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Abstract: Wolfberry (*Lycium barbarum* L.) is important for health care and ecological protection, yet faces problems of low productivity and resource utilization during cultivation. Exploring reasonable water and nitrogen management models is crucial for addressing these challenges. Based on field trials conducted in 2021 and 2022, this study analyzed the effects of controlled soil water and nitrogen application levels on wolfberry height, stem diameter, crown width, yield, water use efficiency (WUE), and nitrogen use efficiency (NUE). Soil water limits were controlled as percentages of field water capacity (f), with four water levels: adequate irrigation (W0, 75%-85% f), mild water deficit (W1, 65%-75% f), moderate water deficit (W2, 55%-65% f), and severe water deficit (W3, 45%-55% f). Three nitrogen application levels were applied: no nitrogen (N0, 0 kg/hm²), low nitrogen (N1, 150 kg/hm²), medium nitrogen (N2, 300 kg/hm²), and high nitrogen (N3, 450 kg/hm²). The results showed that irrigation and nitrogen application significantly affected plant height, stem diameter, and crown width at different growth stages ($P < 0.01$), with maximum values observed in W1N2, W0N2, and W1N3 treatments, respectively. Dry weight per plant and yield first increased and then decreased with increasing nitrogen application under the same water treatment. Dry weight per hundred grains and dry weight percentage increased with nitrogen application under W0 treatment, but under other water treatments, these values first increased and then decreased with increasing nitrogen application. Yield and its components first increased and then decreased as water deficit intensified under the same nitrogen treatment. Irrigation water use efficiency (IWUE, 8.46 kg/(hm² · mm)), WUE (6.83 kg/(hm² · mm)), partial factor productivity of nitrogen (PFPN, 2.56 kg/kg), and

NUE (14.29 kg/kg) reached their highest values in W2N2, W1N2, W1N2, and W1N1 treatments, respectively. Principal component analysis (PCA) showed that yield, WUE, and NUE performed best under W1N2 treatment, making it a suitable water and nitrogen management mode for the Yellow River irrigation area of Gansu Province, China, and similar planting regions.

Keywords: water deficit; growth characteristics; yield; water and nitrogen use efficiency; principal component analysis

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1 Introduction

Wolfberry (*Lycium barbarum*) is a perennial deciduous shrub belonging to the Solanaceae family [?]. It is a saline-alkali resistant, barren-resistant, and drought-resistant plant [?] with numerous biological activities, including anti-aging, neuroprotection, metabolism promotion, and immune regulation [?, ?]. The crop holds great significance for improving saline-alkali land, wind prevention, sand fixation, and promoting human health [?]. In recent years, the wolfberry industry has experienced rapid development. By 2020, Chinese wolfberry planting area and output reached more than 9.33×10^4 hm² and 4.00×10^5 t, respectively, accounting for over 95% of the global total [?]. However, wolfberry is primarily cultivated in northwestern China, where soils are poor and water resources are limited [?]. Traditional cultivation practices consume high amounts of water and fertilizer, resulting in low marginal yields, poor water and fertilizer utilization efficiency, substantial greenhouse gas emissions, and declining soil quality [?]. Therefore, exploring reasonable water and nitrogen management strategies is essential for improving wolfberry productivity and ensuring sustainable development.

Water is a critical resource for agricultural production that directly affects crop growth, development, and yield [?, ?]. Appropriate water stress can stimulate plant antioxidant defense mechanisms and osmoregulation, improve cell structure stability, and promote dry matter accumulation [?]. Conversely, excessive or insufficient irrigation can reduce root vitality and slow nutrient absorption, hindering crop growth [?]. Studies have found that moderate water stress benefits wolfberry by increasing plant height, stem diameter, crown width, and shoot growth [?, ?]. Wolfberry yield, WUE, and fruit quality increase with irrigation amount up to a threshold, beyond which they decline [?, ?]. Fertilizer represents another vital agricultural resource, with nitrogen being particularly important [?]. Reasonable nitrogen application can improve root water absorption capacity, coordinate plant water-nitrogen metabolism, promote photosynthesis, and

delay leaf senescence [?]. Research has shown that appropriate nitrogen application significantly increases wolfberry leaf area index and chlorophyll content while promoting fruit shape index development [?, ?]. Wolfberry yield components and WUE increase initially then decrease with rising nitrogen application [?, ?].

