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Alternating Partial Root-Zone Subsurface Drip Irrigation Enhances the Productivity and Water Use Efficiency of Alfalfa by Improving Root Characteristics

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Abstract: Water scarcity is one of the significant constraints on sustainable agricultural development in arid and semi-arid regions. The challenges faced in forage production are even more severe than those encountered with general crops. The industry still struggles to achieve water-efficient, high-yield quality forage in water-scarce pastoral areas. This study focuses on alfalfa, a high-quality forage crop, employing a combination of "subsurface drip irrigation (SDI) + alternate partial root-zone irrigation (APRI)" and establishing three water supply gradients (full irrigation, 75% deficit, 50% deficit), in comparison with the widely used subsurface drip irrigation, to study the effects of two irrigation methods and three moisture gradients on alfalfa. The aim is to provide some theoretical basis and data support for achieving water-saving and high-yield quality forage in water-scarce pastoral areas. The main findings are as follows: First, compared with SDI, the two-year alternate dry and wet environment provided by alternate partial root-zone drip irrigation (ARDI) significantly increased the specific root length, specific surface area, and root length density of alfalfa at 20~40 cm depth, increasing by 33.3~76.8%, 6.4~32.97%, and 15.2~93.9%, respectively, compared to SDI. Under ARDI irrigation, the alfalfa root system has a greater contact area with the soil, which lays a solid foundation for the water and nutrient supply needed for the accumulation of its above-ground biomass. Secondly, over the two-year production process, the plant height of alfalfa under ARDI treatment was 12~14.5% higher than that under SDI, the total fresh forage yield was 43.5~64% higher, and the total dry forage yield was 23.2~33.8% higher than SDI. Under ARDI, the 75% water deficit treatment could still maintain the plant height and stem thickness of alfalfa compared to full irrigation with SDI and increased the dry forage yield by 6.6% without significantly reducing the quality, significantly enhancing the productive performance of alfalfa. Moreover, during the two years of production and utilization, the nutritional quality of alfalfa under the ARDI irrigation mode did not significantly decrease compared to SDI, maintaining the stable nutritional quality of alfalfa over multiple years of production. Lastly, thanks to the improved root system and increased yield of alfalfa under ARDI irrigation, and based on this, its water evapotranspiration did not significantly increase compared to SDI; the annual average Alfalfa Water Productivity Index (AWP_I) and Alfalfa Water Productivity of Crop (AWP_C) under ARDI irrigation increased by 28.8% and 37.2%, respectively, improving the water use efficiency of alfalfa production. In summary, in the production of alfalfa in water-scarce pastoral areas, ARDI and its water deficit treatment have more potential for water-saving than SDI as a water-saving irrigation strategy.

Keywords: alfalfa; alternating partial root-zone irrigation; subsurface drip irrigation; water use efficiency

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1. Introduction

The growth in global crop demand and the expansion of agricultural land have placed unprecedented pressure on the world's water and land resources. Water is a critical input for global agricultural production, and its irreplaceable role in agriculture is undeniable [1,2].

In some parts of the world, the expansion of irrigation projects to meet the demands of agricultural production has put unprecedented pressure on already depleting water bodies and groundwater resources, with groundwater being severely overexploited in some regions [3]. This has also sparked concerns about whether the Earth's finite water resources are sufficient to sustain human activities [4]. Alfalfa (*Medicago sativa* L.), hailed as the "king of pastures", is the most widely cultivated high-yield, high-quality perennial leguminous forage around the world, known for its high nutritional value, cutting tolerance, high yield, and strong adaptability [5]. However, taking the Xinjiang region of China as an example, the climatic characteristics of dryness, scarce rainfall, and uneven distribution across seasons, to some extent, limit the production of high-quality forages such as alfalfa. As one of China's main pastoral areas, Xinjiang produces only 4.5% of the total forage resources in terms of alfalfa and other perennial high-quality forages, a relatively low proportion that, along with the uneven distribution across regions, poses industrial challenges that constrain the development of animal husbandry to a certain extent [6]. Forage production, as an essential part of agricultural production, faces challenges that are even greater than those of general crops [7]. The competition for water between crop production and forage production occurs from time to time, and in the long run, the water demand for artificial grasslands is increasing, while the total water supply cannot increase [8]. The supply and demand contradiction for quality forage will continue to intensify, making it imperative to develop water-saving production technologies that can enhance water use efficiency in the field of forage production.

Subsurface drip irrigation (SDI) is one of the water-saving irrigation technologies widely applied in the artificial grasslands of China's arid and semi-arid regions [9]. It involves laying drip irrigation tubing 0–30 cm below the surface according to different crops, allowing irrigation water to reach the root system directly [10]. Compared to traditional surface irrigation, SDI can effectively reduce surface evaporation of water, prevent surface runoff, and decrease the risk of soil salinization. SDI allows for precise control of irrigation amounts and frequencies according to different water demands and growth stages, providing crops with a uniform and adequate water supply, thereby achieving the goal of increasing yield and quality [11]. Compared to other water-saving irrigation methods, SDI also has the advantage of being usable for multiple years without affecting field machinery operations [12]. Alternate root-zone irrigation is a new type of water-saving irrigation technique derived from deficit irrigation theory, which originated in the 1960s and 1970s. In 1968, Grimes and others first applied partial root-zone drying (PRD) in water-saving studies of cotton fields in the United States, noting that the technique could effectively reduce irrigation quotas and frequency and improve water use efficiency but not significantly reduce yield [13]. Alternate partial root-zone drying irrigation (APRI) was first proposed by Kang Shaozhong in 1997 in China. Its implementation involves irrigating only part of the crop's root system during the irrigation process while the other part remains in relatively dry soil. To avoid growth inhibition due to prolonged drought in some roots, dry and wet areas need to be alternated periodically [14,15]. APRI is currently considered one of the most promising water-saving irrigation techniques. This irrigation method imposes mild and brief drought stress on a portion of the crop's root zone, generating drought stress signals that are transmitted to the plant's interior, inducing an internal drought stress response, and improving the crop's water use efficiency [16]. This technique changes the traditional water-saving irrigation mindset of controlling irrigation timing and volume to improve water efficiency. It proposes regulating soil moisture in different root zones of the crop to generate endogenous hormone feedback, optimize stomatal aperture, and achieve physiological water-saving, paving a new path for agricultural water conservation [17].

Current research on the application of alternate root-zone drip irrigation (ARDI) in forage production in arid and semi-arid regions is not yet comprehensive. Therefore, this study takes alfalfa, a high-quality forage, as the research subject and adopts ARDI in combination with water deficit as a water-saving + biological water-saving irrigation strategy. It examines alfalfa's production performance, nutritional quality, water use efficiency, and root distribution response to ARDI and SDI, exploring whether ARDI and its water deficit can save water without reducing yield or nutritional quality compared to SDI. Secondly, does ARDI possess higher water productivity than SDI under the same irrigation volume? Lastly, will years of alternate root-zone drought training change the root distribution of alfalfa and benefit its water utilization? Through the exploration of the ARDI water-saving irrigation technology, this study aims to provide some theoretical basis and data support for achieving water-efficient and high-yield alfalfa production in water-scarce pastoral areas, which holds significant practical importance for ensuring forage production in arid and semi-arid regions with tight water resources.

2. Materials and Methods

2.1. Overview of the Experimental Site

Experimental site overview: The experimental site is located at the Sanping Farm Teaching and Training Base of Xinjiang Agricultural University, situated at 43°56′26″ N, 87°20′41″ E on the alluvial fan plains of the middle and upper reaches of Toutun River on the northern slope of the Tianshan Mountains. The terrain is flat, and the land is open. It is a typical temperate continental arid climate zone with sparse annual precipitation unevenly distributed across seasons. Early spring and summer often bring strong winds and sudden drops in temperature. The highest average temperature in July is above 24 °C, with extreme temperatures reaching 42 °C. The site receives 2829.4 h of sunshine annually, with an average annual precipitation of 228.8 mm, average annual evaporation of 2657 mm, and an average frost-free period of 160 days, suitable for the cultivation of a variety of crops. In the 0–70 cm soil profile, the alkali-hydrolyzable nitrogen content is 15.4 mg·kg^{-1}, the available phosphorus content is 11.32 mg·kg^{-1}, the exchangeable potassium content is 173.73 mg·kg^{-1}, the available sulfur content is 13.73 mg·kg^{-1}, the organic matter content is 19.29 g·kg^{-1}, and the pH value is 8.47.

