agronomy

MDPI

Article

Coupling Effect of Water and Soluble Organic Fertilizer on Yield and Quality of *Panax notoginseng* under Micro-Sprinkler Irrigation in Southwest China

Tianqi Mu [1,2,3], Xiulu Yue [1,2,3], Zhennan Zang [1,2,3], Haidong Wang [1,2,3,*], Jiaping Liang [1,2,3,*], Qiliang Yang [1,2,3,*], Jinjin Guo [1,2,3], Na Li [1,2,3], Xiaogang Liu [1,2,3] and Qi You [1]

1 Faculty of Modern Agricultural Engineering, Kunming University of Science and Technology, Kunming 650500, China
2 Yunnan Provincial Field Scientific Observation and Research Station on Water-Soil-Crop System in Seasonal Arid Region, Kunming University of Science and Technology, Kunming 650500, China
3 Yunnan Provincial Key Laboratory of High-Efficiency Water Use and Green Production of Characteristic Crops in Universities, Kunming University of Science and Technology, Kunming 650500, China
* Correspondence: wanghd@nwsuaf.edu.cn (H.W.); liangjpxaut@163.com (J.L.); yangqilianglovena@163.com (Q.Y.)

Abstract: The cultivation of *Panax notoginseng* has been plagued by a multitude of challenges, including recurrent diseases, suboptimal value, inadequate quality, and environmental degradation resulting from improper water and fertilizer management. To address these issues and improve the yield of *P. notoginseng* and its saponin content, this study endeavors to identify the optimal irrigation and fertilization levels in shaded environments in Yunnan Province in Southwest China. In this field experiment, three-year-old plants were tested to evaluate the effects of water, soluble organic fertilizers, and their combinations on plant growth, physiological parameters, yield, and saponin content. The experiment included 12 treatments with three types of irrigation (10 (W_1), 15 (W_2), and 20 (W_3) mm), totaling 440, 660, and 880 mm, and four levels of the total amount of fertilization (F_1 (60, total N 12.6, total P 5.5, and total K 10.5 kg ha^{-1}), F_2 (90, total N 18.9, total P 8.3, and total K 15.7 kg ha^{-1}), F_3 (120, total N 25.2, total P 11.0, and total K 20.9 kg ha^{-1}), F_4 (150, total N 31.5, total P 13.8, and total K 26.1 kg ha^{-1})). The randomized complete block design was used, with 36 plots in total and 3 replications. The study utilized the TOPSIS method to determine the most effective water and fertilizer management strategy for the growth and production of *P. notoginseng*. The assessment of yield, water and fertilizer productivity, and saponin content across all treatments revealed that the W_3F_3 treatment resulted in significant increases in the plant's height, stem diameter, and net photosynthetic rate. Meanwhile, the W_2F_3 treatment exhibited the best root morphological traits. The W_3F_4 treatment effectively increased dry matter and transpiration. The combination of water and fertilization had a coupling effect that not only increased yield to 1400 kg ha^{-1} but also improved water–fertilizer productivity. The application of the W_2F_3 treatment resulted in a significant increase in the accumulation of active components, leading to a total *P. notoginseng* saponin (*PNS*) content of 24.94%. Moreover, the comprehensive index obtained through the TOPSIS model indicated that the W_2F_3 treatment outperformed other treatments. Therefore, this treatment can be considered a promising water and fertilizer model for *P. notoginseng* cultivation, which can enhance its yield, quality, and productivity while promoting sustainable green development.

Keywords: *Panax notoginseng*; irrigation; soluble organic fertilizer; yield; saponin content; TOPSIS model

Citation: Mu, T.; Yue, X.; Zang, Z.; Wang, H.; Liang, J.; Yang, Q.; Guo, J.; Li, N.; Liu, X.; You, Q. Coupling Effect of Water and Soluble Organic Fertilizer on Yield and Quality of *Panax notoginseng* under Micro-Sprinkler Irrigation in Southwest China. *Agronomy* **2023**, *13*, 1742. https://doi.org/10.3390/agronomy13071742

Academic Editor: Robert J. Lascano

Received: 17 May 2023
Revised: 20 June 2023
Accepted: 23 June 2023
Published: 28 June 2023

1. Introduction

Panax notoginseng is a perennial herb belonging to the Araliaceae family and is primarily found in Southwest China, growing at an altitude range of 1200 to 1800 m [1,2].

It possesses hemostatic, detumescence, and pain-relief properties, making it effective in treating cancer, cardiovascular disease, and atherosclerosis [3–5]. Yunnan produced over 90% of *P. notoginseng* in China, and the industry's output value there increased from around CNY 380 million in 2000 to approximately CNY 38 billion in 2020. Thus, improving *P. notoginseng* quality benefits both human health and local economic development. However, excessive irrigation, chemical fertilizers, and pesticide usage cause soil acidification, increased incidence rates of *P. notoginseng*, and decreased yield and quality [6,7]. Therefore, a realistic irrigation and fertilization regulation management tactic was required to develop green products and protect the ecological environment of *P. notoginseng* while managing yield and quality pressures.

P. notoginseng was irrigated primarily based on historical experience and without any scientific direction, which resulted in a significant waste of water resources and made *P. notoginseng* susceptible to ponding and stunted root growth [8]. Excessive soil water reduced soil aeration, inhibited the physiological metabolism and extension of roots, reduced the absorption of nutrients by roots and the active elements in plants, and ultimately led to reduced yield and the frequent occurrence of root rot [6,9–11]. In addition, the pressure caused by the water shortage will hinder gas exchange, limit photosynthesis, affect the accumulation of dry matter, and reduce yield [8,12,13]. For increasing production and quality, efficient water management strategies are essential for *P. notoginseng*'s industrial growth. By keeping the balance between nutrition and reproductive growth, moderate irrigation not only enhances the physiological properties of plants but also increases production [14–16]. Yet, relatively little research has been undertaken on how moderate irrigation affects *P. notoginseng* production and quality.

For enhancing crop yields, fertilizer is the second most important factor [17]. In order to make up for the lack of nutrients in red soil and obtain a higher yield, *P. notoginseng* was treated with a large number of chemical fertilizers during the planting process [11,18,19]. This resulted in soil acidification, nutrient loss, and nitrate pollution, and the remaining chemical fertilizer would also be discharged into the soil and surrounding waters in large amounts, causing great damage to the ecology [11,20]. A reasonable fertilizer plan is needed to ensure the long-term growth of agriculture [21]. To improve soil health and increase crop yields, organic fertilizers are a great alternative to chemical fertilizers [22,23]. The benefits of applying organic fertilizer to soil include the strengthening of soil physical properties, the preservation of fertilizer and water functions, the enhancement of soil nutrient content, the improvement of soil microbial community structure and microenvironment, and the promotion of crop growth for roots and branches [24–29]. Consequently, more research was required to determine how organic fertilizer affected *P. notoginseng* during planting.

P. notoginseng has largely been grown in Yunnan Province using conventional field management techniques. Despite earlier research that concentrated on a single factor, such as fertilization or irrigation, this strategy did not address the difficulties of juggling various goals, such as high efficiency, yield, and quality. Some of these studies were conducted in a controlled pot experiment environment, which would limit their applicability in field studies [30]. A more thorough approach was needed to manage water and fertilizer efficiently, increase output performance, and reduce waste. Consequently, water and fertilizer management strategies based on *P. notoginseng* yield and quality were urgently investigated. As a result, we sought to investigate the effects of irrigation in conjunction with soluble organic fertilizer on the growth, photosynthesis, dry matter, yield, and quality of *P. notoginseng* in this study. In 2019, micro-sprinkler irrigation and shading were used in a field experiment. Thus, this study aimed to (1) investigate the effects of irrigation mixed with soluble organic fertilizer on *P. notoginseng* growth physiological characteristics, dry matter, yield, and quality and (2) use the TOPSIS approach to construct a complete evaluation model of total yield, water–fertilizer productivity, and saponin content to establish a more effective irrigation and soluble organic fertilizer management strategy.

2. Materials and Methods

2.1. Plant Material and Field Experiment Site

From March 2019 to January 2020, three-year-old plants were investigated at the Luxi Research and Demonstration *P. notoginseng* Base, which was located in Wujiepu Town of Luxi City, Yunnan Province, China, at 24°26′ N, 103°34′ E, and 1945 m height. The experimental site base belongs to the subtropical monsoon climate zone. The annual average sunshine is 2100 h, the average annual rainfall is 950 mm, the frost-free period is 273 days, the average relative humidity is 75%, and the main wind direction is southwest. The soil is red soil (pH = 6.60), with a soil bulk density of 1.31 g cm^{-3}, field capacity of 0.55 cm^3 cm^{-3}, total nitrogen of 0.97 g kg^{-1}, total phosphorus of 0.86 g kg^{-1}, total potassium of 12.41 g kg^{-1}, nitrate nitrogen of 8.10 mg kg^{-1}, ammonium nitrogen of 19.01 mg kg^{-1}, available phosphorus of 11.31 mg kg^{-1}, and available potassium of 316.47 mg kg^{-1}. The proportions of clay, silt, and sand in the soil (0–40 cm) of the experimental site were 8.7%, 34.1%, and 57.2%, respectively, and the soil was classified as silty clay loam soil.

2.2. Experimental Design, Field Management, and Agronomic Practices

In this study, the experiment treatments included three levels of irrigation amount (W_1, W_2, and W_3) with 10, 15, and 20 mm, respectively, and four levels of soluble organic fertilization (F_1, F_2, F_3, and F_4) with 60, 90, 120, and 150 kg ha^{-1} [31,32]. The precise watering and fertilization schedule is shown in Table 1. The experiment was conducted with three replicates for each treatment, randomly distributed within 36 plots. Each plot had an area of 22.8 m^2 and was irrigated with an independent micro-sprinkler irrigation system. A lateral pipe with a control valve and a water meter was installed in each plot to control the amount of irrigation. The irrigation and fertilization processes utilized the MixRite2502 water fertilizer integrated equipment from Israel's TEFEN Company. The fertilizer used was a water-soluble organic compound fertilizer (21% N–21% P_2O_5–21% K_2O + 6% humic acid + trace elements) produced by Sichuan Shifang Demei Industrial Co., Ltd. A rain shelter was set up with plastic film at a height of 2.5 m. The experimental site was treated with three layers of net, providing 8.3% light transmittance [6]. *P. notoginseng* seedlings were transplanted at a density of 4.4 × 10^5 plants ha^{-1} after being purchased from local farmers in Luxi County. The layout is illustrated in Figure 1. Pine needles that were 5 mm thick were then used to cover the surface of each plot. Other management procedures, such as plant trimming, controlling insects, and controlling weeds were carried out with the help of the local farmers' experience.