Water and nitrogen exhibit interactive effects [?]. The cooperative supply of water and nitrogen forms the material basis of plant physiological metabolism and provides an important guarantee for improving crop quality and production efficiency [?, ?]. In India, Kumar et al. [?] found that cotton leaf area index, dry matter accumulation, growth rate, and relative growth rate peaked with 225 kg/hm² nitrogen application and 600 mm irrigation. In the North China Plain, Si et al. [?] observed that winter wheat yield, WUE, and NUE declined when water and nitrogen application exceeded critical thresholds. In Egypt, Badr et al. [?] found that coupling nitrogen application with appropriate crop water demand significantly increased potato NUE. In Pakistan, Ahmad et al. [?] reported that maize WUE and economic benefits improved significantly when irrigation at 80%-100% field water capacity was combined with 240 kg/hm² nitrogen application. In summary, coupling water and nitrogen control can achieve the effect of “promoting fertilizer with water and transferring water with fertilizer.”

However, current research on water-nitrogen coupling regulation has focused primarily on cotton [?, ?], wheat [?, ?], potato [?, ?], corn [?, ?], tomato [?, ?], and other crops [?, ?, ?]. Studies on wolfberry production have mainly examined single-factor regulation of water or nitrogen [?]. Investigating the effects of cooperative water-nitrogen supply on wolfberry production could help unlock its production potential. Furthermore, determining optimal irrigation and nitrogen application combinations for wolfberry has relied primarily on single-objective evaluation [?, ?], with few studies integrating multiple objectives to evaluate water-nitrogen regulation effects.

The Gansu Province irrigation area, located in the upper reaches of the Yellow River, offers abundant sunshine and significant diurnal temperature variation, making it ideal for wolfberry cultivation due to its unique geographical advantages [?]. In recent years, wolfberry industry development in this region has been rapid, with planting area and dried fruit output both exceeding 45% of the national total, establishing it as an important wolfberry production base in China [?]. However, water resource shortages, extensive agricultural production, and low resource utilization rates seriously restrict local wolfberry industry development [?, ?]. Therefore, this research aimed to: (1) analyze the effects of water and nitrogen regulation on wolfberry growth, yield, WUE, and NUE; and (2) comprehensively evaluate the water-nitrogen management mode that improves wolfberry productivity in the study area and similar regions.

2.1 Study Area

The experiment was conducted at the Irrigation Experimental Station (37°23 N, 104°08 E) of the Jingtaichuan Electric Power Irrigation Water Resource Utilization Center in Gansu Province, China, from May to September in 2021 and 2022. The station is located in the Yellow River irrigation area of Gansu Province, where wolfberries are widely cultivated. The region has an average altitude of 1562 m and a temperate continental arid climate characterized by low precipitation and high evaporation. Annual average precipitation, evaporation, temperature, sunshine duration, radiation, and frost-free period were 184 mm, 3029 mm, 8.6°C, 2652 h, 6.18×10^5 J/cm², and 191 d, respectively. The soil texture was sandy loam with a dry bulk density of 1.61 g/cm³ and field water holding capacity of 24.10%. In the 0–60 cm soil layer, organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium were 1.32 g/kg, 1.62 g/kg, 1.32 g/kg, 34.03 g/kg, 74.51 mg/kg, 26.31 mg/kg, and 173.00 mg/kg, respectively, with a pH of 8.11. Meteorological data were obtained from a small weather station installed in the field. Precipitation and average temperature distributions during the experiment are shown in Figure 1 [Figure 1: see original paper].