2.2. Experimental Design

The experimental alfalfa, the Xinmu No. 4 variety of purple alfalfa, was planted on 8 May 2022, using row seeding with a row spacing of 30 cm. The first irrigation was on 9 May, followed by two full irrigations during the alfalfa seedling stage under the same conditions. Irrigation treatments began once the alfalfa reached the branching stage, with conventional field management (weeding, pest control, etc.) during the experiment. During the two-year experimental period, no form of fertilizer was applied.

The experiment adopted a randomized block design, with two irrigation methods, ARDI and SDI, set during the two-year production process of alfalfa. Based on previous research experience, the irrigation quota [18] was determined, and three water supply gradients were set for each irrigation method: W1: 70 mm, W2: 52.5 mm, W3: 35 mm. The experiment consisted of 6 treatments with 18 plots, each plot measuring 5 m × 5 m. Each experimental plot was irrigated by the drip tube system shown in Figure 1, with a 75 mm PE hose as the main line. Plots using the ARDI irrigation method were connected to 17 16 mm drip irrigation tubes, buried at a depth of 15 cm with a spacing of 30 cm. Red and blue colored valves were installed at the front end of the connection to the main line, allowing for alternate irrigation by switching the adjacent bypass valves. Plots using the SDI irrigation method were connected to 9 16 mm drip irrigation tubes, buried at a depth of 15 cm with a spacing of 60 cm. Each water control unit was equipped with ball valves and water meters to control the irrigation volume for each treatment, with all drip irrigation tubes being of the inlaid patch type.

Two full irrigations were conducted on 9 May 2022 and 16 May 2022, the year the alfalfa was planted. Irrigation treatments began on 17 June 2022 and 18 May 2023, with specific irrigation dates and volumes as shown in Table 1. During the experiment, a manual weather station was used to record meteorological conditions at the experimental site, as shown in Figure 2, including the highest temperature, the lowest temperature, the average temperature, and precipitation. The changes in soil moisture content at the experimental site are shown in Figure 3. Soil samples were taken using a soil auger 2–3 days and 8–10 days after irrigation, and the soil moisture content by weight (%) was calculated.

Figure 1. The photo shows the underground drip irrigation system used for water control in each plot of the test plot, which forms alternating irrigation on both sides of the crops by opening and closing the adjacent red and blue bypass valves.

Table 1. Details of the various irrigation treatments in 2022–2023.

Irrigation Date		**Single Irrigation Amount (mm)**					
		ARDI1	**ARDI2**	**ARDI3**	**SDI1**	**SDI2**	**SDI3**
2022	9 May	70	70	70	70	70	70
	16 May	70	70	70	70	70	70
	17 June	70	52.5	35	70	52.5	35
	6 July	70	52.5	35	70	52.5	35
	22 July	70	52.5	35	70	52.5	35
	15 August	70	52.5	35	70	52.5	35
	winter irrigation	140	140	140	140	140	140
2023	18 May	70	52.5	35	70	52.5	35
	6 June	70	52.5	35	70	52.5	35
	1 July	70	52.5	35	70	52.5	35
	13 July	70	52.5	35	70	52.5	35
	8 August	70	52.5	35	70	52.5	35
	28 August	70	52.5	35	70	52.5	35

Note: ARDI1, ARDI2, and ARDI3 represent three levels of water supply gradients under alternate root-zone drip irrigation treatment; SDI1, SDI2, and SDI3 represent three levels of water supply gradients under subsurface drip irrigation treatment.

2.3. Measurement Indicators and Methods

2.3.1. Soil Water Content

Soil samples are collected using a soil auger at depths of 0–20 cm, 20–40 cm, and 40–60 cm from each experimental plot 2–3 days and 8–10 days after irrigation, with increments of 20 cm. The samples are then placed in aluminum boxes of equal volume. The boxes filled with soil samples are labeled and weighed immediately. Afterwards, they are taken back to the laboratory and dried in an oven at 105 °C for more than 12 h. The aluminum boxes with the soil samples are removed and weighed, and the weight is recorded. The soil moisture content by weight (%) is calculated by the ratio of the difference in weight of the soil sample before and after drying to the initial weight of the soil sample [19].

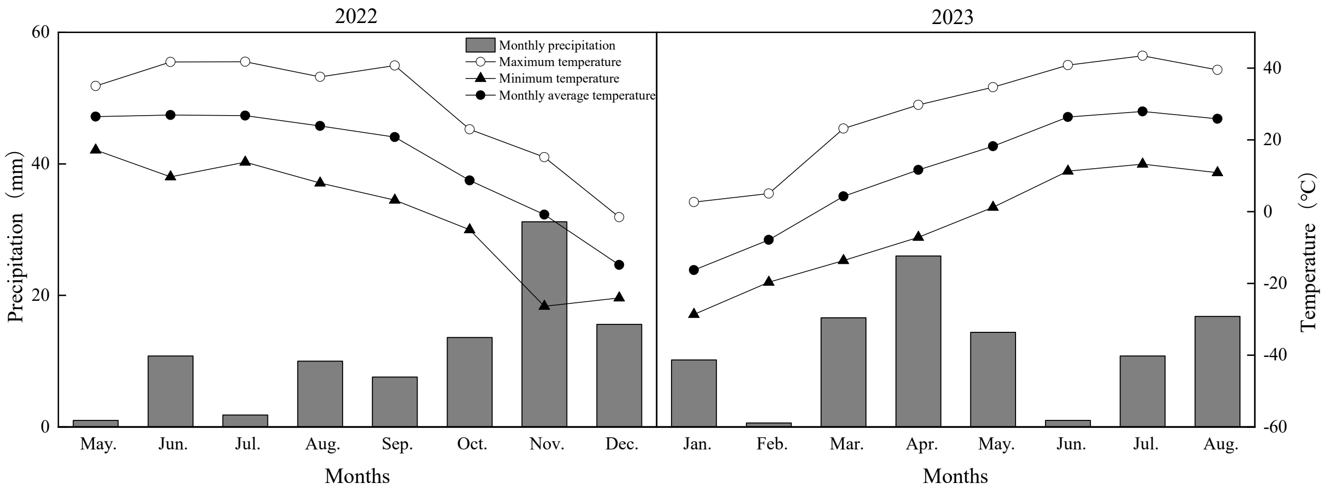

Figure 2. Monthly precipitation, minimum, maximum, and mean air temperature values from 2022 to 2023.