Table 1. Experiment design of various irrigation and soluble organic fertilization levels for *P. notoginseng*.

Treatments		Irrigation Amount (mm)		Fertilization Amount (kg ha^{-1})				
Irrigation Level (W)	Soluble Organic Fertilization Level (F)	Total Irrigation Amount	Single Irrigation Amount	Single Fertilization Amount	Total Fertilization Amount	Total N	Total P	Total K
W_1	F_1	440	10	5.5	60	12.6	5.5	10.5
	F_2	440	10	8.2	90	18.9	8.3	15.7
	F_3	440	10	10.9	120	25.2	11.0	20.9
	F_4	440	10	13.6	150	31.5	13.8	26.1
W_2	F_1	660	15	5.5	60	12.6	5.5	10.5
	F_2	660	15	8.2	90	18.9	8.3	15.7
	F_3	660	15	10.9	120	25.2	11.0	20.9
	F_4	660	15	13.6	150	31.5	13.8	26.1
W_3	F_1	880	20	5.5	60	12.6	5.5	10.5
	F_2	880	20	8.2	90	18.9	8.3	15.7
	F_3	880	20	10.9	120	25.2	11.0	20.9
	F_4	880	20	13.6	150	31.5	13.8	26.1

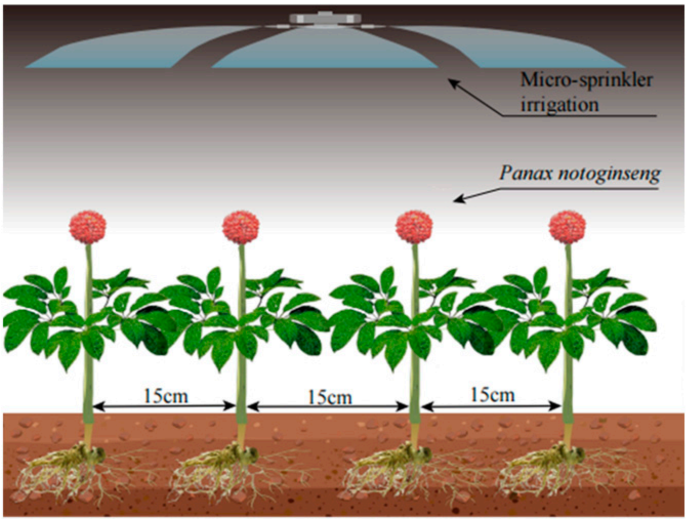

Figure 1. Micro-sprinkler irrigation system layout for *P. notoginseng*.

2.3. Measurements

2.3.1. Growth and Physiology of *P. notoginseng*

(1) Growth index: Three healthy and equally developing *P. notoginseng* plants were randomly selected at various stages of growth for this investigation. The plant height was measured using a ruler, and the stem diameter was measured at 1 cm from the ground with a vernier caliper. Root samples were gathered using the monolith method [33] and cleaned to eliminate dirt. The WinRHIZO root analysis system was used to scan and inspect the roots, as well as collect data on their morphology [34]. Each step was repeated three times.

(2) Photosynthetic characteristics: The photosynthetic characteristics of *P. notoginseng* leaves were measured using the LI-6400 photosynthetic apparatus (LiCor, Lincoln, NE, USA) under clear, cloudless, and natural light conditions from 9 A.M. to 12:00 A.M. at the seedling, budding, flowering, and fruiting stages. We repeated each treatment three times, randomly selected disease-free, evenly growing, and fully stretched *P. notoginseng* leaves for each repetition, and fixed and labeled them [8].

(3) Canopy water conductivity of *P. notoginseng*: *P. notoginseng* plants that were uniformly growing and disease-free were chosen and intercepted 1 cm from the ground. The HPFM high-pressure current meter's quasi-steady flow rate technique was used to assess canopy hydraulic conductivity [35], and this was repeated three times to achieve reliable results.

(4) Dry matter and yield: We randomly selected three plants from each plot for cleaning and cutting off their roots and tree crowns. The sample was placed in an oven at 105 °C for 30 min and dried to a constant weight at 50 °C. Finally, the dry matter of the sample was weighed. Yield was determined by measuring the dry matter of the harvested roots. The calculation methods for root–shoot ratio and root drying rate were as follows [11]:

$$Root\ shoot\ ratio = M_1/M_2 \tag{1}$$

$$Root\ drying\ rate = M_1/M_0 \tag{2}$$

where M_0 is the wet weight of the underground part, g; M_1 is the dry weight of the underground part, g; and M_2 is the dry weight of the overground part, g.

2.3.2. Irrigation Water Productivity (*IWP*) and Partial Fertilizer Productivity (*PFP*)

IWP and *PFP* were calculated as follows [6,36]:

$$IWP = Y/I \tag{3}$$

$$PFP = Y/F \tag{4}$$

where Y is the yield of *P. notoginseng*, kg ha^{-1}; I is the total irrigation amount, mm; *IWP*, kg m^{-3}; F is the total mass of soluble organic fertilizer, kg ha^{-1}; *PFP*, kg kg^{-1}.

2.3.3. Saponin Content of *P. notoginseng*

To determine the content of five saponins (R_1, R_{g1}, R_e, R_{b1}, and R_d) in *P. notoginseng*, the LC-20AB high-performance liquid chromatograph produced by Shimadzu Company of Japan was utilized. The total *P. notoginseng* saponins (*PNS*) are the sum of the five saponin contents. The first step was to rinse the plants with clean water and dry them in the air before decolorizing them in an envelope. The dried plants were then crushed and passed through a 60-mesh sieve. After 0.60 g of the screened *P. notoginseng* powder was weighed, it was placed in a 50 mL centrifuge tube, covered with 50 mL of a 75% methanol solution, and then subjected to ultrasound extraction at 60 °C for 45 min. After shaking it for 40 min and leaving it overnight, it was ultrasonically extracted again the following day. After cooling, it was weighed and replenished with 75% methanol before being filtered through a 0.45 µm organic filter membrane into a 2.00 mL sample injection bottle, forming the sample solution used to test the *P. notoginseng* saponin. For the chromatographic analysis, a 250 mm × 4.6 mm, 5 µm Agilent C18 column was utilized, with a column temperature of 30 °C, a DAD detector, a wavelength of 203 nm, mobile phase A: ultrapure water, and mobile phase B: acetonitrile. The flow rate was set at 1.00 mL min^{-1}, with an injection volume of 10.00 µL [6,7].

2.4. TOPSIS Model

TOPSIS is a decision analysis method for solving multiple objectives. The calculation steps of the TOPSIS method were based on the research of Li and Seyedmohammadi [6,37].

Step 1. Establishing a performance decision matrix A_{ij}:

$$A_{ij} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mm} \end{bmatrix}; i = (1, 2\cdots, m); j = (1, 2\cdots, n) \tag{5}$$

where a_{ij} is the j-th evaluation index in the i-th treatment, m = 12, and n = 9.

Step 2. The normalized value b_{ij} and decision matrix B_{ij} are calculated as follows:

$$b_{ij} = \frac{a_{ij}}{\sqrt{\left(\sum_{i=1}^{m} a_{ij}^2\right)}} \tag{6}$$

$$B_{ij} = \begin{bmatrix} b_{11} & \cdots & b1n \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{bmatrix} \tag{7}$$

Step 3. Calculating the weighted normalized decision matrix Z_{ij}. The calculation method is as follows:

$$Z_{ij} = B_{ij} \times W_{n\times n} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix} \tag{8}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{9}$$

where w_j is the j-th criterion's weight.

Step 4. Determining the positive ideal ($Z_j{}^+$) and negative ideal ($Z_j{}^-$) solutions:

$$Z_j^+ = \begin{cases} \max z_{ij} \cdots\cdots j = J \\ \min z_{ij} \cdots\cdots j = J' \end{cases} \tag{10}$$

$$Z_j^- = \begin{cases} \min z_{ij} \cdots\cdots j = J \\ \max z_{ij} \cdots\cdots j = J' \end{cases} \tag{11}$$

where J and J' are the sets of criteria "with a positive effect" and criteria "with a negative effect", respectively.

Step 5. Using the m-dimensional Euclidean distance to calculate the separation measures of each alternative from the positive ($D_i{}^+$) and negative ($D_i{}^-$) ideal solutions:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - z_j^+\right)^2} \tag{12}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - z_j^-\right)^2} \tag{13}$$

Step 6. Calculating the relative closeness to the ideal solution and ranking it:

$$CI_i = \frac{D_i^-}{D_i^+ + D_i^-} \cdots\cdots (0 \le ci_i \le 1) \tag{14}$$

The CI_i value was used to rank each treatment. In descending order, options were ranked based on their CI_i value.

2.5. Statistical Analysis

Using SPSS 26 software, experimental data were processed and subjected to variance analysis (ANOVA). The significance of data differences was analyzed using the Duncan method. Excel 2019 was used for data processing and TOPSIS model construction. Origin 2018 was used for plotting. Figure 2 shows the flow chart of the research steps carried out in this study.

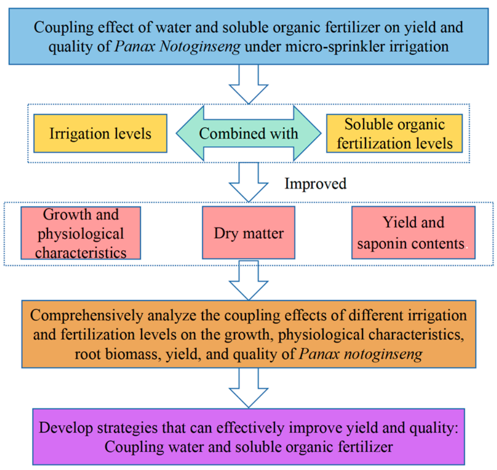

Figure 2. Flowchart of the experimental project.