2.2 Experimental Design and Soil Sampling

The experiment adopted a randomized block design based on local production practices and previous research [?], with two factors: water and nitrogen application levels. The water treatments controlled the wetting layer depth at 60 cm, with upper and lower soil water limits set as percentages of field water capacity (f): adequate irrigation (W0, 75%–85% f), mild water deficit (W1, 65%–75% f), moderate water deficit (W2, 55%–65% f), and severe water deficit (W3, 45%–55% f). Nitrogen application levels (pure nitrogen as urea with 46% nitrogen content) were: no nitrogen (N0, 0 kg/hm²), low nitrogen (N1, 150 kg/hm²), medium nitrogen (N2, 300 kg/hm²), and high nitrogen (N3, 450 kg/hm²). Sixteen treatments were performed in three replicates. Nitrogen fertilizer was applied at a 6:2:2 ratio during the vegetative growth, full flowering, and summer full fruit stages. Phosphate fertilizer (Ca(H₂PO₄)₂, 12% phosphorus content) and potassium fertilizer (KCl, 60% potassium content) were applied at 130 kg/hm² once annually at the germination stage.

Wolfberry (Ningqi No. 5) was planted in early April 2021 with a plant row spacing of 1.5 m × 3.0 m, with five rows of five trees per plot (76.5 m², 10.2 m × 7.5 m), totaling 20 trees (Fig. 2 [Figure 2: see original paper]). The experiment integrated drip irrigation with water and fertilizer delivery. Irrigation pipes were laid in each plot with valves and water meters installed to control irrigation amounts. Drip irrigation was applied 15 cm from wolfberry trees at a flow rate of 2 L/h. Other field management practices and pest control followed local farming standards.

2.3.1 Soil Moisture Content

A portable time domain reflectometer (TDR, PICO-BT, IMKO, Ettlingen, Germany) measured soil moisture content once every 7 d, both before and after irrigation and rainfall events. The drying method was used regularly to verify soil moisture content. Water consumption (WC; mm) during the wolfberry growth period was calculated as follows:

$$WC = P + W_2 - W_1 + I + K + R + D_p$$

where P is rainfall during the growth period (mm); W_2 is annual water storage (mm) of the 0-120 cm soil layer after harvest; W_1 is annual water storage (mm) in the 0-120 cm soil layer at the experiment's beginning; I is irrigation amount (mm); K is groundwater recharge (mm); R is runoff (mm); and D is deep leakage (mm). Because groundwater depth exceeded 5 m, terrain was flat, and individual rainfall events were small, K , R , and D were considered negligible.

2.3.2 Growth Index

Three wolfberry plants with similar growth trends were randomly selected from each plot to measure plant height, stem diameter, and crown width at vegetative growth, full flowering, summer peak fruit, and autumn peak fruit stages. Plant height (cm) was measured from ground to top using a steel tape. Stem diameter (mm) was measured approximately using vernier calipers. Crown width (cm) was measured in both east-west (E-W) and south-north (N-S) directions using a steel tape.

2.3.3 Yield and Constituent Elements

From late July to August, ripe wolfberries were harvested every 7 d, naturally dried, weighed, and converted to yield (Y ; kg/hm²) per unit area based on plot area (only 2022 production was counted). Three wolfberry plants per plot were grown, and after each fresh fruit harvest, plants were dried and weighed. Dry weights (g) from multiple harvests were summed and averaged to represent dry weight per plant. For each plot, one hundred berries were randomly selected per harvest and immediately weighed to determine fresh weight (FW; g). Dry weight (DW; g) was determined after drying, and dry weight percentage was calculated as:

$$\text{Dry/fresh percentage} = \frac{DW}{FW} \times 100\%$$

2.3.4 Irrigation Water Use Efficiency (IWUE), WUE, Partial Factor Productivity of Nitrogen (PFPN), and NUE

IWUE (kg/(hm² · mm)) was calculated as:

$$\text{IWUE} = \frac{Y}{I}$$

where Y is yield (kg/hm²).