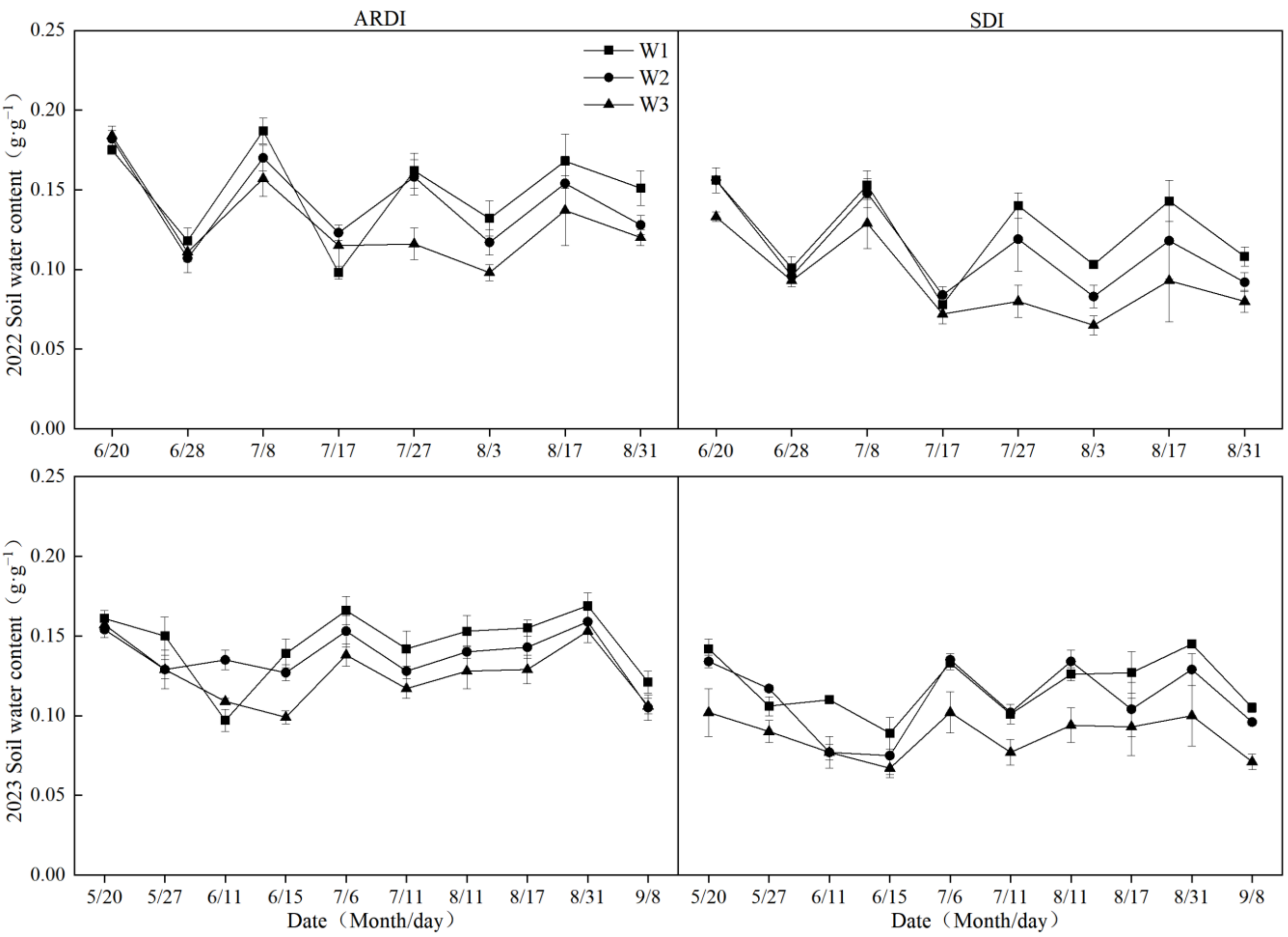

Figure 3. Average soil moisture content over time during the 2022–2023 experimental period under two irrigation methods (ARDI: alternate root-zone drying irrigation, SDI: subsurface drip irrigation) and three water supply gradients (W1, W2, W3).

2.3.2. Soil Water Storage

Soil water storage was calculated based on the soil water content measured by the oven-drying method using the following formula [20].

$$W = \frac{h \cdot \theta_v}{10} \quad (1)$$

W = soil water storage (mm), *h* = soil layer depth (cm), *θv* = soil volumetric water content (%).

2.3.3. Crop Evapotranspiration

The actual evapotranspiration of each crop was estimated using the soil water balance method, with the formula:

$$ET_a = I + P + S - \Delta W - R - D \quad (2)$$

ETa = actual crop evapotranspiration (mm), Δ*W* = change in soil water storage (mm), *P* = precipitation (mm), *I* = irrigation amount (mm), *S* = groundwater recharge (mm), *R* = surface runoff (mm), *D* = deep percolation.

2.3.4. Plant Height, Stem Diameter

In each experimental plot, a 1 m × 1 m square quadrat was established, from which 5 random alfalfa plants were selected to measure their plant height and stem diameter. A tape measure was used to measure the vertical height from the highest point of the plant to the ground to determine plant height. A vernier caliper was used to measure the stem diameter at the base of the rhizome.

2.3.5. Fresh Weight, Dry Weight

A 1 m × 1 m square quadrat was established in each experimental plot, and the harvested alfalfa from this area was cleaned of surface soil and impurities and weighed for fresh weight. The cleaned alfalfa was then dried in an oven to a constant weight to obtain the dry weight within the quadrat. The dry forage yield of alfalfa was calculated using the dry-to-fresh weight ratio.

2.3.6. Nutritional Quality

The determination of crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF). In each differently treated experimental area, 20 fresh grass plants were randomly selected and placed in an oven at 105 °C for 1 h to wilt; then, the temperature was adjusted to 65 °C to dry the alfalfa to a constant weight. The dried samples were ground into fine powder and sieved through a 0.5 mm mesh; then, the crude protein (CP) content was determined using a Kjeldahl apparatus, and the neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were determined by the Van Soest method.

2.3.7. Water Use Efficiency

In this study, water productivity (WP_C) was calculated as the ratio of dry hay yield to the transpiration of alfalfa in each cut [21]; irrigation water productivity (WP_I) was calculated as the ratio of dry hay yield to the actual irrigation amount applied in each cut, with the formulas as follows [22]:

$$WP_C = \frac{Hay\ yield}{ETa} \quad (3)$$

$$WP_I = \frac{Hay\ yield}{IWU} \quad (4)$$

2.3.8. Root System Indicators

After two years of alfalfa production, a 10 cm diameter root auger was used to randomly select one alfalfa plant as the center and dig down in 20 cm increments to a depth of 0–60 cm to collect alfalfa roots, with two samples taken from each experimental plot on a diagonal basis. The obtained root samples were soaked in clean water for 24 h and then washed with running water to remove the surface soil. They were placed on a root tray and scanned with an Epson GT-X980 scanner to obtain root images. The WSEEN LA-S version 2.6.5.5 root analysis software was used to analyze and obtain indicators such as root length (cm), average diameter (mm), and average volume (cm^3) for each soil layer of alfalfa roots. The dry weight of the roots was determined after scanning by drying the numbered roots at 105 °C to a constant weight and weighing them.

2.4. Data Processing and Statistical Methods

All data were compiled using Microsoft Excel software 2021, and Two-Way ANOVA was performed using IBM SPSS 26.0 statistical analysis software. Graphs were created using Origin 2021.

3. Results

3.1. Effects of Different Irrigation Strategies on Alfalfa Production Performance

The effects of irrigation method and irrigation gradient on the height of alfalfa plants are shown in Figure 4. The irrigation method significantly affected the height of alfalfa plants in all cuts except for the first cut in 2022 ($p < 0.05$), and the irrigation gradient significantly affected the height of alfalfa plants in all cuts except for the first cut in 2023 ($p < 0.05$). However, the interaction between the two did not significantly affect the height of the plants in any of the cuts ($p > 0.05$). ARDI significantly increased the height of alfalfa plants in the second cut of 2022 and in all cuts of 2023 compared to SDI ($p < 0.05$). In the cuts of alfalfa harvested from 2022 to 2023, the height of alfalfa plants under both irrigation methods showed a decreasing trend with the reduction in water. However, there was no significant difference in the height of alfalfa plants under the W3 and W2 treatments of ARDI and SDI in the first cut of 2022 and under the W2 treatment of ARDI in the second cut of 2023 compared to their respective fully irrigated heights ($p > 0.05$).

The effects of irrigation method and irrigation gradient on the stem diameter of alfalfa plants are shown in Figure 5. Both the irrigation method and the irrigation gradient significantly affected the stem diameter of alfalfa in all cuts except for the first cut in 2022 ($p < 0.05$), but the interaction between the two did not significantly affect the stem diameter in any of the cuts ($p > 0.05$). ARDI significantly increased the stem diameter of alfalfa in the second cut of 2022 and in all cuts of 2023 compared to SDI ($p < 0.05$). In the alfalfa harvested over two years, the stem diameter under both irrigation methods showed a decreasing trend with the reduction in water. The stem diameter of alfalfa under the W2 gradient of both irrigation methods in the second cut of 2022 and the first cut of 2023 did not significantly decrease compared to their respective fully irrigated treatments ($p > 0.05$).

3.2. Effects of Different Irrigation Strategies on Alfalfa Yield

The effects of irrigation method and irrigation gradient on the fresh forage yield of alfalfa are shown in Figure 6. The irrigation strategy significantly affected the fresh forage yield of alfalfa in each cut during 2022–2023 ($p < 0.05$), and the irrigation gradient significantly affected the yield in all cuts except for the first cut in 2023 ($p < 0.05$), but their interaction did not significantly affect the yield in any of the cuts ($p > 0.05$). ARDI significantly increased the fresh forage yield in each cut and the total fresh forage yield in 2022 and 2023 compared to SDI. Over the two years, the fresh forage yield in each cut decreased with the reduction in water supply. In the second cut of 2022 and 2023, and the total fresh forage yield of 2023, the yield under the W2 water supply gradient of SDI treatment was significantly reduced compared to the full irrigation treatment ($p < 0.05$), while under the ARDI treatment with the W2 gradient, the reduction was not significant ($p > 0.05$).