3. Results

3.1. Effects of Irrigation and Soluble Organic Fertilization on the Growth and Physiology of *P. notoginseng*

The root of *P. notoginseng* is mainly used for medicinal purposes. In this study, the F_3 treatment had the highest values of root length, surface area, average diameter, and root volume under the same irrigation level, whereas the W_2 and W_3 treatments had the highest values under the same fertilization level. In the W_1 treatment, there was no significant difference in root length across treatments. Among the other irrigation treatments, the F_3 treatment had much longer roots than the others. There was no statistically significant difference in root surface area between F_1 and F_2 under W_2 and W_3 circumstances. F_3 and F_4 had no significant difference under the same irrigation circumstances. There was no significant change in root volume between the F_2, F_3, and F_4 treatments under W_1. There was no significant change in the average diameter and root volume across irrigation treatments under F_4 conditions. It was worth noting that when irrigation and fertilization were combined, the root morphological characteristics (root length, surface area, average diameter, and volume of root) of the W_2F_3 treatment were significantly higher than those of the W_3F_3 treatment, increasing by 3.13%, 22.52%, 7.10%, and 15.85%, respectively (Figure 3).

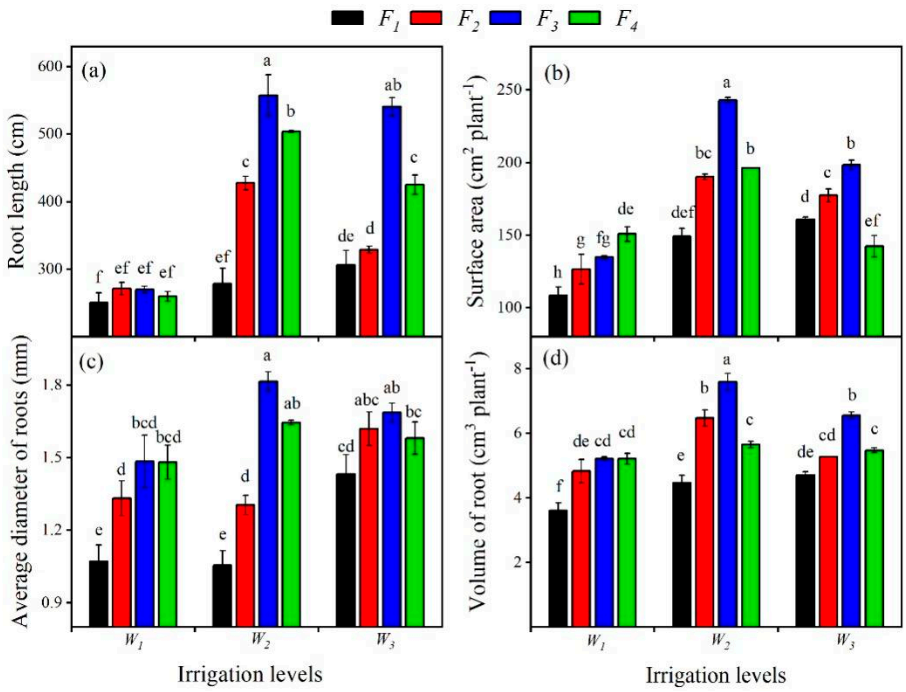

Figure 3. Effects of various irrigation and soluble organic fertilization levels on root growth. The data represent the average of three replicates. Error bars represent standard errors. Different letters above the bars indicate significance in each treatment at the 0.05 level. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

Table 2 shows that irrigation levels and soluble organic fertilization levels had significant ($p < 0.05$) effects on the net photosynthetic rate and transpiration rate. At the seedling, budding, flowering, and fruiting stages, the net photosynthetic rate was highest under F_3 fertilization, followed by F_2, F_4, and F_1. On the other hand, the transpiration rate was highest under F_4 fertilization, followed by F_3, F_2, and F_1 at these same growth stages. Under the F_3 fertilization level, the maximum net photosynthetic rate appeared at the flowering stage, with no significant difference between the W_2 and W_3 net photosynthetic rates. The transpiration rate was highest under the W_3 treatment at the same fertilization level. Compared to the W_1F_1 treatment, the seedling, budding, flowering, and fruiting stages of *P. notoginseng* showed that under the W_3F_3 treatment, the net photosynthetic rate significantly increased by 106.66%, 269.30%, 9.11%, and 147.99%, respectively, due to the interaction between irrigation and fertilization. Under the W_3F_4 treatment, the transpiration rate significantly increased by 38.53%, 98.75%, 63.47%, and 168.33% at the seedling, budding, flowering, and fruiting stages, respectively, compared to W_1F_1.

In addition, W_3F_3 treatment could promote plant height and stem diameter growth. W_2F_3 treatment could significantly improve the water conductivity of the plant canopy ($p < 0.05$) (Figures 3 and 4, Table 3).

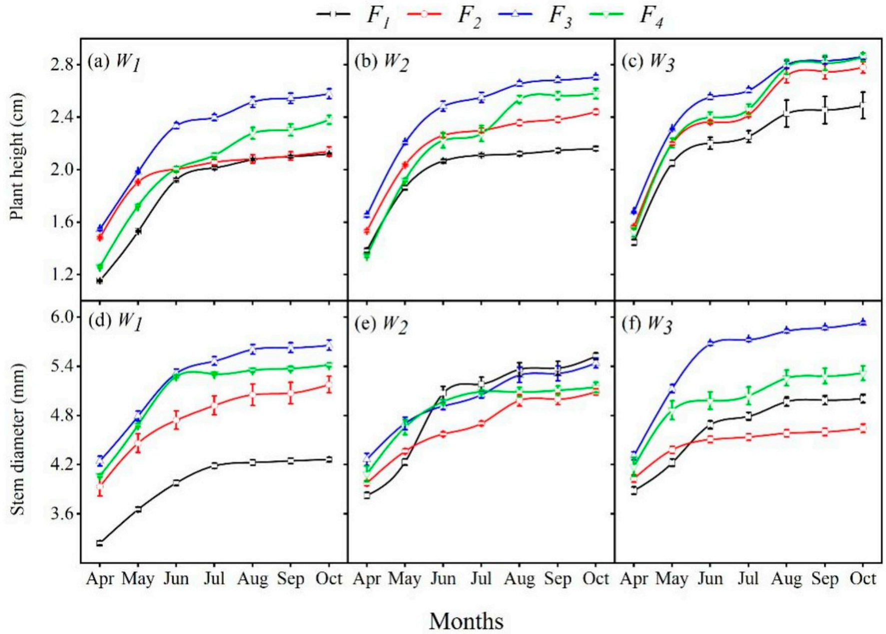

Figure 4. Effects of various irrigation and soluble organic fertilization levels on plant height and stem diameter. The data represent the average of three replicates. Error bars represent standard errors. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}. (**a**–**c**) represent plant height under different irrigation amount (W_1, W_2, and W_3); (**d**–**f**) represent stem diameter under different irrigation amount (W_1, W_2, and W_3).

Table 2. The effects of various irrigation and soluble organic fertilization levels on the net photosynthetic rate and transpiration rate of *P. notoginseng*.

Treatments		Net Photosynthetic Rate ($\mu mol \cdot m^{-2} \cdot s^{-1}$)				Transpiration Rate (mmol m^{-2} s^{-1})			
Irrigation Level (W)	**Soluble Organic Fertilization Level (F)**	**Seedling Stage**	**Budding Stage**	**Flowering Stage**	**Fruiting Stage**	**Seedling Stage**	**Budding Stage**	**Flowering Stage**	**Fruiting Stage**
W_1	F_1	0.44 ± 0.02 f	0.48 ± 0.01 i	3.36 ± 0.09 c	0.76 ± 0.04 e	0.38 ± 0.00 e	0.26 ± 0.00 h	0.38 ± 0.00 j	0.32 ± 0.00 k
	F_2	0.44 ± 0.01 f	0.6 ± 0.00 h	3.53 ± 0.04 b	0.87 ± 0.05 e	0.26 ± 0.00 g	0.28 ± 0.00 gh	0.36 ± 0.00 k	0.31 ± 0.00 l
	F_3	0.48 ± 0.01 f	1.11 ± 0.01 d	2.91 ± 0.05 e	1.18 ± 0.02 d	0.26 ± 0.00 g	0.31 ± 0.00 g	0.36 ± 0.00 k	0.38 ± 0.00 j
	F_4	0.75 ± 0.01 c	1.11 ± 0.01 d	3.13 ± 0.02 d	1.47 ± 0.01 b	0.31 ± 0.00 f	0.38 ± 0.00 f	0.40 ± 0.00 i	0.42 ± 0.00 h
W_2	F_1	0.63 ± 0.02 d	0.66 ± 0.01 g	2.98 ± 0.07 e	1.14 ± 0.04 d	0.41 ± 0.03 e	0.48 ± 0.01 cd	0.42 ± 0.00 h	0.40 ± 0.00 i
	F_2	0.84 ± 0.00 b	1.11 ± 0.01 d	3.52 ± 0.01 b	1.49 ± 0.04 b	0.47 ± 0.01 cd	0.58 ± 0.00 a	0.49 ± 0.00 g	0.45 ± 0.01 g
	F_3	0.85 ± 0.00 b	1.4 ± 0.00 c	3.71 ± 0.08 a	1.78 ± 0.05 a	0.45 ± 0.02 d	0.45 ± 0.02 e	0.51 ± 0.00 f	0.48 ± 0.00 f
	F_4	0.66 ± 0.03 d	0.72 ± 0.01 f	3.36 ± 0.00 c	1.32 ± 0.07 c	0.50 ± 0.0 bc	0.45 ± 0.02 de	0.59 ± 0.00 d	0.53 ± 0.00 d
W_3	F_1	0.56 ± 0.01 e	0.82 ± 0.00 e	2.91 ± 0.03 e	1.33 ± 0.01 c	0.58 ± 0.00 a	0.5 ± 0.00 bc	0.70 ± 0.00 a	0.64 ± 0.00 c
	F_2	0.78 ± 0.00 c	1.8 ± 0.01 a	3.2 ± 0.01 d	1.15 ± 0.02 d	0.58 ± 0.00 a	0.58 ± 0.00 a	0.66 ± 0.00 b	0.50 ± 0.00 e
	F_3	0.92 ± 0.00 a	1.76 ± 0.02 b	3.66 ± 0.03 ab	1.88 ± 0.05 a	0.52 ± 0.02 b	0.51 ± 0.01 b	0.57 ± 0.00 e	0.73 ± 0.00 b
	F_4	0.55 ± 0.05 e	0.84 ± 0.00 e	2.92 ± 0.03 e	1.86 ± 0.01 a	0.53 ± 0.01 b	0.53 ± 0.01 b	0.62 ± 0.00 c	0.87 ± 0.00 a
Source of variance									
W		**	**	**	**	**	**	**	**
F		**	**	**	**	**	**	**	**
$W \times F$		**	**	**	**	**	**	**	**

The data represent the average of three replicates. "Means ± standard deviation" inside columns followed by various lowercase letters indicate significance in each treatment at the 0.05 level; significant at ** $p < 0.01$. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

Table 3. The effects of various irrigation and soluble organic fertilization levels on canopy hydraulic conductivity characteristics of *P. notoginseng*.