WUE (kg/(hm² · mm)) was calculated as:

$$\text{WUE} = \frac{Y}{WC}$$

PFPN (kg/kg) was calculated as:

$$\text{PFPN} = \frac{Y}{N}$$

where N is nitrogen application rate (kg/hm²).

NUE (kg/kg) was calculated as:

$$\text{NUE} = \frac{Y_{NPK} - Y_{PK}}{N}$$

where $Y_{\{NPK\}}$ is dried fruit yield (kg/hm²) in nitrogen application plots and $Y_{\{PK\}}$ is dried fruit yield (kg/hm²) in plots without nitrogen application.

2.4 Principal Component Analysis (PCA)

PCA is a widely used dimensionality reduction method that converts multiple indicators into several principal components [?].

2.5 Statistical Analysis

Microsoft Excel v.2010 was used for data processing, Origin v.2021 for mapping, and SPSS Statistics v.27.0 for variance analysis, significance testing ($P < 0.05$), and PCA.

3.1.1 Plant Height

Water and nitrogen application levels significantly affected plant height at different wolfberry growth stages ($P < 0.01$). Their interaction also significantly affected plant height at summer and autumn peak fruit stages in both years ($P < 0.01$) and at the full flowering stage in 2022 ($P < 0.05$; Fig. 3 [Figure 3: see original paper]). Under different water and nitrogen levels, wolfberry growth rates varied across stages. Growth was fastest from vegetative to full flowering stages, averaging 24.69% over two years, and slowest from summer to autumn peak fruit stages, averaging 8.50%. Under the same water level, plant height initially increased then decreased with rising nitrogen application, with effects ranking $N2 > N3 > N1 > N0$. Specifically, compared with $N0$, plant height increased by 7.85% for $N1$, 15.33% for $N2$, and 11.83% for $N3$. At the same nitrogen level, plant height initially increased then decreased with intensifying water deficit, ranking $W1 > W0 > W2 > W3$. On average, $W1$ increased 3.03% compared with $W0$, while $W2$ and $W3$ decreased by 6.84% and 19.87%, respectively. Among all treatments, $W1N2$ produced the highest plant height, 19.67% greater than $W0N0$. In conclusion, proper irrigation and nitrogen application promote wolfberry growth, with vegetative and full flowering stages being more sensitive to water and nitrogen than other stages.

3.1.2 Stem Diameter

Water and nitrogen application levels significantly affected stem diameter at different growth stages ($P < 0.01$). Their interaction significantly impacted stem diameter at summer and autumn peak fruit stages in 2021 and at all growth stages in 2022 ($P < 0.05$; Fig. 4 [Figure 4: see original paper]). Under different water and nitrogen levels, stem diameter increased by an average of 33.30% from vegetative to full flowering stages over two years, and by 9.65% from summer to autumn peak fruit stages. Stem diameter initially increased then decreased with rising nitrogen application, peaking under $N2$ treatment, and decreased with reduced irrigation, peaking under $W0$ treatment. Among all treatments, $W0N2$ produced the largest stem diameter, 22.34% greater than $W0N0$. In conclusion, appropriate nitrogen application and irrigation promote stem diameter growth at different wolfberry growth stages, particularly during vegetative and full flowering stages.

3.1.3 Crown Width

Water and nitrogen application levels significantly affected crown width at each growth stage ($P < 0.01$), and their interaction significantly affected crown width at summer and autumn peak fruit stages in 2021 and at each growth stage (except vegetative) in 2022 ($P < 0.05$; Table 1). Under different water and ni-

trogen levels, crown width increased fastest from vegetative to full flowering stages, slowest from summer to autumn peak fruit stages, and east-west crown width was significantly larger than north-south crown width. Under W0 and W1 treatments, north-south and east-west crown widths increased with nitrogen application at each growth stage. Under W2 and W3 treatments, crown widths initially increased then decreased with nitrogen application, ranking $N2 > N3 > N1 > N0$. With the same nitrogen application, north-south and east-west crown widths initially increased then decreased with intensifying water deficit, ranking $W1 > W0 > W2 > W3$. Maximum crown widths occurred in W1N3 treatment, increasing by 26.03% (north-south) and 21.88% (east-west) compared with W0N0. Minimum values occurred in W3N0 treatment, decreasing by 20.15% and 19.92%, respectively, compared with W0N0. The W1N3 treatment demonstrated the best water-nitrogen coupling effect for crown width.