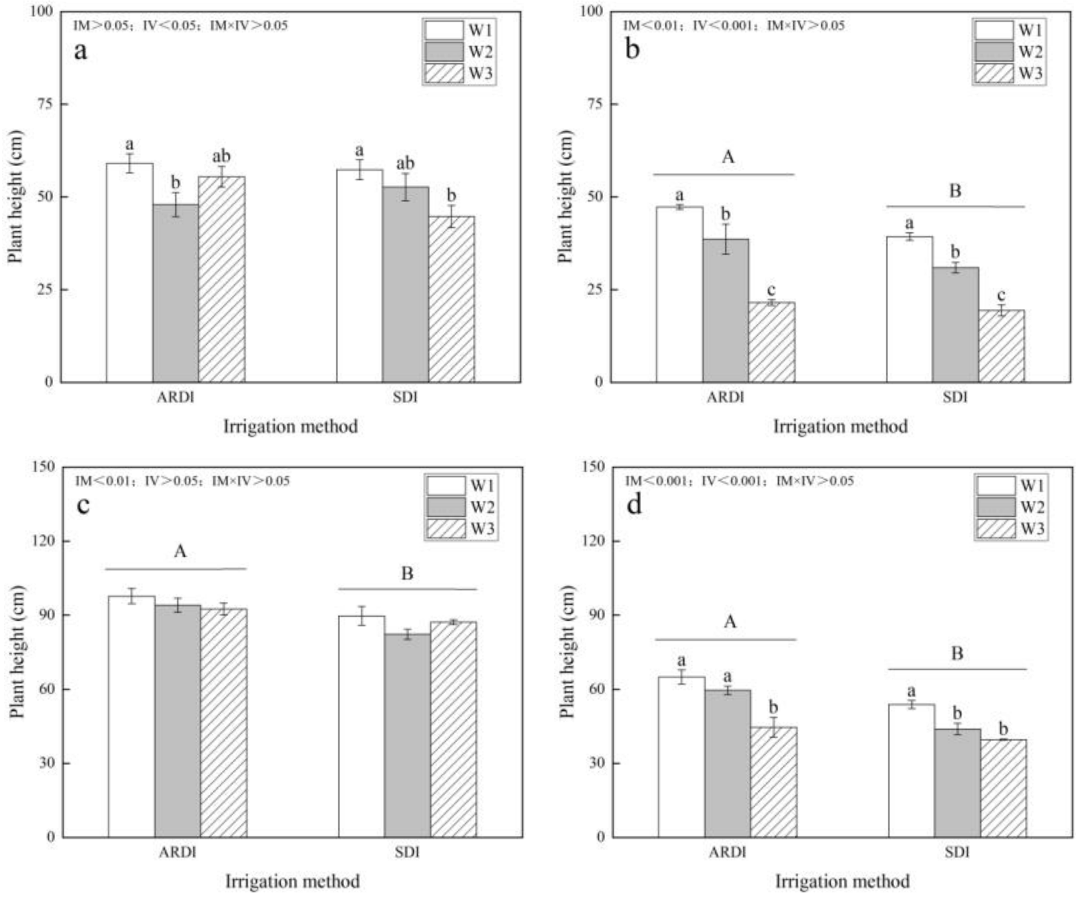

Figure 4. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the height of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively, while (**c**,**d**) correspond to the 1st and 2nd cuts in 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

The effects of irrigation method and irrigation gradient on the dry hay yield of alfalfa are shown in Figure 7. The irrigation strategy significantly affected the dry hay yield of alfalfa in each cut during 2022–2023 ($p < 0.05$), and the irrigation gradient significantly affected the yield in all cuts except for the first cut in 2023 ($p < 0.05$), but their interaction did not significantly affect the yield in any of the cuts ($p > 0.05$). ARDI significantly increased the dry hay yield in each cut and the total dry hay yield in 2022 and 2023 compared to SDI. Over the two years, the dry hay yield in each cut decreased with the reduction in water supply. However, in the second cut of 2023 and the total dry hay yield of 2023, the yield under the W2 water supply gradient of ARDI treatment did not significantly decrease compared to full irrigation ($p > 0.05$).

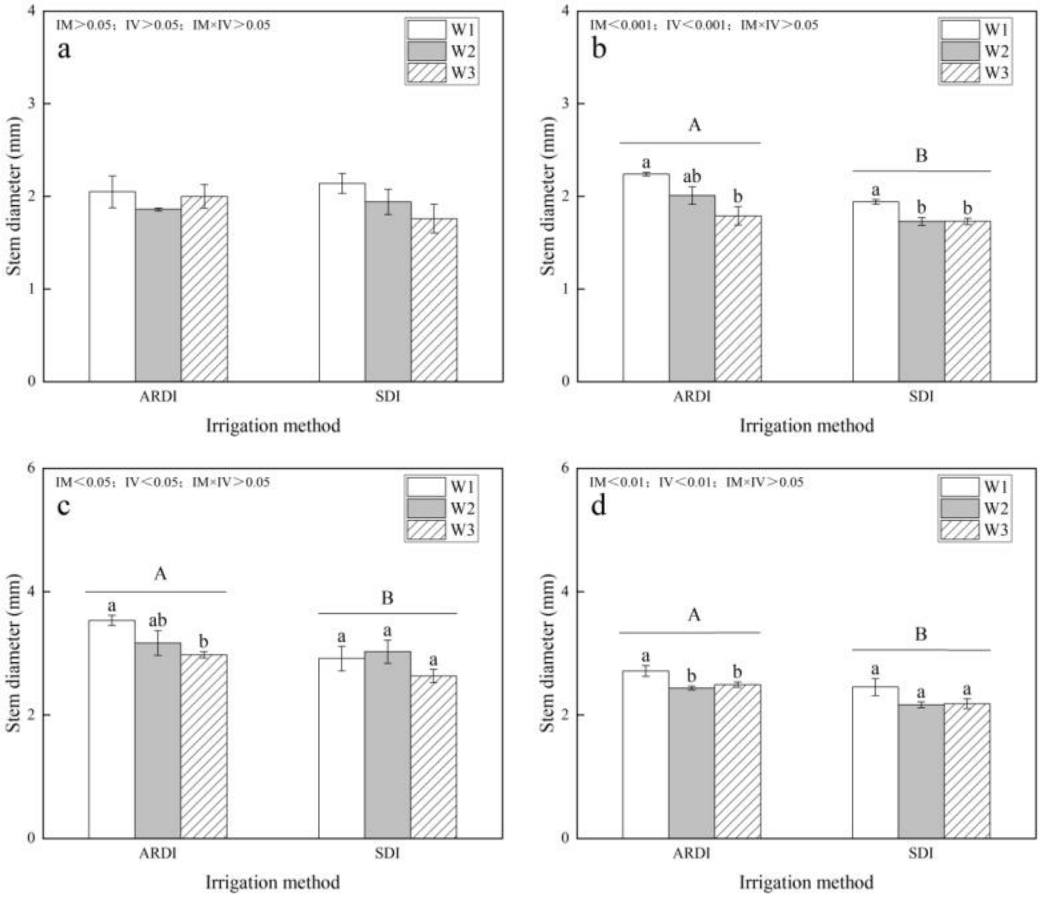

Figure 5. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the stem diameter of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively, while (**c**,**d**) correspond to the 1st and 2nd cuts in 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

3.3. Effects of Different Irrigation Strategies on Nutritional Quality of Alfalfa

3.3.1. Crude Protein Content

The effects of irrigation method and irrigation gradient on the crude protein (CP) content of alfalfa are shown in Figure 8. The irrigation method had a significant effect on the CP content of alfalfa in each cut of 2022 ($p < 0.05$), and the irrigation gradient had a significant effect on the CP content in the second cut of 2022 and the first cut of 2023 ($p < 0.05$), but their interaction did not significantly affect the CP content in any of the cuts ($p > 0.05$). ARDI significantly increased the CP content of alfalfa in the first cut of 2022 ($p < 0.05$) and significantly decreased it in the second cut of 2022 ($p < 0.05$). In the second cut of 2022, the CP content under the W3 gradient of ARDI and SDI treatments did not significantly decrease compared to W1 ($p > 0.05$); in the first cut of 2023, the CP content under the W2 gradient of ARDI and SDI treatments did not significantly decrease compared to W1 ($p > 0.05$).