Treatments		Canopy Hydraulic Conductivity (10^{-6} kg s^{-1} MPa^{-1})	
Irrigation Level (W)	Soluble Organic Fertilization Level (F)	Seedling Stage	Fruiting Stage
W_1	F_1	0.81 ± 0.01 h	2.88 ± 0.04 i
	F_2	0.82 ± 0.01 h	3.12 ± 0.03 hi
	F_3	1.02 ± 0.00 g	3.20 ± 0.10 h
	F_4	1.27 ± 0.04 f	3.91 ± 0.10 g
W_2	F_1	1.75 ± 0.07 e	4.81 ± 0.17 f
	F_2	2.22 ± 0.03 b	5.61 ± 0.01 b
	F_3	2.31 ± 0.03 b	6.89 ± 0.10 a
	F_4	2.04 ± 0.08 c	5.59 ± 0.12 b
W_3	F_1	1.82 ± 0.06 de	4.91 ± 0.06 ef
	F_2	2.46 ± 0.05 a	5.44 ± 0.12 bc
	F_3	2.18 ± 0.06 b	5.21 ± 0.09 cd
	F_4	1.89 ± 0.01 d	5.14 ± 0.07 de
Source of variance			
W		**	**
F		**	**
$W \times F$		**	**

The data represent the average of three replicates. "Means ± standard deviation" inside columns followed by various lowercase letters indicate significance in each treatment at the 0.05 level; significant at ** $p < 0.01$. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

3.2. Effects of Various Irrigation and Soluble Organic Fertilization Levels on Dry Matter, Yield, IWP, and PFP of P. notoginseng

The yield was significantly affected by irrigation, fertilization, and their interaction ($p < 0.05$) (Figure 5). Under W_1, there was no significant difference in yield among treatments F_1, F_2, and F_3. Likewise, the yield difference between F_3 and F_4 under the W_2 condition was not statistically significant, but it was significantly higher than that of the other two fertilizer treatments. The yield was substantially higher under F_4 than the other three treatments under W_3. Interestingly, there was no substantial variation in yield between W_1 and W_3 with F_1, F_2, and F_3.

Irrigation, fertilization, and their interactions all had a substantial ($p < 0.05$) influence on *IWP* (Figure 5). There was no discernible difference in *IWP* between F_1, F_2, and F_3 for W_1. When compared to the other treatments, *IWP* was much greater with F_4. Similarly, no significant variation in *IWP* was discovered between F_3 and F_4 for W_2. Under W_3, however, *IWP* was much greater with F_4 than with the other three treatments.

The *PFP* was significantly affected by irrigation and fertilization ($p < 0.05$) (Figure 5). Interestingly, there was no significant interaction between these variables that affected *PFP* ($p > 0.05$). Under identical irrigation circumstances, the *PFP* of the F_1 treatment was substantially higher in comparison to that of the others. However, there was no significant difference in *PFP* between W_1 and W_2 when under F_1, F_2, and F_3 levels.

Furthermore, irrigation, fertilization, and their interactions significantly affected the underground weight, aboveground weight, root:shoot ratio, and root drying rate ($p < 0.05$) (Table 4).

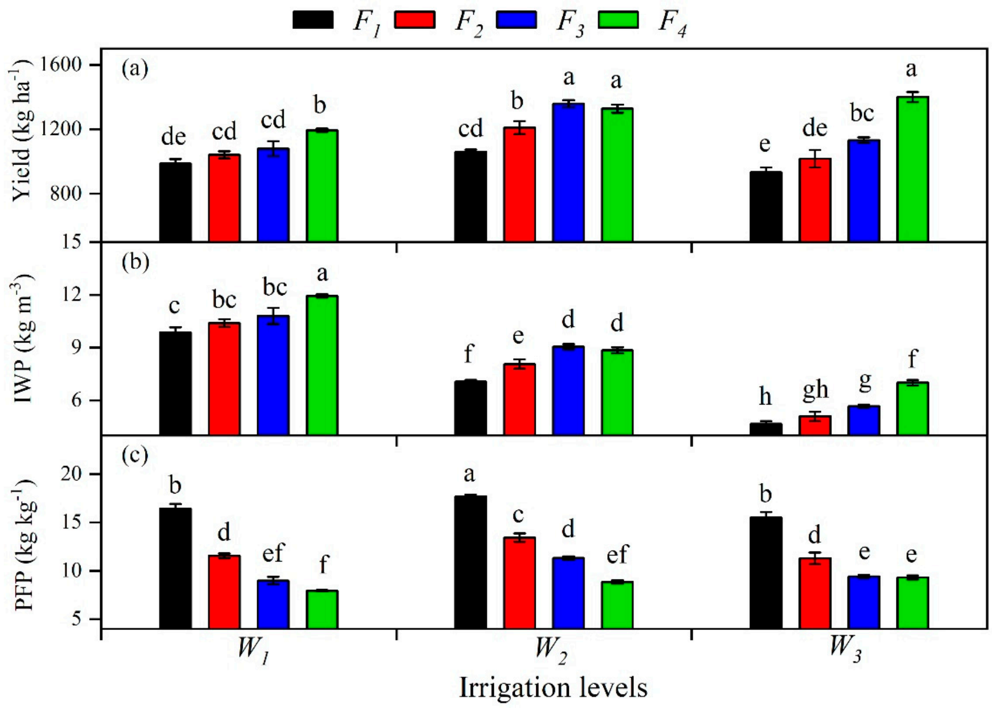

Figure 5. Effects of various irrigation and soluble organic fertilization levels on yield, irrigation water productivity (*IWP*), and partial fertilizer productivity (*PFP*). The data represent the average of three replicates. Error bars represent standard errors. Different letters above the bars indicate significance in each treatment at the 0.05 level. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

Table 4. The effects of various irrigation and soluble organic fertilization levels on dry matter accumulation of *P. notoginseng*.

Treatments		**Underground (kg ha^{-1})**	**Aboveground (kg ha^{-1})**	**Root–Shoot Ratio**	**Root Drying Rate (%)**
Irrigation Level (*W*)	**Soluble Organic Fertilization Level (*F*)**				
W_1	F_1	1452.00 ± 41.97 g	638.00 ± 11.64 fg	2.28 ± 0.05 d	0.33 ± 0.01 ab
	F_2	1493.07 ± 31.76 g	640.93 ± 15.31 fg	2.33 ± 0.01 d	0.31 ± 0.01 bc
	F_3	1431.47 ± 60.45 g	589.60 ± 22.58 g	2.43 ± 0.11 cd	0.30 ± 0.00 bc
	F_4	1765.87 ± 13.99 ef	730.40 ± 17.78 e	2.42 ± 0.04 cd	0.32 ± 0.01 bc
W_2	F_1	1840.67 ± 22.91 def	767.07 ± 19.07 de	2.40 ± 0.05 cd	0.32 ± 0.02 bc
	F_2	1874.40 ± 61.6 de	737.73 ± 10.58 e	2.54 ± 007 bcd	0.33 ± 0.01 ab
	F_3	2202.93 ± 36.05 c	724.53 ± 6.39 e	3.04 ± 0.07 a	0.35 ± 0.01 a
	F_4	2505.07 ± 47.55 b	906.40 ± 17.6 bc	2.76 ± 0.01 b	0.36 ± 0.01 a
W_3	F_1	1677.87 ± 54.86 f	718.67 ± 57.39 ef	2.36 ± 0.16 cd	0.30 ± 0.01 c
	F_2	1997.60 ± 105.14 d	830.13 ± 27.16 cd	2.40 ± 0.05 cd	0.31 ± 0.01 bc
	F_3	2431.73 ± 36.05 b	938.67 ± 37.19 b	2.60 ± 0.14 bc	0.33 ± 0.00 ab
	F_4	3198.80 ± 71.67 a	1057.47 ± 35.6 a	3.03 ± 0.03 a	0.33 ± 0.01 ab
Source of variance					
W		**	**	**	**
F		**	**	**	*
W × *F*		**	**	**	*

The data represent the average of three replicates. "Means ± standard deviation" inside columns followed by various lowercase letters indicate significance in each treatment at the 0.05 level; significant at ** $p < 0.01$, significant at * $p < 0.05$. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

3.3. Effects of Various Irrigation and Soluble Organic Fertilization Levels on the Content of *P. notoginseng* saponins (PNS)

This study investigated irrigation and fertilization's impact on notoginsenoside R_1, ginsenosides (R_{g1}, R_e, R_{b1}, and R_d), and total *P. notoginseng* saponins (*PNS*). The results showed that both irrigation and fertilization, as well as their interaction, had significant effects on R_1, R_{g1}, R_{b1}, R_d, and total *PNS* ($p < 0.05$). However, R_e had no significant response to water–fertilizer coupling ($p > 0.05$), although irrigation and fertilization separately had significant effects ($p < 0.05$) (Table 5). In addition, the study discovered that R_1 was not significantly different among F_2, F_3, and F_4 under the W_1 condition. However, the F_3 treatment outperformed the other treatments under W_2. Under W_3, R_1 did not differ significantly between F_1 and F_4, nor between F_2 and F_3. Furthermore, R_{g1}, R_e, and R_d showed no significant differences among fertilization treatments under W_3. Irrigation treatments under F_1 and F_2 did not differ significantly in R_e, and fertilization treatments under the W_1 condition did not differ significantly in R_{b1}. Finally, the total saponin contents of fertilization treatments under W_3 did not differ significantly from one another. The water–fertilizer coupling produced the highest total saponin content under the W_2F_3 at 24.94% (Table 5).