3.2 Effects of Water and Nitrogen Application Levels on Yield and Yield Components of Wolfberry

Water and nitrogen application levels significantly affected wolfberry yield and yield components ($P < 0.01$), and their interaction significantly affected dry weight per hundred grains, dry:fresh ratio, and yield ($P < 0.05$; Table 2). Under the same water level, dry weight per plant and yield initially increased then decreased with rising nitrogen application, with N2 producing the highest yield, followed by N3, N1, and N0. Under W0 treatment, dry weight per hundred grains and dry weight percentage increased with nitrogen application, while under W1, W2, and W3 treatments, these parameters initially increased then decreased with nitrogen application. Under the same nitrogen level, yield and yield components initially increased then decreased with intensifying water deficit, ranking $W1 > W0 > W2 > W3$. The W1N2 treatment produced the highest values for dry weight per plant, dry weight per hundred grains, dry weight percentage, and yield, increasing by 47.55%, 47.85%, 16.31%, and 47.55%, respectively, compared with W0N0. The W3N0 treatment produced the lowest dry weight per plant, dry weight per hundred grains, and yield, decreasing by 23.04%, 22.74%, and 23.04%, respectively, compared with W0N0. The W3N3 treatment had the smallest dry weight percentage, 6.42% lower than W0N0. In conclusion, under mild water deficit, excessive nitrogen application can inhibit wolfberry yield.

3.3 Effects of Water and Nitrogen Application Levels on WUE and NUE of Wolfberry

Water and nitrogen application levels significantly affected WUE and NUE ($P < 0.01$), and their interaction significantly affected WC, WUE, and PFPN

($P < 0.01$; Table 3). Under the same water level, IWUE, WUE, and NUE initially increased then decreased with rising nitrogen application, while PFPN decreased with nitrogen application. Under the same nitrogen level, IWUE and WUE initially increased then decreased with intensifying water deficit under N2 and N3 treatments, while PFPN and NUE initially increased then decreased under other treatments. Among all treatments, W2N2 had the highest IWUE (8.46 kg/($\text{hm}^2 \cdot \text{mm}$)), W1N2 had the highest WUE (6.83 kg/($\text{hm}^2 \cdot \text{mm}$)) and NUE (2.56 kg/kg), and W1N1 had the highest PFPN (14.29 kg/kg).

3.4 Comprehensive Analysis of Wolfberry Under Different Water and Nitrogen Application Levels

3.4.1 Correlation Analysis

Correlation analysis was conducted for plant height, stem diameter, north-south crown width, east-west crown width, dry weight per plant, dry weight per hundred grains, dry weight percentage, irrigation amount, nitrogen application rate, WC, IWUE, WUE, PFPN, NUE, and yield under different water and nitrogen levels (Fig. 5 [Figure 5: see original paper]). Correlation coefficients among indicators exceeded 0.600, indicating highly significant correlations among selected parameters.

3.4.2 PCA

PCA revealed that PC1 and PC2 accounted for 61.58% and 23.25% of variance, respectively, with cumulative variance of 84.82% (Fig. 6 [Figure 6: see original paper]). PC1 contained 61.58% of total variation, reflecting effects of 12 indices including plant height, stem diameter, north-south crown width, east-west crown width, dry weight per plant, dry weight per hundred grains, dry weight percentage, nitrogen application rate, yield, PFPN, NUE, and WUE. PC2 explained 23.25% of total variation, reflecting effects of three indices: irrigation, WC, and IWUE. According to comprehensive score rankings (Fig. 7 [Figure 7: see original paper]), W1 had the highest score among water levels, and N2 had the highest score among nitrogen levels. Among all treatments, W1N2 achieved the highest comprehensive score.