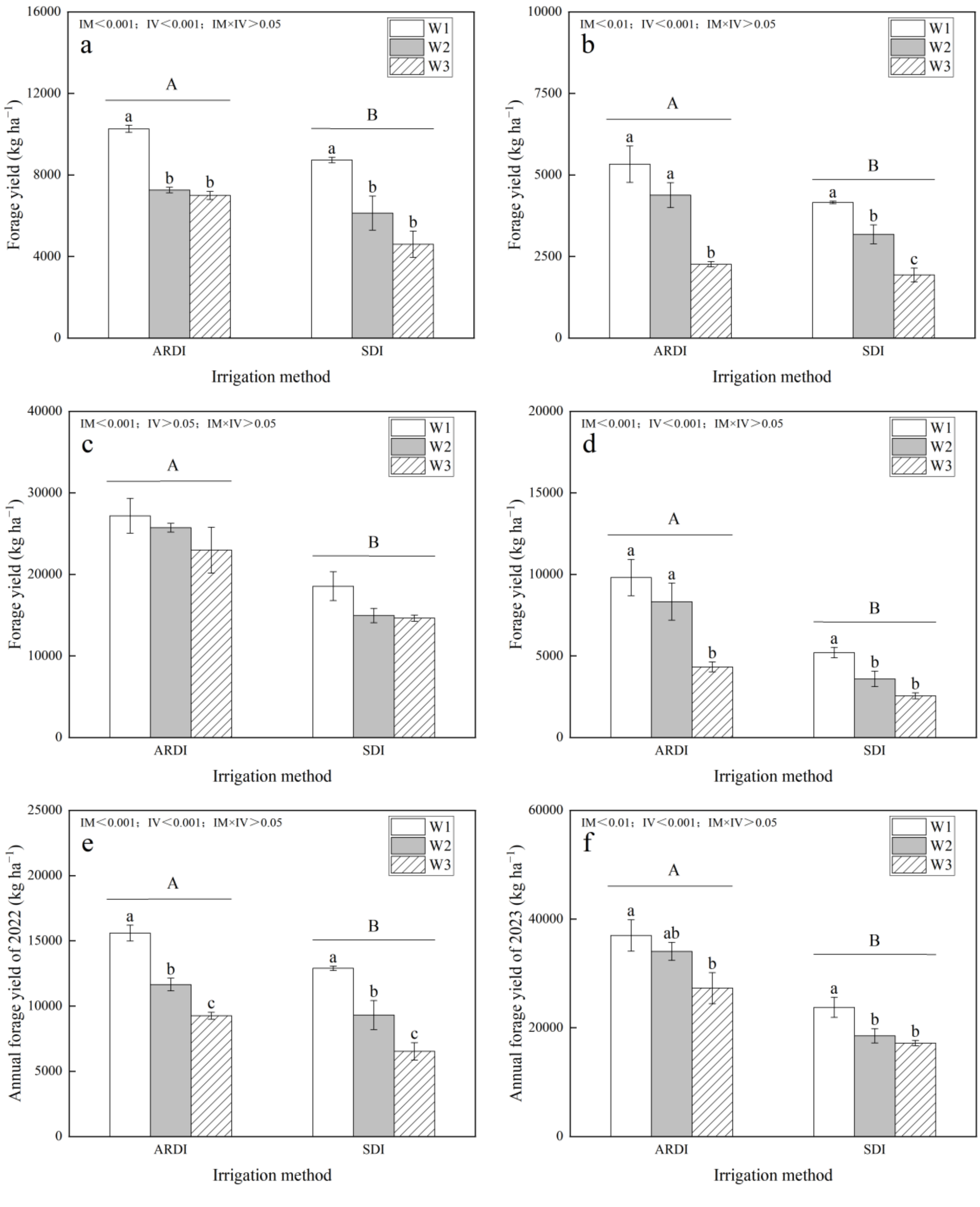

Figure 6. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the fresh forage yield of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively; (**c**,**d**) correspond to the 1st and 2nd cuts in 2023; and (**e**,**f**) correspond to the annual data for alfalfa for the years 2022 and 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

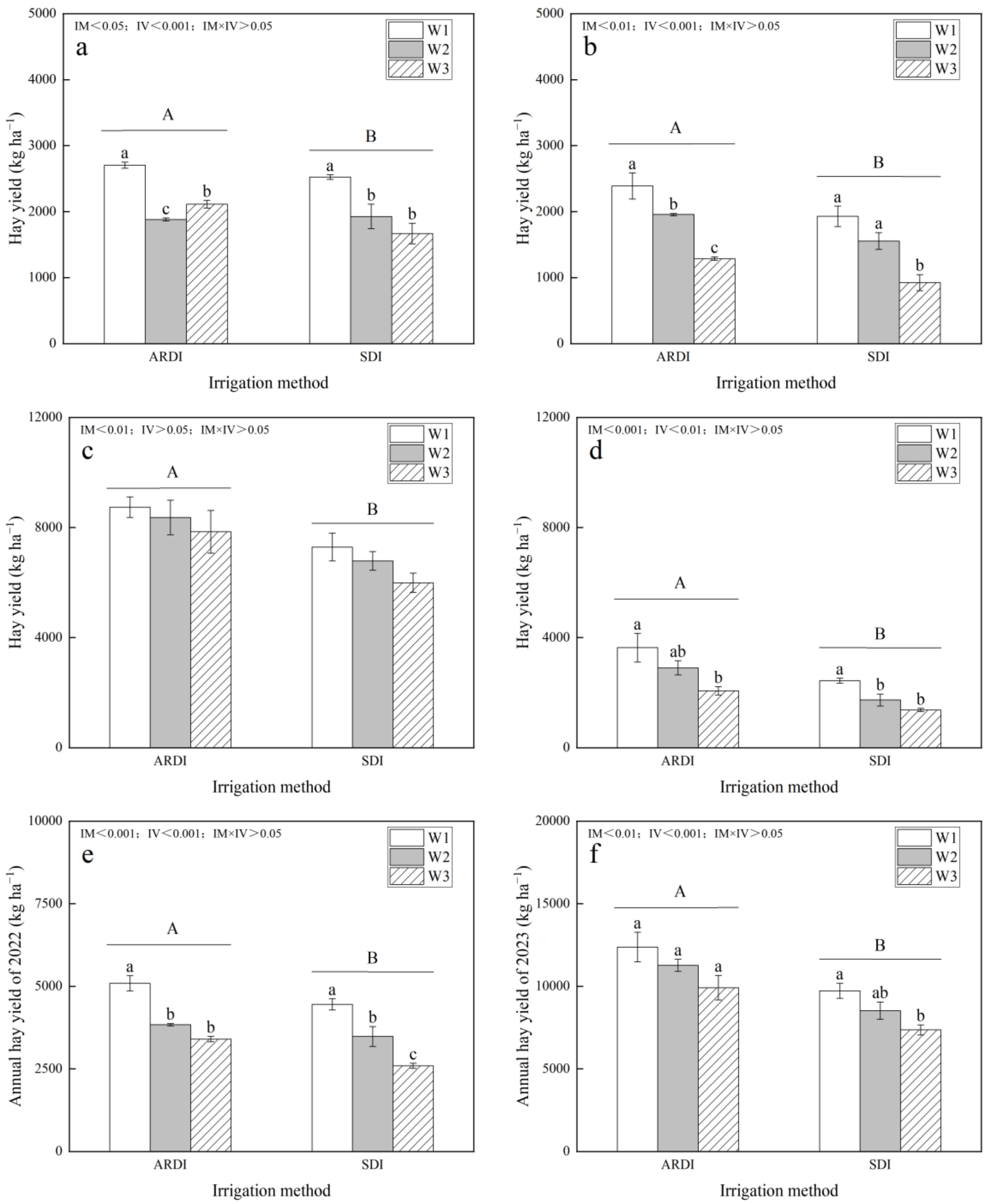

Figure 7. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the hay yield of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively; (**c**,**d**) correspond to the 1st and 2nd cuts in 2023; and (**e**,**f**) correspond to the annual data for alfalfa for the years 2022 and 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