3.4. Comprehensive Assessment

A comprehensive analysis was necessary because there were several best practices for the saponin content as well as for yield, *IWP*, *PFP*, and yield. To analyze 12 various irrigation and soluble organic fertilization levels, the TOPSIS model was employed along with yield, *IWP*, *PFP*, R_1, R_{g1}, R_e, R_{b1}, R_d, and total *PNS* as evaluation indices. The comprehensive evaluation indexes were 0.442, 0.334, 0.302, 0.540, 0.527, 0.646, 0.541, 0.304, 0.342, 0.361, and 0.363. The comprehensive evaluation of each treatment was $W_2F_3 > W_2F_4 > W_2F_1 > W_2F_2 > W_1F_2 > W_1F_1 > W_3F_4 > W_3F_3 > W_3F_2 > W_1F_3 > W_3F_1 > W_1F_4$ (Table 6).

The outcome showed that the W_2F_3 treatment could balance yield, *IWP*, *PFP*, R_1, R_{g1}, R_e, R_{b1}, R_d, and total *PNS* and had the greatest overall effect for *P. notoginseng*. The TOPSIS model evaluation findings and the comparative examination of data from multiple variables indicated that the W_2F_3 treatment was the most effective combination of irrigation and soluble organic fertilization.

Table 5. The effects of various irrigation and soluble organic fertilization levels on the accumulation of effective ingredients in roots of *P. notoginseng*.

Treatments: Irrigation Level (W)	Treatments: Soluble Organic Fertilization Level (F)	R_1 (%)	R_{g1} (%)	R_e (%)	R_{b1} (%)	R_d (%)	Total *PNS* (%)
W_1	F_1	2.28 ± 0.10 d	8.99 ± 0.11 bcde	1.20 ± 0.10 abc	2.26 ± 0.13 f	1.19 ± 0.01 e	15.92 ± 0.37 cde
	F_2	1.46 ± 0.04 e	16.20 ± 0.55 a	1.01 ± 0.16 abc	2.30 ± 0.09 f	0.76 ± 0.07 f	21.74 ± 0.53 ab
	F_3	1.72 ± 0.06 e	9.25 ± 0.47 bcde	0.30 ± 0.02 d	2.23 ± 0.07 f	1.84 ± 0.04 cd	15.35 ± 0.46 de
	F_4	1.76 ± 0.04 e	9.74 ± 0.36 bc	0.19 ± 0.01 d	2.35 ± 0.04 f	0.82 ± 0.05 f	14.86 ± 0.39 de
W_2	F_1	3.67 ± 0.17 bc	6.14 ± 0.45 cdef	1.11 ± 0.05 abc	3.17 ± 0.17 de	2.72 ± 0.16 a	16.81 ± 0.27 cd
	F_2	4.03 ± 0.34 b	9.95 ± 3.74 b	0.99 ± 0.33 bc	2.35 ± 0.14 f	2.12 ± 0.07 b	19.44 ± 3.66 bc
	F_3	4. 88 ± 0. 16 a	13. 92 ± 0. 69 a	1. 52 ± 0. 11 ab	2.58 ± 0.15 ef	2.03 ± 0.04 bc	24.94 ± 0.87 a
	F_4	3.48 ± 0.30 c	9.56 ± 0.45 bcd	1.57 ± 0.37 a	3.36 ± 0.18 d	1.69 ± 0.14 d	19.66 ± 1.23 bc
W_3	F_1	1.54 ± 0.06 e	4.73 ± 0.56 f	0.96 ± 0.13 bc	3.60 ± 0.36 d	1.12 ± 0.06 e	11.95 ± 0.56 e
	F_2	0.77 ± 0.05 f	5.52 ± 0.22 ef	0.99 ± 0.07 bc	5.48 ± 0.27 b	1.23 ± 0.08 e	13.99 ± 0.43 de
	F_3	0.74 ± 0.02 f	5.94 ± 0.05 def	0.86 ± 0.11 c	6.36 ± 0.54 a	1.09 ± 0.09 e	14.98 ± 0.52 de
	F_4	1.32 ± 0.21 e	5.72 ± 0.26 ef	1.20 ± 0.13 abc	4.57 ± 0.17 c	1.14 ± 0.10 e	13.96 ± 0.31 de
Source of variance							
W		**	**	**	**	**	**
F		*	**	NS	*	**	**
$W \times F$		**	**	**	**	**	**

The data represent the average of three replicates. "Means ± standard deviation" inside columns followed by various lowercase letters indicate significance in each treatment at the 0.05 level; "NS" means no significant; significant at ** $p < 0.01$, significant at * $p < 0.05$. The total *P. notoginseng* saponins (*PNS*) are the sum of the five saponin contents. W_1, W_2, and W_3 represent irrigation amounts of 10, 15, and 20 mm; F_1, F_2, F_3, and F_4 represent soluble organic fertilizer amounts of 60, 90, 120, and 150 kg ha^{-1}.

Table 6. TOPSIS analysis of yield, *IWP*, *PFP* and *PNS*.

Treatments		Comprehensive Index									D^+	D^-	CI	Ranking
Irrigation Level (W)	**Organic Fertilization Level (F)**	**Yield**	IWP	PFP	R_1	R_{g1}	R_e	R_{b1}	R_d	**Total** PNS				
W_1	F_1	0.029	0.039	0.045	0.024	0.030	0.035	0.021	0.023	0.030	0.065	0.049	0.429	6
	F_2	0.031	0.041	0.031	0.015	0.054	0.029	0.021	0.015	0.042	0.070	0.055	0.442	5
	F_3	0.032	0.042	0.024	0.018	0.031	0.009	0.020	0.036	0.029	0.076	0.038	0.334	10
	F_4	0.035	0.047	0.022	0.019	0.033	0.006	0.021	0.016	0.028	0.084	0.036	0.302	12
W_2	F_1	0.031	0.028	0.048	0.039	0.021	0.032	0.029	0.053	0.032	0.055	0.064	0.540	3
	F_2	0.036	0.032	0.037	0.043	0.033	0.029	0.021	0.042	0.037	0.053	0.059	0.527	4
	F_3	0.040	0.035	0.031	0.052	0.047	0.044	0.024	0.040	0.048	0.043	0.078	0.646	1
	F_4	0.039	0.035	0.024	0.037	0.032	0.046	0.031	0.033	0.038	0.052	0.061	0.541	2
W_3	F_1	0.028	0.018	0.042	0.016	0.016	0.028	0.033	0.022	0.023	0.079	0.035	0.304	11
	F_2	0.030	0.020	0.031	0.008	0.018	0.029	0.050	0.024	0.027	0.077	0.040	0.342	9
	F_3	0.034	0.022	0.026	0.008	0.020	0.025	0.058	0.021	0.029	0.078	0.044	0.361	8
	F_4	0.041	0.027	0.025	0.014	0.019	0.035	0.042	0.022	0.027	0.073	0.041	0.363	7
Weight W		0.119	0.115	0.115	0.097	0.109	0.107	0.115	0.108	0.115				
Positive ideal solution Z^+		0.041	0.047	0.048	0.052	0.054	0.046	0.058	0.053	0.048				
Negative ideal solution Z^-		0.028	0.018	0.022	0.008	0.016	0.006	0.020	0.015	0.023				

D^+: positive ideal distance, D^-: negative ideal distance, *CI*: the comprehensive index, *W*: weight, Z^+: positive ideal solution, Z^-: negative ideal solution.

4. Discussion

Although water absorption and nutrient absorption are two distinct processes, they affect the soil's physical and chemical characteristics and the physiological functions of plants. Therefore, the relationship between crop water and nutrient absorption is close and complex [38]. To enhance crop productivity and fertilizer utilization rates, the coupling of irrigation and fertilization is a method that emphasizes the organic relationship between water and fertilizer. By capitalizing on the synergistic effect between them, this method helps manage water, fertilizer, and crops [39]. Various studies indicated that moderate irrigation and fertilization led to improvements in the physiological and ecological traits of crops, resulting in increased dry matter accumulation, yield, and quality [40–43]. In this study, to balance output and quality, a water and fertilizer control approach was proposed. Moderate irrigation and fertilization efficiently enhanced the morphology of the root, yield, and saponin contents during the production phase. The data presented in Tables 3–5 and Figures 3 and 4 support these theories.