4.1 Effects of Water and Nitrogen Application Levels on Wolfberry Growth

Plant height, stem diameter, and crown width are important indicators of wolfberry growth [?]. An appropriate water-nitrogen ratio provides suitable environmental conditions for wolfberry and promotes healthy growth [?]. This study found that east-west crown width was generally larger than north-south crown

width, likely because greater photosynthetically active radiation absorption by the east-west orientation increased photosynthetic intensity, which is more conducive to plant elongation [?]. Plant height, stem diameter, and crown width increased fastest from vegetative to full flowering stages, while growth was slowest from summer to autumn peak fruit stages. This phenomenon indicates that wolfberry is more sensitive to water and nitrogen during vegetative and full flowering stages than other stages.

Plant height initially increased then decreased with decreasing irrigation amount (204.69–452.84 mm). However, Yin et al. [?] reported that plant height initially increased, then decreased, then increased again with decreasing irrigation amount (210.00–510.00 mm). These differences may relate to soil texture (sandy loam vs. lime soil) and groundwater depth (5 m vs. 1 m). Lime soil has lower water and gas permeability than sandy loam, and root rot occurs under excessive irrigation. When irrigation is insufficient and groundwater is shallow, wolfberry can utilize groundwater for growth. A certain degree of water deficit and reduced nitrogen application benefits crop growth, while excessive or insufficient water and nitrogen cause growth retardation [?, ?]. This study showed that plant height initially increased then decreased with decreasing irrigation and nitrogen application. Stem diameter decreased with decreasing irrigation but initially increased then decreased with decreasing nitrogen application. Water drives plant cell expansion and growth; suitable soil water status promotes nitrogen migration, absorption, and utilization, enhancing root and canopy growth [?]. Dissolved nitrogen reduces soil water evaporation, enhances leaf photosynthesis, and promotes stem and leaf growth [?, ?]. This study also concluded that water-nitrogen interaction significantly affected plant height, stem diameter, and crown width at summer and autumn peak fruit stages.

4.2 Effects of Water and Nitrogen Application Levels on Wolfberry Yield and Yield Components

Appropriate water and nitrogen input during crop growth promotes nutrient and water absorption, increasing yield [?, ?]. Proper nitrogen application increases leaf chlorophyll content, promotes photosynthetic product accumulation, and facilitates yield formation [?]. Dry weight per plant, dry weight per hundred grains, and dry weight percentage are main wolfberry yield components. This study showed that under the same water treatment, dry weight per plant and yield initially increased then decreased with decreasing nitrogen application. Under W0 treatment, dry weight per hundred grains and dry weight percentage increased with nitrogen application, while under W1, W2, and W3 treatments, these parameters initially increased then decreased with nitrogen application.

Under the same nitrogen application, wolfberry yield initially increased then decreased with increasing irrigation amount (204.69–452.84 mm). However, Wang et al. [?] found that wolfberry yield increased as the lower irrigation limit rose

from 30% to 70% f when the upper limit was 95% f. These differences may stem from smaller irrigation gradients (10% f) in this study, resulting in longer irrigation durations. Frequent irrigation aggravates ion flow, particularly of available nutrients, reducing soil fertility in the root layer and limiting crop ability to obtain sufficient water and fertilizer, ultimately restricting dry matter accumulation [?]. Under suitable water-nutrient conditions, enhanced soil nitrogen assimilation and transport capacity improve root vitality, increase enzyme synthesis in the photosynthetic system, accelerate net photosynthetic rate, and improve dry matter accumulation capacity [?, ?].