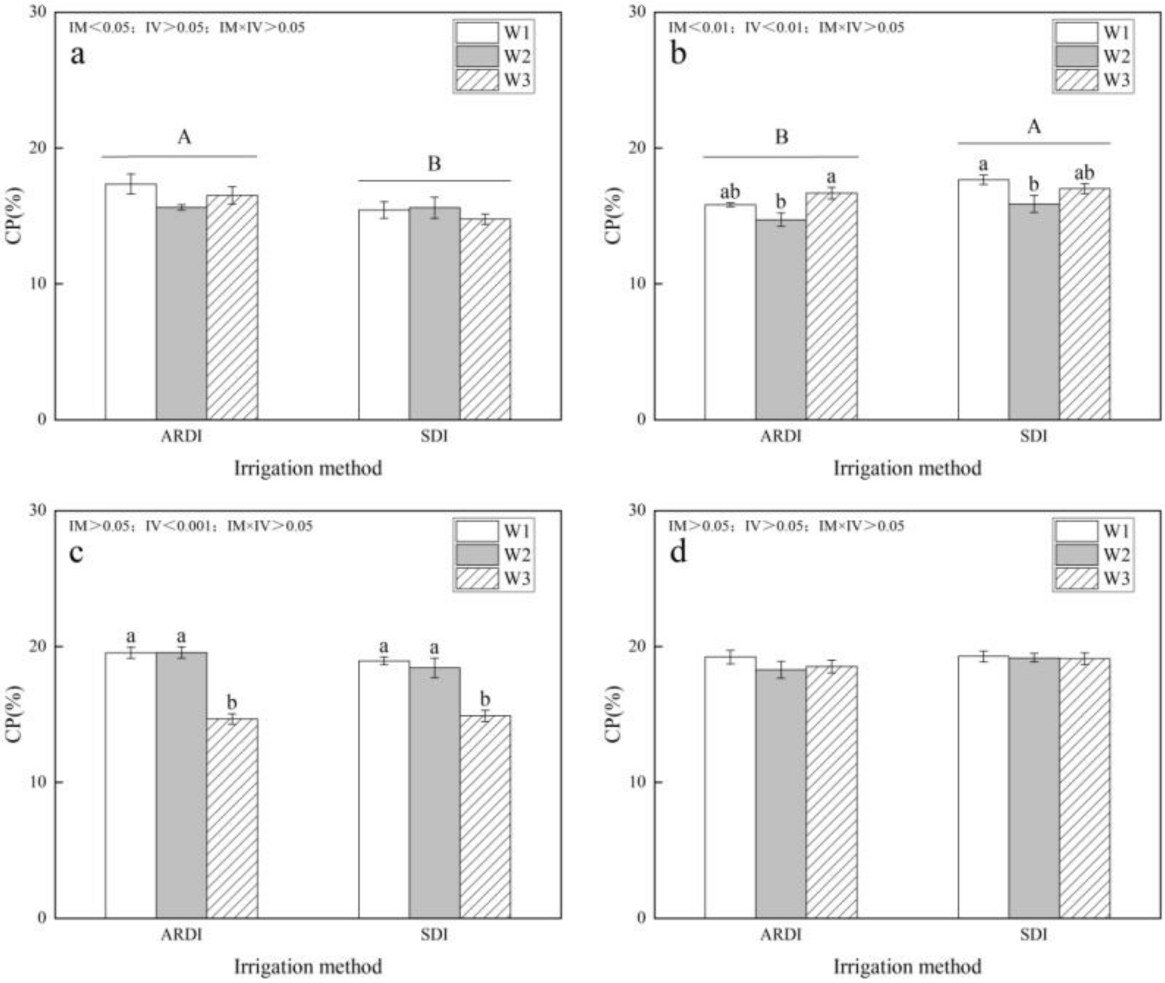

Figure 8. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the crude protein content of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively, while (**c**,**d**) correspond to the 1st and 2nd cuts in 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

3.3.2. Neutral Detergent Fiber

The effects of irrigation method and irrigation gradient on the neutral detergent fiber (NDF) content of alfalfa are shown in Table 2. Their interaction significantly affected the NDF content of alfalfa in the first cut of 2022 and the second cut of 2023 ($p < 0.05$), and the irrigation gradient significantly affected the NDF content in the second cut of 2022 and the first cut of 2023 ($p < 0.05$). In the first cut of 2022, the NDF content of alfalfa under ARDI irrigation decreased significantly with the reduction in water supply ($p < 0.05$), while the NDF content under SDI irrigation did not show significant differences across water supply gradients ($p > 0.05$). The NDF content under the W3 gradient of ARDI treatment was significantly lower than that of SDI treatment ($p < 0.05$). In the second cut of 2023, the lowest NDF content was observed under the W2 gradient for both ARDI and SDI treatments, which was significantly lower than the W1 gradient ($p < 0.05$); the NDF content under the W3 gradient of ARDI was significantly higher than that of the same water supply under

SDI treatment ($p < 0.05$). In the second cut of 2022, the NDF content under the W3 gradient of ARDI treatment was significantly lower than the W1 and W2 treatments ($p < 0.05$), while there were no significant differences in NDF content under different irrigation gradients of SDI treatment ($p > 0.05$). In the first cut of 2023, there were no significant differences in NDF content under different irrigation gradients of ARDI treatment ($p > 0.05$), but the lowest NDF content under SDI treatment was observed in the W2 gradient, which was significantly lower than the W1 gradient ($p < 0.05$).

Table 2. The effect of irrigation method and amount on the ADF, NDF, and RFV of alfalfa harvested from 2022 to 2023.

Treament		ADF				NDF				RFV			
		2022		2023		2022		2023		2022		2023	
		Cutting1	Cutting2	Cutting1	Cutting2	Cutting1	Cutting2	Cutting1	Cutting2	Cutting1	Cutting2	Cutting1	Cutting2
IM	ARDI	26.387 b	25.993 a	19.843	19.302	31.526 b	33.865	26.968	24.707 a	203.972 a	190.785 b	257.085	282.271 b
	SDI	29.483 a	23.444 b	20.137	18.659	34.181 a	31.928	26.96	23.219 b	182.749 b	208.433 a	255.572	299.94 a
	sig.	**	***	ns	ns	*	ns	ns	*	*	*	ns	*
IV	W1	29.693 a	24.976 a	20.89	19.026	33.079	34.231 a	28.624 a	24.664 a	189.345	190.53 b	239.055 b	282.255 b
	W2	27.193 b	26.372 a	17.966	18.268	33.333	33.82 a	25.496 b	22.046 b	191.504	190.418 b	275.809 a	316.719 a
	W3	26.92 b	22.807 b	21.114	19.648	32.15	30.639 b	26.773 ab	25.179 a	199.233	217.878 a	254.121 ab	274.342 b
	sig.	*	***	ns	ns	ns	*	*	***	ns	**	*	***
IM×IV	ARDI + W1	27.798 b	26.135	19.176	18.809 b	31.512 ab	35.810	28.393	24.674 b	202.014 ab	178.888	248.152	282.235 b
	ARDI + W2	27.623 b	28.373	18.498	18.034 b	33.933 a	34.691	25.164	22.165 c	185.029 b	179.492	278.069	317.27 a
	ARDI + W3	23.74 c	23.470	21.854	21.064 a	29.135 b	31.093	27.348	27.283 a	224.873 a	213.975	245.035	247.308 c
	SDI + W1	31.588 a	23.817	22.603	19.244 b	34.645 a	32.651	28.856	24.653 b	176.676 b	202.172	229.959	282.275 b
	SDI + W2	26.763 bc	24.371	17.433	18.502 b	32.733 ab	32.949	25.828	21.927 c	197.978 ab	201.345	273.549	316.167 a
	SDI + W3	30.1 ab	22.143	20.374	18.232 b	35.165 a	30.184	26.197	23.076 bc	173.593 b	221.781	263.207	301.377 ab
	sig.	**	ns	ns	**	*	ns	ns	*	*	ns	ns	*

Note: The data in the table are the average values of experimental replicates, with *, **, *** representing $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively, and ns indicating not significant. ARDI and SDI refer to alternate root-zone drip irrigation and subsurface drip irrigation, respectively, while W1, W2, W3 represent the three water supply gradients of alfalfa. Different lowercase letters within the table indicate significant differences among treatments.

3.3.3. Acid Detergent Fiber

The effects of irrigation method and irrigation gradient on the acid detergent fiber (ADF) content of alfalfa are shown in Table 2. Their interaction significantly affected the ADF content of alfalfa in the first cut of 2022 and the second cut of 2023 ($p < 0.05$), and both the irrigation method and gradient significantly affected the ADF content in the second cut of 2022 ($p < 0.05$). In the first cut of 2022, the ADF content of alfalfa under the W1 and W3 gradients of ARDI irrigation was significantly lower compared to the same gradients of SDI ($p < 0.05$). In the second cut of 2022, ARDI significantly increased the ADF content of alfalfa compared to SDI ($p < 0.05$), and the ADF content under ARDI treatment increased significantly with the reduction in irrigation gradient and then decreased significantly ($p < 0.05$), while the ADF content under different gradients of SDI treatment did not change significantly ($p > 0.05$). In the second cut of 2023, ARDI significantly increased the ADF content under the W3 gradient compared to SDI ($p < 0.05$), but there were no significant differences in ADF content under other irrigation gradients between the two irrigation methods ($p > 0.05$).

3.3.4. Relative Feed Value

The effects of irrigation method and irrigation gradient on the relative feed value (RFV) content of alfalfa are shown in Table 2. The interaction between the two significantly affected the RFV of the first cut in 2022 and the second cut in 2023 ($p < 0.05$). The irrigation gradient significantly affected the RFV of the second cut in 2022 and the first cut in 2023 ($p < 0.05$). In the first cut of 2022, the RFV under the W3 gradient of ARDI treatment was the highest, significantly higher than that of the same gradient under SDI treatment ($p < 0.05$). In the second cut of 2022, ARDI significantly reduced the RFV of alfalfa compared to SDI treatment ($p < 0.05$), with no significant difference in RFV across the gradients under SDI treatment ($p > 0.05$). In the two cuts harvested in 2023, the highest RFV under both ARDI and SDI irrigation methods was at the W2 gradient. Throughout the cuts harvested in 2022–2023, there was a trend of increasing RFV with decreasing irrigation gradients under both irrigation methods.