4.1. Effects of Irrigation and Fertilization on the Growth and Physiology

Due to the higher requirements for water and fertilizer in the cultivation of *P. notoginseng*, a more accurate water and fertilizer management model was needed. This study found that the plant height, stem diameter, photosynthetic characteristics, and canopy hydraulic conductivity of *P. notoginseng* increased to the maximum level under W_3 treatment (Tables 2 and 3, Figures 3 and 4). This phenomenon was mainly due to insufficient irrigation. It was reported that insufficient irrigation would affect cell elongation and mitosis, reduce water movement through the xylem and adjacent cells, and reduce the number and area of leaves, all of which hinder the normal growth of crops [44,45]. Additionally, stomatal closure caused by water stress prevented the expansion of the net photosynthetic area, reduced the photosynthetic rate per unit leaf area, and inhibited photosynthesis and carbon dioxide assimilation, ultimately reducing photosynthetic efficiency [7,45,46]. It was worth noting that the F_4 treatment had a lower net photosynthetic rate than the other treatments. The decrease in the photosynthetic capacity of plant mesophyll cells caused by excessive fertilizer was a possible reason for this phenomenon [47]. Nitrogen stress could lower the chlorophyll content and net photosynthetic rate, compromising photosynthetic function [48,49]. Phosphorus stress could inhibit the synthesis of chlorophyll and cause a decrease in the net photosynthetic rate [50]. Similarly, some of the values in the W_3 treatment exhibited a lower net photosynthetic rate than the other treatments. This individual difference might be associated with the formation of waterlogging stress, whereby the photosynthetic system and chlorophyll synthesis were impacted, decreasing the net photosynthetic rate [51,52]. Furthermore, this deviation mainly arose in high water and fertilizer treatments, which might be assigned to a fall in light saturation point caused by a rise in temperature, leading to a decrease in net photosynthetic rate during measurement [53]. The root is the most critical part affecting the growth of *P. notoginseng*. Under W_2 treatment, the roots of *P. notoginseng* had the best morphology. Because the roots of *P. notoginseng* were very sensitive to changes in soil moisture, sufficient water promoted their growth and development [8]. Moreover, under F_3 treatment, the plant height and stem diameter, root morphological characteristics, net photosynthetic rate, and canopy hydraulic conductivity of *P. notoginseng* reached their highest levels with the increased fertilization amount. Appropriate fertilization could promote the growth of *P. notoginseng* by improving the environment around the roots, promoting plant root development, enhancing root activity, and improving crop osmotic and stomatal regulation, which increased the photosynthetic rate to support crop growth [54–57]. Phosphorus also influences the metabolic functions of plants, including cell division and development, photosynthesis, and respiration, promoting plant growth through these processes [58,59]. Furthermore, sufficient nitrogen levels in organic fertilizers increase the activity of photosynthetic enzymes in chloroplasts, and the amount of carbon dioxide emitted from the soil significantly increases, thereby improving the photosynthesis rate of crops [60–63]. Organic fertilizers might have also stimulated nitrogen-fixing bacteria and increased yield by promoting the secretion of plant hormones such as gibberellic acid and acetic acid [64,65]. The study by Zhong also showed that long-term application of organic fertilizers could increase the variety and activity of soil microorganisms, promoting crop growth [66].

4.2. Effects of Irrigation and Fertilization on Dry Matter, Yield, IWP, and PFP

Dry matter accumulation is a crucial factor for crop yield [67]. Recent studies have shown that low-level irrigation may harm dry matter accumulation, while higher fertilization levels tend to contribute to increased dry matter accumulation [68]. This study confirmed previous research, showing that the maximum dry matter was achieved under W_3 treatment (Table 4). Low soil moisture content might be the reason for the decline in dry matter accumulation, as it causes stomata closure, leaf cell damage, and reduced photosynthesis [7]. It is clear from previous studies that reasonable water and fertilizer inputs are necessary for improving crop yield and water–fertilizer productivity. For example, Liao discovered that low soil moisture concentration lowered *P. notoginseng* production considerably [8]. According to the findings of this study, higher dry matter buildup increased *P. notoginseng* production, which peaked under W_2 and W_3 conditions (Figure 5). Thus, within a certain range of water and fertilizer inputs, the yield tended to increase as irrigation and fertilization increased [30,69,70]. Furthermore, the outcomes of this investigation demonstrated that increased irrigation volume resulted in lower *IWP* (Figure 5), corroborating the findings by Ali [71]. This phenomenon might be due to increased evapotranspiration resulting in a lower *IWP* [72]. Additionally, the results indicated that *PFP* decreased with increasing fertilization (Figure 5), consistent with the findings of Wang and Peng [73,74]. This could be due to the diminishing marginal returns of yield with increasing fertilizer application [75]. As a result, rational water and fertilizer inputs might boost crop yield and water–fertilizer productivity in *P. notoginseng* production.

4.3. Effects of Irrigation and Fertilization on Saponin Content

Secondary metabolites, which represent active ingredients in Chinese herbal medicine, could be increased in *P. notoginseng* through the provision of adequate water, nitrogen, and potassium [76–78]. The highest content of R_{g1} was found in this study, and the overall concentration of ginsenosides R_{g1} and R_{b1} and notoginsenoside R_1 was not less than 5.0%, which was in agreement with the standard for *P. notoginseng* saponins [6]. The maximum amounts of notoginsenoside R_1, ginsenosides R_{g1}, R_e, and R_d, and total saponin were obtained under W_2 treatment, while the total saponin content initially increased and then decreased with increasing irrigation volume. Similar research suggested that the amount of soil water affected the active ingredients in *P. notoginseng* differently and that under extreme water scarcity, the accumulation of active ingredients decreased [11,79]. Irrigation had a greater effect on the synthesis of notoginsenoside R_1 and ginsenosides R_{g1}, R_e, R_{b1}, and R_d, indicating that saponins were more responsive to water. Adequate soil moisture could optimize the activity of antioxidant enzymes and stabilize the gene expression of essential enzymes required for saponin production, thus facilitating saponin synthesis [80]. Organic fertilizer significantly affected the contents of notoginsenoside R_1 and ginsenosides R_{g1}, R_e, R_{b1}, and R_d by increasing the number of soil microorganisms, soil porosity, diversity, and organization of the microbial community [81]. Proper irrigation and fertilization practices could enhance the permeability of the soil, stimulate microbial activity, and ultimately increase the saponin content of *P. notoginseng* [6]. Thus, regulating water and fertilizer was essential for increasing the saponin content of *P. notoginseng*. According to the TOPSIS model assessment, W_2F_3 showed the best treatment effect for *P. notoginseng*.

5. Conclusions

Under the conditions of shade and shelter from the rain, the coupling of water and organic fertilizer significantly increased the yield and saponin content of *P. notoginseng*. Through comprehensive evaluation, we found that the yield and saponin content of the

W_2F_3 treatment were the best. The yield of *P. notoginseng* was 1359 kg ha^{-1}, and the total saponin content was 24.94%. In addition, the coupling effect of water and organic fertilizer treatments could significantly increase plant height, stem diameter, root morphology, photosynthetic characteristics, canopy hydraulic conductivity, dry matter, irrigation water productivity, yield, and quality. Therefore, the combination of irrigation levels (W_2, 15 mm) and soluble organic fertilization levels (F_3, 120 kg ha^{-1}) should be suggested as an appropriate agronomic management method to improve the yield and saponin content of *P. notoginseng*.

Author Contributions: Conceptualization, T.M., H.W., J.L. and Q.Y. (Qiliang Yang); methodology, T.M., H.W., J.L. and Q.Y. (Qiliang Yang); software, X.Y., Z.Z., J.G. and N.L.; validation, H.W., J.L. and Q.Y.; formal analysis, H.W., J.L. and Q.Y. (Qiliang Yang); investigation, T.M., X.Y., Z.Z. and Q.Y. (Qi You); resources, Q.Y. (Qiliang Yang) and X.L.; data curation, T.M., X.Y., Z.Z. and Q.Y. (Qi You); writing—original draft preparation, T.M.; writing—review and editing, T.M., H.W., J.L. and Q.Y. (Qiliang Yang); visualization, T.M., J.G., N.L. and X.L.; supervision, H.W., J.L. and Q.Y. (Qiliang Yang); project administration, H.W., J.L. and Q.Y. (Qiliang Yang); funding acquisition, Q.Y. (Qiliang Yang). All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (No. 51979134), Applied Basic Research Key Project of Yunnan (No. 202201AS070034), Yunnan Science and Technology Talent and Platform Program (No. 202305AM070006), and Yunnan Fundamental Research Projects (No. 202301AU070061). We especially thank all research subjects for their assistance and participation in this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are contained within the article.

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

References

1. Shang, C.B.; Porter, I.I. *Araliaceae*; Flora of China: Beijing, China, 2007.
2. Xia, P.; Guo, H.; Liang, Z.; Cui, X.; Liu, Y.; Liu, F. Nutritional composition of Sanchi (*Panax notoginseng*) seed and its potential for industrial use. Genet. *Resour. Crop Evol.* **2014**, *61*, 663–667. [CrossRef]
3. Wang, N.; Wan, J.B.; Chan, S.W.; Deng, Y.H.; Yu, N.; Zhang, Q.W.; Lee SM, Y. Comparative study on saponin fractions from *Panax notoginseng* inhibiting inflammation-induced endothelial adhesion molecule expression and monocyte adhesion. *Chin. Med.* **2011**, *6*, 1–12. [CrossRef] [PubMed]
4. He, N.W.; Zhao, Y.; Guo, L.; Shang, J.; Yang, X.B. Antioxidant, antiproliferative, and pro-apoptotic activities of a saponin extract derived from the roots of *Panax notoginseng* (Burk.) FH Chen. *J. Med. Food* **2012**, *15*, 350–359. [CrossRef] [PubMed]
5. Yang, B.R.; Yuen, S.C.; Fan, G.Y.; Cong, W.H.; Leung, S.W.; Lee SM, Y. Identification of certain Panax species to be potential substitutes for *Panax notoginseng* in hemostatic treatments. *Pharmacol. Res.* **2018**, *134*, 1–15. [CrossRef] [PubMed]
6. Li, J.; Yang, Q.; Shi, Z.; Zang, Z.; Liu, X. Effects of deficit irrigation and organic fertilizer on yield, saponin and disease incidence in *Panax notoginseng* under shaded conditions. *Agric. Water Manag.* **2021**, *256*, 107056. [CrossRef]
7. Zang, Z.; Liang, J.; Yang, Q.; Zhou, N.; Li, N.; Liu, X.; Tang, Z. An adaptive abiotic stresses strategy to improve water use efficiency, quality, and economic benefits of *Panax notoginseng*: Deficit irrigation combined with sodium chloride. *Agric. Water Manag.* **2022**, *274*, 107923. [CrossRef]
8. Liao, P.; Liu, D.; Xu, T.R.; Yang, Y.; Cui, X. Soil water stress attenuate the growth and development but enhance the saponin synthesis of Panax notogesing during flowering stage. *Ind. Crop. Prod.* **2017**, *108*, 95–105. [CrossRef]
9. Silberbush, M.; Gornat, B.; Goldberg, D. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. *Plant Soil.* **1979**, *52*, 507–514. [CrossRef]
10. Meyer, W.S.; Barrs, H.D.; Smith, R.C.G.; White, N.S.; Heritage, A.D.; Short, D.L. Effect of irrigation on soil oxygen status and root and shoot growth of wheat in a clay soil. *Aust. J. Agric. Res.* **1985**, *36*, 171–185. [CrossRef]
11. Xia, P.; Guo, H.; Zhao, H.; Jiao, J.; Deyholos, M.K.; Yan, X.; Liang, Z. Optimal fertilizer application for *Panax notoginseng* and effect of soil water on root rot disease and saponin contents. *J. Ginseng Res.* **2016**, *40*, 38–46. [CrossRef]
12. Wang, R.; Chen, S.; Zhou, X.; Shen, X.; Deng, L.; Zhu, H.; Polle, A. Ionic homeostasis and reactive oxygen species control in leaves and xylem sap of two poplars subjected to NaCl stress. *Tree Physiol.* **2008**, *28*, 947–957. [CrossRef] [PubMed]
13. Shao, G.C.; Liu, N.; Zhang, Z.Y.; Yu, S.E.; Chen, C.R. Growth, yield and water use efficiency response of greenhouse-grown hot pepper under Time-Space deficit irrigation. *Sci. Hortic.* **2010**, *126*, 172–179.