This study also showed that wolfberry yield initially increased then decreased with decreasing irrigation and nitrogen levels. The W1N2 treatment produced the highest dry weight per plant, dry weight per hundred grains, dry weight percentage, and yield, increasing by 47.55%, 47.85%, 16.31%, and 47.55%, respectively, compared with W0N0. However, Liu et al. [?] found that wolfberry yield initially increased then decreased with decreasing irrigation but gradually decreased with decreasing nitrogen application (207-345 kg/hm²). These differences may be attributed to: (1) varying nitrogen application rates, where lower rates may not have reached the nitrogen requirement threshold; and (2) differences in baseline soil nutrient status (total nitrogen contents of 1.62 vs. 0.36 g/kg). When inherent soil nitrogen content is low, wolfberry growth becomes more dependent on exogenous nitrogen, requiring increased nitrogen application.

4.3 Effects of Water and Nitrogen Application Levels on Wolfberry WUE and NUE

WUE and NUE directly reflect crop water and nitrogen input effects [?, ?]. Insufficient nitrogen in irrigation water weakens plant nitrogen absorption and utilization, while excessive nitrogen causes root rot, reducing WUE and NUE [?, ?]. IWUE, the ratio of yield to irrigation amount, measures irrigation water utilization degree [?]. WUE, the ratio of yield to water consumption, reflects plant production energy conversion efficiency and evaluates growth suitability [?]. This study found that wolfberry IWUE and WUE were higher under mild to moderate water deficit than under full irrigation or severe water deficit, primarily because excessive irrigation caused water accumulation and nutrient loss, while insufficient irrigation induced stomatal closure, chloroplast structure damage, weakened photosynthesis, and reduced dry matter accumulation [?, ?].

PFPN, the ratio between yield and nitrogen application, reflects the combined effect of local soil baseline nutrient level and fertilizer application amount [?]. NUE, the ratio between yield differences in nitrogen and no-nitrogen zones, reflects nitrogen fertilizer utilization rate [?]. Results showed that wolfberry PFPN decreased with increasing nitrogen application, consistent with findings by Abdalhi et al. [?] for corn and cucumber in Jiangsu, China, and Hao et

al. [?] for apple in the Loess Plateau. This indicates a threshold for crop nitrogen absorption; when nitrogen application rates are too high, PFPN decreases significantly, causing serious nitrogen resource waste [?]. This study found that wolfberry PFPN initially increased then decreased with decreasing irrigation amount, while Li et al. [?] reported that tomato PFPN gradually decreased with decreasing irrigation amount under the same nitrogen application. This difference may be crop-type related. Wolfberry water requirement during growth is 60%-70% f, and the maximum irrigation amount (75%-85% f) in this experiment exceeded the appropriate requirement. Tomato water requirement is 60%-80% f, and the maximum irrigation amount (60%-65% f) set by Li et al. [?] did not reach the appropriate requirement. Appropriate water and nitrogen stress can improve plant drought resistance, water-fertilizer absorption capacity, yield, and NUE [?]. This study also found that NUE was highest under mild water deficit (65%-75% f) and moderate nitrogen application (300 kg/hm²).

This study examined water and nitrogen application levels during the entire growth stage. However, wolfberry water and nitrogen requirements vary across growth stages, suggesting that future research should apply water and nitrogen at different growth stages. Additionally, as wolfberry is a perennial economic forest, this research only investigated water and nitrogen effects on 2- and 3-year-old plants. Subsequent studies should examine water-nitrogen regulation thresholds for different planting ages.

5 Conclusions

Irrigation and nitrogen application significantly affected wolfberry growth. The W1N2 treatment produced the highest yield, dry weight per plant, dry weight per hundred grains, and dry weight percentage, which were 47.55%, 47.85%, 16.31%, and 47.55% higher than W0N0, respectively. Appropriate water and nitrogen application can achieve higher wolfberry WUE and NUE. PCA results showed that mild water deficit (65%-75% f) combined with nitrogen application of 300 kg/hm² produced higher yield, WUE, and NUE, representing an appropriate water-nitrogen control mode for wolfberry production in the Yellow River irrigation area of Gansu Province and similar planting regions.

Conflict of Interest

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

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