3.4. Effects of Different Irrigation Strategies on Irrigation Water Productivity of Alfalfa

The effects of irrigation method and irrigation gradient on the irrigation water productivity (WP_I) of alfalfa are shown in Figure 9. The interaction between the two significantly affected the WP_I of the first cut in 2022 ($p < 0.05$). The irrigation method significantly affected the WP_I of each cut harvested in 2022 and 2023 ($p < 0.05$), and the irrigation gradient significantly affected the WP_I of the first cut and the entire year of 2022 ($p < 0.05$). ARDI significantly increased the WP_I for each cut harvested in 2022 and 2023 and for the entire years of 2022 and 2023 ($p < 0.05$). For the cuts harvested in 2022–2023, the highest WP_I under ARDI irrigation was at the W3 gradient.

The effects of irrigation method and irrigation gradient on the actual evapotranspiration (ETa) are shown in Figure 10. The interaction between the two significantly affected the ETa of the second cut in 2022 and each cut in 2023, and the irrigation gradient significantly affected the ETa of the first cut in 2022 ($p < 0.05$). In each cut of alfalfa during 2022–2023, the ETa under the W3 gradient of ARDI irrigation was the lowest. In the second cut of 2022 and the first cut of 2023, the ETa under the W3 gradient of ARDI treatment was significantly lower than that under the same gradient of SDI treatment ($p < 0.05$). Throughout the years 2022 and 2023, the ETa under ARDI treatment significantly decreased with decreasing irrigation gradient ($p < 0.05$), while under SDI treatment, after a significant reduction in ETa at the W2 gradient, there was no significant difference between ETa at W3 and W2 ($p > 0.05$).

The effects of irrigation method and irrigation gradient on crop water productivity (WP_C) are shown in Figure 11. Neither the interaction between the two nor the irrigation gradient significantly affected the WP_C of alfalfa in any of the cuts between 2022 and 2023 ($p > 0.05$). However, the irrigation method significantly affected the WP_C of all cuts except for the first cut in 2022 ($p < 0.05$). ARDI, compared to SDI, significantly improved the WP_C for the second cut in 2022, each cut in 2023, and for the entire years of 2022 and 2023 ($p < 0.05$).

3.5. The Impact of Different Irrigation Strategies on the Spatial Distribution Characteristics of Alfalfa Root Systems

The effects of irrigation method and irrigation gradient on the dry weight of alfalfa roots are shown in Figure 12. The interaction between the two did not significantly affect the dry weight of alfalfa roots in any soil layer ($p > 0.05$). The irrigation gradient significantly affected the root dry weight at a depth of 20–40 cm ($p < 0.05$). In the 0–20 cm soil layer, neither irrigation method nor gradient significantly affected root dry weight ($p > 0.05$); at the 20–40 cm depth, there was no significant difference in root dry weight among different water supply gradients under ARDI treatment ($p > 0.05$), while under SDI treatment, the root dry weight at the W3 irrigation level was significantly lower than at the W1 level ($p < 0.05$), and the root dry weight at the W2 level was reduced compared to the W1 level but not significantly ($p > 0.05$); in the 40–60 cm soil layer, neither irrigation method nor gradient significantly affected root dry weight ($p > 0.05$).

The effects of irrigation method and irrigation gradient on the average diameter of alfalfa roots are shown in Figure 13. The interaction between the two significantly affected the average root diameter at a depth of 40–60 cm ($p < 0.05$); the irrigation method significantly affected the average root diameter at a depth of 20–40 cm ($p < 0.05$), and the irrigation gradient significantly affected the average root diameter at depths of 20–40 cm and 40–60 cm ($p < 0.05$). In the 0–20 cm soil layer, neither the irrigation method nor gradient significantly affected the average root diameter ($p > 0.05$); at the 20–40 cm depth, the average diameter under ARDI treatment was significantly lower than under SDI treatment ($p < 0.05$), and significantly decreased with the reduction in water supply ($p < 0.05$); under SDI treatment, there was no significant difference in average diameter across water supply levels ($p > 0.05$). At the 40–60 cm depth, the average root diameter under ARDI treatment at the W2 irrigation level was significantly lower compared to the W1 level ($p < 0.05$) but not significantly different from the W3 level ($p > 0.05$); under SDI treatment, there was no significant difference in average root diameter between the W1 and W2 levels ($p > 0.05$), but the average diameter at the W3 level was significantly lower compared to other irrigation levels ($p < 0.05$).

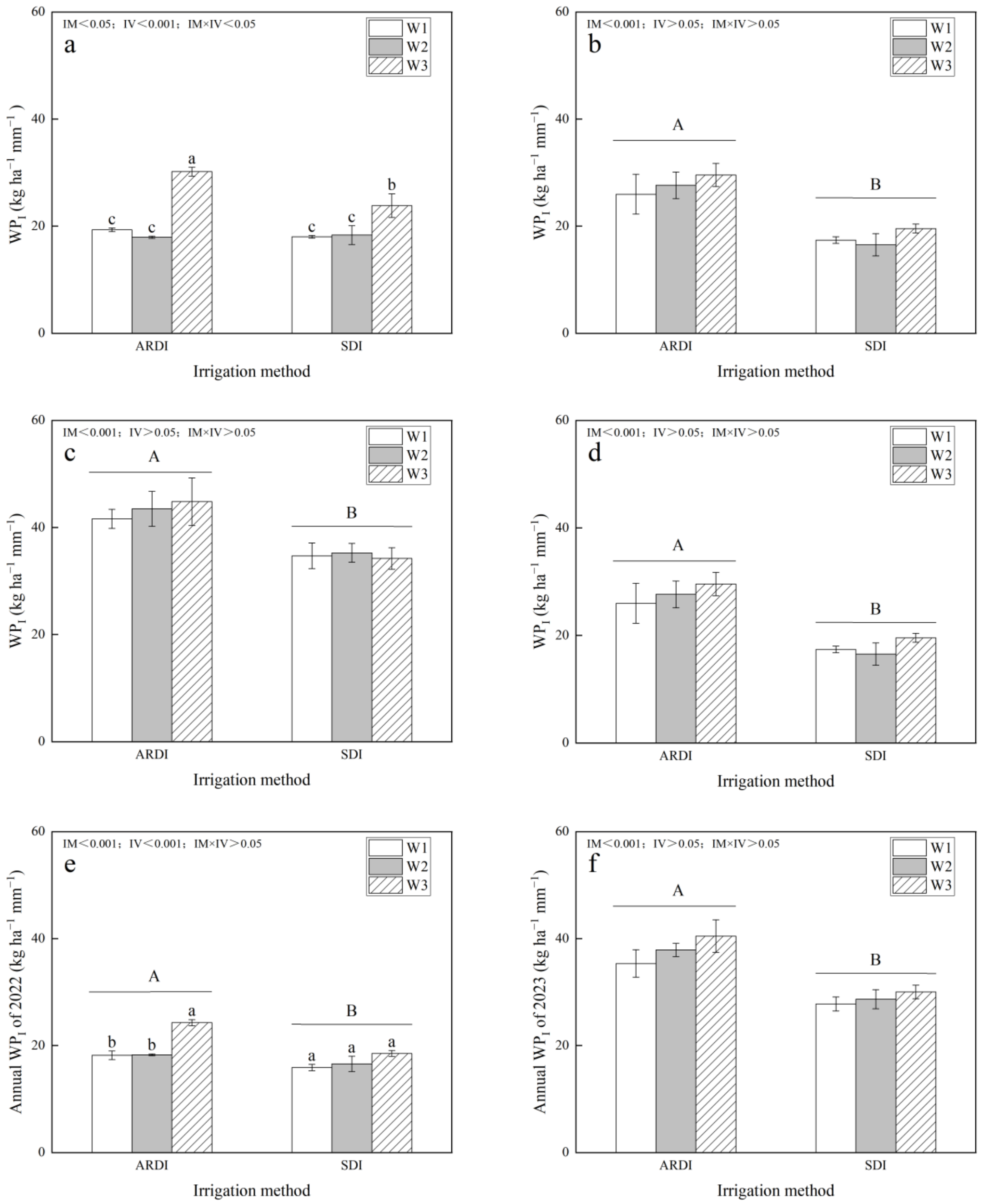

Figure 9. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the water productivity index of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively; (**c**,**d**) correspond to the 1st and 2nd cuts in 2023; and (**e**,**f**) correspond to the annual data for alfalfa for the years 2022 and 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