14. Cutillas, A.M.; Plaza ME, G.; Roca JM, L.; de la Hera Orts, M.L. Effects of moderate irrigation on vegetative growth and productive parameters of Monastrell vines grown in semiarid conditions. *Span. J. Agric. Res.* **2004**, *2*, 273–282.
15. De La Hera Orts, M.L.; Martínez Cutillas, A.; Lopez Roca, J.M.; Gómez Plaza, E. Effect of moderate irrigation on grape composition during ripening. *Span. J. Agric. Res.* **2005**, *3*, 352–361. [CrossRef]
16. Wang, X.; Xing, Y. Evaluation of the effects of irrigation and fertilization on tomato fruit yield and quality: A principal component analysis. *Sci. Rep.* **2017**, *7*, 1–13. [CrossRef] [PubMed]
17. Cao, H.X.; Zhang, Z.B.; Sun, C.X.; Shao, H.B.; Song, W.Y.; Xu, P. Chromosomal location of traits associated with wheat seedling water and phosphorus use efficiency under different water and phosphorus stresses. *Int. J. Mol. Sci.* **2009**, *10*, 4116–4136. [CrossRef]
18. Chen, W.; Teng, Y.; Li, Z.; Liu, W.; Ren, W.; Luo, Y.; Christie, P. Mechanisms by which organic fertilizer and effective microbes mitigate peanut continuous cropping yield constraints in a red soil of south China. *Appl. Soil Ecol.* **2018**, *128*, 23–34. [CrossRef]
19. Ou, X.; Cui, X.; Zhu, D.; Guo, L.; Liu, D.; Yang, Y. Lowering nitrogen and increasing potassium application level can improve the yield and quality of *Panax notoginseng*. *Front. Plant Sci.* **2020**, *11*, 595095. [CrossRef]
20. Xie, S.; Feng, H.; Yang, F.; Zhao, Z.; Hu, X.; Wei, C.; Geng, Y. Does dual reduction in chemical fertilizer and pesticides improve nutrient loss and tea yield and quality? A pilot study in a green tea garden in Shaoxing, Zhejiang Province, China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 2464–2476. [CrossRef]
21. Duan, Y.; Xu, M.; Gao, S.; Liu, H.; Huang, S.; Wang, B. Long-term incorporation of manure with chemical fertilizers reduced total nitrogen loss in rain-fed cropping systems. *Sci. Rep.* **2016**, *6*, 1–10. [CrossRef]
22. Oladele, S.O.; Adeyemo, A.J.; Awodun, M.A. Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. *Geoderma* **2019**, *336*, 1–11. [CrossRef]
23. Shi, R.; Wang, S.; Xiong, B.; Gu, H.; Wang, H.; Ji, C.; He, X. Application of Bioorganic Fertilizer on *Panax notoginseng* Improves Plant Growth by Altering the Rhizosphere Microbiome Structure and Metabolism. *Microorganisms* **2022**, *10*, 275. [CrossRef] [PubMed]
24. Sheoran, H.S.; Kakar, R.; Kumar, N. Impact of organic and conventional farming practices on soil quality: A global review. *Appl. Ecol. Environ. Res.* **2019**, *17*, 951–968. [CrossRef]
25. Sihi, D.; Dari, B.; Sharma, D.K.; Pathak, H.; Nain, L.; Sharma, O.P. Evaluation of soil health in organic vs. conventional farming of basmati rice in North India. *J. Plant Nutr. Soil Sci.* **2017**, *180*, 389–406. [CrossRef]
26. Bei, S.; Zhang, Y.; Li, T.; Christie, P.; Li, X.; Zhang, J. Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil. *Agric. Ecosyst. Environ.* **2018**, *260*, 58–69. [CrossRef]
27. Qaswar, M.; Jing, H.; Ahmed, W.; Dongchu, L.; Shujun, L.; Lu, Z.; Huimin, Z. Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil Tillage Res.* **2020**, *198*, 104569. [CrossRef]
28. Powlson, D.S.; Prookes, P.C.; Christensen, B.T. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. *Soil Biol. Biochem.* **1987**, *19*, 159–164. [CrossRef]
29. Liu, J.; Shu, A.; Song, W.; Shi, W.; Li, M.; Zhang, W.; Gao, Z. Long-term organic fertilizer substitution increases rice yield by improving soil properties and regulating soil bacteria. *Geoderma* **2021**, *404*, 115287. [CrossRef]
30. Wang, H.; Wu, L.; Cheng, M.; Fan, J.; Zhang, F.; Zou, Y.; Wang, X. Coupling effects of water and fertilizer on yield, water and fertilizer use efficiency of drip-fertigated cotton in northern Xinjiang, China. *Field Crop. Res.* **2018**, *219*, 169–179. [CrossRef]
31. Reddy, T.Y.; Sulochanamma, B.N. Effect of minimal amount of supplemental irrigation during drought stress on yield and quality of groundnut. *Legume Res.* **2008**, *31*, 118–121.
32. Tran, T.S.; Tremblay, G. Recovery of 15N-labeled fertilizer by spring bread wheat at different N rates and application times. *Can. J. Soil Sci.* **2000**, *80*, 533–539. [CrossRef]
33. Bohm, W. *Methods of Studying Root Systems*; Springer: New York, NY, USA, 1979.
34. Pang, W.; Crow, W.T.; Luc, J.E.; McSorley, R.; Giblin-Davis, R.M.; Kenworthy, K.E.; Kruse, J.K. Comparison of water displacement and WinRHIZO software for plant root parameter assessment. *Plant Dis.* **2011**, *95*, 1308–1310. [CrossRef] [PubMed]
35. Yang, Q.; Zhang, F.; Li, F.; Liu, X. Hydraulic conductivity and water-use efficiency of young pear tree under alternate drip irrigation. *Agric. Water Manag.* **2013**, *119*, 80–88. [CrossRef]
36. Liang, J.; Shi, W. Cotton/halophytes intercropping decreases salt accumulation and improves soil physicochemical properties and crop productivity in saline-alkali soils under mulched drip irrigation: A three-year field experiment. *Field Crop. Res.* **2021**, *262*, 108027. [CrossRef]
37. Seyedmohammadi, J.; Sarmadian, F.; Jafarzadeh, A.A.; Ghorbani, M.A.; Shahbazi, F. Application of SAW, TOPSIS and fuzzy TOPSIS models in cultivation priority planning for maize, rapeseed and soybean crops. *Geoderma* **2018**, *310*, 178–190. [CrossRef]
38. Viets, F.G. Fertilizers and the efficient use of water. *Adv. Agron.* **1962**, *14*, 223–264.
39. De Haan, F.A.M.; Van der Zee, S.E.A.T.M.; Van Riemsdijk, W.H. The role of soil chemistry and soil physics in protecting soil quality: Variability of sorption and transport of cadmium as an example. *Neth. J. Agric. Sci.* **1987**, *35*, 347–359.
40. Zhao, J.; Zhang, W.; Wang, K.; Song, T.; Du, H. Responses of the soil nematode community to management of hybrid napiergrass: The trade-off between positive and negative effects. *Appl. Soil Ecol.* **2014**, *75*, 134–144. [CrossRef]
41. Luo, H.H.; Tao, X.P.; Hu, Y.Y.; Zhang, Y.L.; Zhang, W.F. Response of cotton root growth and yield to root restriction under various water and nitrogen regimes. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 384–392. [CrossRef]

42. Mehanna, H.M.; Safi-naz, S.Z.; Hussien, M.M. Influences of irrigation and fertilizer on growth and yield of two sugar beet varieties in Egypt. *Middle East J. Agric. Res.* **2017**, *6*, 1295–1300.
43. Chen, Z.; Tao, X.; Khan, A.; Tan, D.K.; Luo, H. Biomass accumulation, photosynthetic traits and root development of cotton as affected by irrigation and nitrogen-fertilization. *Front. Plant Sci.* **2018**, *9*, 173. [CrossRef] [PubMed]
44. Nonami, H. Plant water relations and control of cell elongation at low water potentials. *J. Plant Res.* **1998**, *111*, 373–382. [CrossRef]
45. Farooq, M.; Wahid, A.; Kobayashi, N.S.M.A.; Fujita, D.B.S.M.A.; Basra, S.M.A. Plant drought stress: Effects, mechanisms and management. *Agron. Sustain. Dev.* **2009**, *29*, 185–212. [CrossRef]
46. Parkash, V.; Singh, S. A review on potential plant-based water stress indicators for vegetable crops. *Sustainability* **2020**, *12*, 3945. [CrossRef]
47. Zhou, X.; Wang, R.; Gao, F.; Xiao, H.; Xu, H.; Wang, D. Apple and maize physiological characteristics and water-use efficiency in an alley cropping system under water and fertilizer coupling in Loess Plateau, China. *Agric. Water Manag.* **2019**, *221*, 1–12. [CrossRef]
48. Joshi, V.; Joshi, M.; Penalosa, A. Comparative analysis of tissue-specific transcriptomic responses to nitrogen stress in spinach (*Spinacia oleracea*). *PLoS ONE* **2020**, *15*, e0232011. [CrossRef]
49. Kong, L.; Xie, Y.; Hu, L.; Si, J.; Wang, Z. Excessive nitrogen application dampens antioxidant capacity and grain filling in wheat as revealed by metabolic and physiological analyses. *Sci. Rep.* **2017**, *7*, 43363. [CrossRef]
50. Chen, G.; Li, Y.; Jin, C.; Wang, J.; Wang, L.; Wu, J. Physiological and Morphological Responses of Hydroponically Grown Pear Rootstock Under Phosphorus Treatment. *Front. Plant Sci.* **2021**, *12*, 2637. [CrossRef]
51. Zeng, R.; Chen, T.; Wang, X.; Cao, J.; Li, X.; Xu, X.; Zhang, L. Physiological and expressional regulation on photosynthesis, starch and sucrose metabolism response to waterlogging stress in peanut. *Front. Plant Sci.* **2021**, *12*, 601771. [CrossRef]
52. Jaafar, H.Z.; Ibrahim, M.H.; Fakri, N.F.M. Impact of soil field water capacity on secondary metabolites, phenylalanine ammonia-lyase (PAL), maliondialdehyde (MDA) and photosynthetic responses of Malaysian Kacip Fatimah (*Labisia pumila* Benth). *Molecules* **2012**, *17*, 7305–7322. [CrossRef]
53. Zhao, Y.; Sun, M.; Guo, H.; Feng, C.; Liu, Z.; Xu, J. Responses of leaf hydraulic traits of Schoenoplectus tabernaemontani to increasing temperature and CO_2 concentrations. *Bot. Stud.* **2022**, *63*, 2. [CrossRef]
54. Zhang, S.; Li, Y. Study on effects of fertilizing on crop yield and its mechanism to raise water use efficiency. *Res Soil and Water Conserv.* **1996**, *3*, 185–191. (In Chinese with English abstract)
55. Zhang, S.Q.; Shan, L. Research progress on water use efficiency of plant. *Agric. Res. Arid Areas.* **2002**, *20*, 1–5. (In Chinese with English abstract)
56. Shi, C.Y.; Zhang, F.D.; Zhang, S.Q.; Li, H.; Fu, C.G. Effects of organic-inorganic compound fertilizers on yield quality and some related physiological characteristics in tomato. *Sci. Agric. Sin.* **2004**, *37*, 1183–1187. (In Chinese with English abstract)
57. Zhang, J.; Fan, T.; Wang, Y.; Tang, X.; Dang, Y. Winter wheat yield and soil nutriments affected by organic fertilizer in Loess Plateau East of Gansu. *Acta Bot. Boreali-Occident. Sin.* **2009**, *29*, 1656–1662. (In Chinese with English abstract)
58. Shenoy, V.V.; Kalagudi, G.M. Enhancing plant phosphorus use efficiency for sustainable cropping. *Biotechnol. Adv.* **2005**, *23*, 501–513. [CrossRef] [PubMed]
59. Khan, M.S.; Zaidi, A.; Ahmad, E. Mechanism of phosphate solubilization and physiological functions of phosphate-solubilizing microorganisms. In *Phosphate Solubilizing Microorganisms*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 31–62.
60. Grassi, G.; Meir, P.; Cromer, R.; Tompkins, D.; Jarvis, P.G. Photosynthetic parameters in seedlings of Eucalyptus grandis as affected by rate of nitrogen supply. *Plant Cell Environ.* **2002**, *25*, 1677–1688. [CrossRef]
61. Sepehri, A.; Modarres Sanavy, S. Water and nitrogen stress on maize photosynthesis. *J Biol Sci.* **2003**, *3*, 578–584.
62. Guo, S.; Yan, X.; Bai, B.; Yu, S. Responses of larch seedling's photosynthetic characteristics to nitrogen and phosphorus deficiency. *Chin. J. Appl. Ecol.* **2005**, *16*, 589–594. (In Chinese with English abstract)
63. Yang, S.; Zhang, Q.; Jiang, Y.; Wang, F.; Zhou, X. Effect of high CO_2 density on photosynthesis speed of *Pinus* massoniana. *J. Anhui Agric. Univ.* **2006**, *23*, 100–104.
64. Mahfouz, S.A.; Sharaf-Eldin, M.A. Effect of mineral vs. biofertilizer on growth, yield, and essential oil content of fennel [Foeniculum vulgare Mill.]. *Int. Agrophys.* **2007**, *21*, 361–366.
65. Kumar, V.; Solanki, A.S.; Sharma, S. Yield and economics of *Withania somnifera* influenced by dual inoculation of *Azotobacter chroococcum* and *Pseudomonas putida*. *Turk. J. Biol.* **2009**, *33*, 219–223. [CrossRef]
66. Zhong, W.; Gu, T.; Wang, W.; Zhang, B.; Lin, X.; Huang, Q.; Shen, W. The effects of mineral fertilizer and organic manure on soil microbial community and diversity. *Plant Soil.* **2010**, *326*, 511–522. [CrossRef]
67. Wang, H.; Wu, L.; Wang, X.; Zhang, S.; Cheng, M.; Feng, H.; Xiang, Y. Optimization of water and fertilizer management improves yield, water, nitrogen, phosphorus and potassium uptake and use efficiency of cotton under drip fertigation. *Agric. Water Manag.* **2021**, *245*, 106662. [CrossRef]
68. Shi, H.; Zhang, J.; Yan, Q.; Li, C.; Li, J. Compensation effects of nitrogen fertilizer on yield and quality cotton under insufficient irrigation. *J. Plant Nutr. Fert.* **2018**, *24*, 134–145. (In Chinese with English abstract)
69. Zheng, Z.; Ma, F.; Mu, Z.X.; Li, J.H.; Yang, H.H. Effects of factors of water and fertilizers under mulch drip irrigation on cotton canopy structure and yield. *Agric. Res. Arid Areas.* **2001**, *19*, 42–47. (In Chinese with English abstract)
70. Wu, L.; Zhang, F.C.; Fan, J.L.; Zhou, H.M.; Liang, F.; Gao, Z.J. Effects of water and fertilizer coupling on cotton yield, net benefits and water use efficiency. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 164–172. (In Chinese with English abstract)

71. Ali, S.; Jan, A.; Sohail, A.; Khan, A.; Khan, M.I.; Zhang, J.; Daur, I. Soil amendments strategies to improve water-use efficiency and productivity of maize under different irrigation conditions. *Agric. Water Manag.* **2018**, *210*, 88–95. [CrossRef]
72. Liu, H.; Yang, H.; Zheng, J.; Jia, D.; Wang, J.; Li, Y.; Huang, G. Irrigation scheduling strategies based on soil matric potential on yield and fruit quality of mulched-drip irrigated chili pepper in Northwest China. *Agric. Water Manag.* **2012**, *115*, 232–241. [CrossRef]
73. Wang, H.; Cheng, M.; Zhang, S.; Fan, J.; Feng, H.; Zhang, F.; Xiang, Y. Optimization of irrigation amount and fertilization rate of drip-fertigated potato based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation methods. *Agric. Water Manag.* **2021**, *256*, 107130. [CrossRef]
74. Peng, Y.; Fei, L.; Liu, X.; Sun, G.; Hao, K.; Cui, N.; Jie, F. Coupling of regulated deficit irrigation at maturity stage and moderate fertilization to improve soil quality, mango yield and water-fertilizer use efficiency. *Sci. Hortic.* **2023**, *307*, 111492. [CrossRef]
75. Zhang, M.; Xiao, N.; Li, Y.; Li, Y.; Zhang, D.; Xu, Z.; Zhang, Z. Growth and Fruit Yields of Greenhouse Tomato under the Integrated Water and Fertilizer by Moistube Irrigation. *Agronomy* **2022**, *12*, 1630. [CrossRef]
76. Wei, H.; Zhang, J.; Long, G.L.; Fan, W.; Meng, Z.; Li, L.; Lu, J. The growth characteristics and ginsenoside content in two-year-old *Panax notoginseng* under potassium regimes. *J. Yunnan Agric. Univ. Nat. Sci.* **2019**, *34*, 695–704. (In Chinese with English abstract)
77. Cun, Z.; Zhang, J.Y.; Chen, J.W. Effects of nitrogen addition on growth, photosynthetic characteristics and saponin content in two-year-old *Panax notoginseng*. *Chin. J. Ecol.* **2020**, *39*, 1101–1111. (In Chinese with English abstract)
78. Liu, Y.; Zhou, X.; Han, H.; Yang, Q.; Liu, X. Coupling scheme optimization of *Panax notoginseng* considering yield, quality and water-fertilizer use efficiency. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 139–146. (In Chinese with English abstract)
79. Zhao, H.; Xia, P.; Wei, M.; Liu, F.; Zhang, C.; Liang, Z. Effects of soil moisture content on root growth, active components and root rot incidence of *Panax notoginseng*. *J. Northwest A F. Uni. Nat. Sci.* **2014**, *42*, 173–178. (In Chinese with English abstract)
80. Gao, Y.; Zhang, T.; Kang, X.P.; Han, M.; Yang, L.M. Preliminary study on response and its mechanism of ginsenoside biosynthesis in Panax ginseng to water regulation. *China J. Chin. Mater. Med.* **2019**, *44*, 2768–2776. (In Chinese with English abstract)
81. Tao, L.; Chu, G.X.; Liu, T.; Tang, C.; Li, J.H.; Liang, Y.C. Impacts of organic manure partial substitution for chemical fertilizer on cotton yield, soil microbial community and enzyme activities in mono-cropping system in drip irrigation condition. *Acta Ecol. Sin.* **2014**, *34*, 6137–6146. (In Chinese with English abstract)