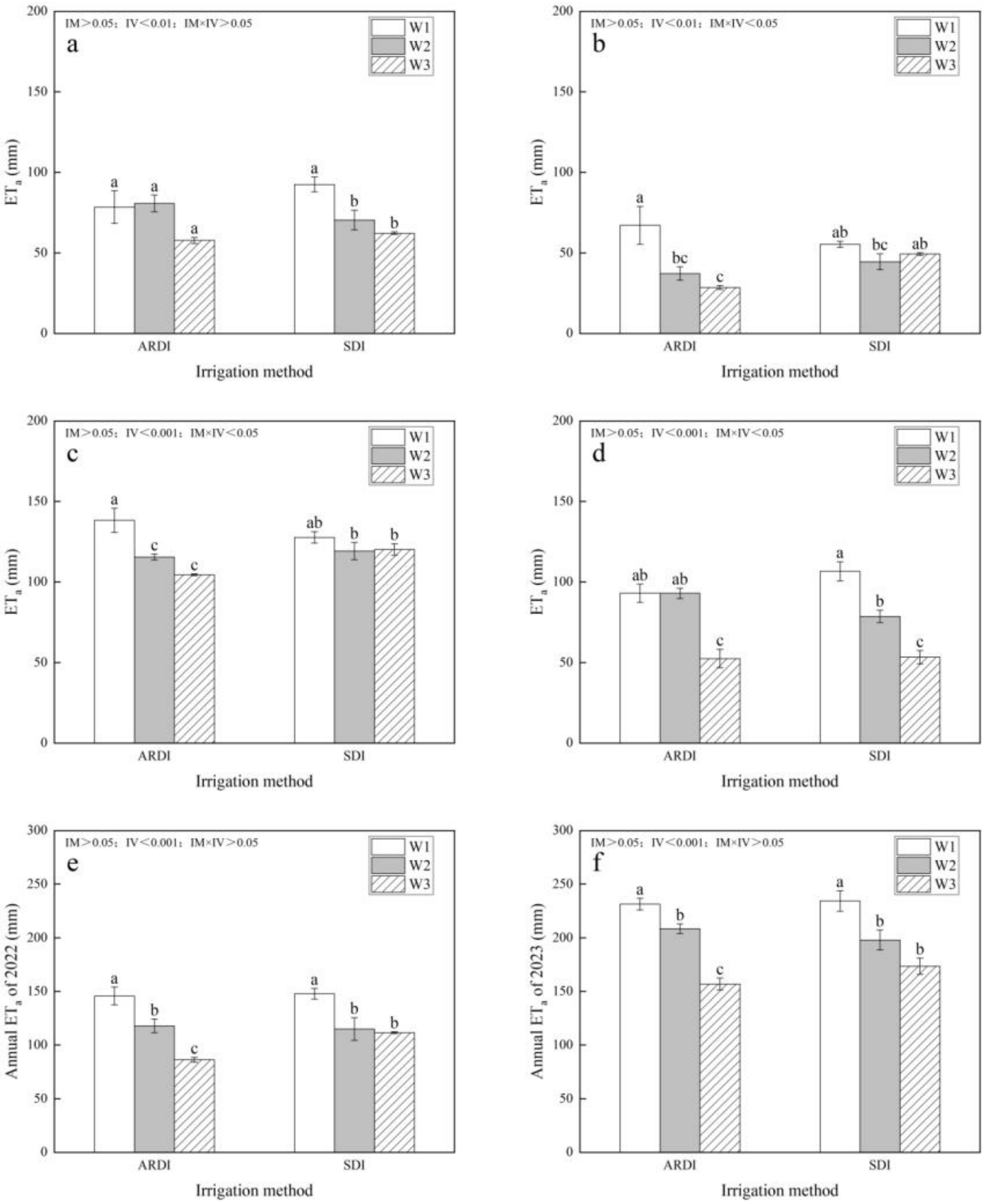

Figure 10. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the amounts of the evapotranspiration of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively, while (**c**,**d**) correspond to the 1st and 2nd cuts in 2023, the labels (**e**,**f**) correspond to the annual data for alfalfa for the years 2022 and 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Lowercase letters in the figure denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

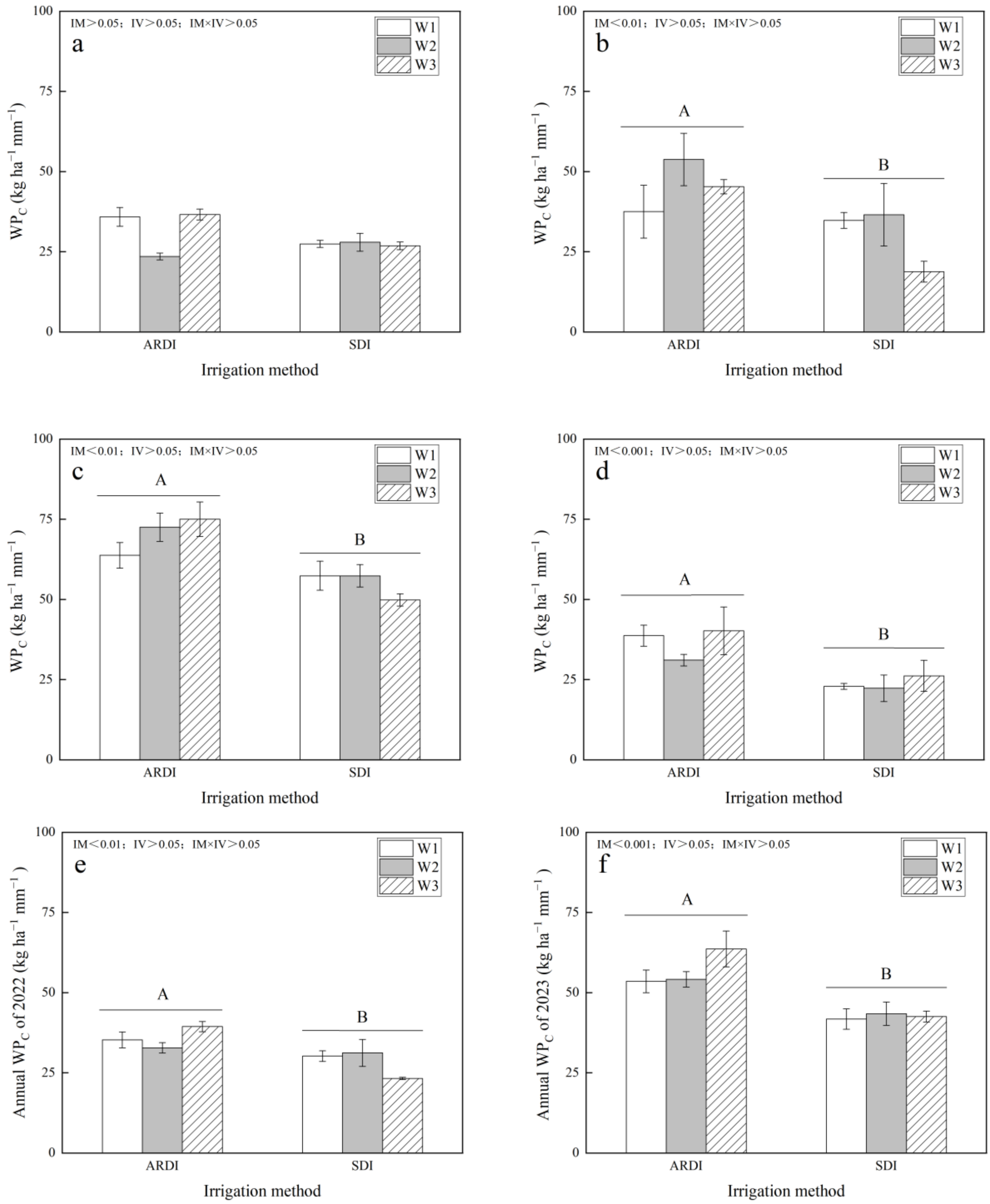

Figure 11. The impact of irrigation methods (alternate partial root-zone drip irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the water productivity of irrigation of alfalfa crops harvested in successive cuts from 2022 to 2023. The labels (**a**,**b**) in the figure correspond to the data for the 1st and 2nd cuts of alfalfa in 2022, respectively; (**c**,**d**) correspond to the 1st and 2nd cuts in 2023; and (**e**,**f**) correspond to the annual data for alfalfa for the years 2022 and 2023. All values represent mean measurements obtained from replicated trials, accompanied by standard errors. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05).

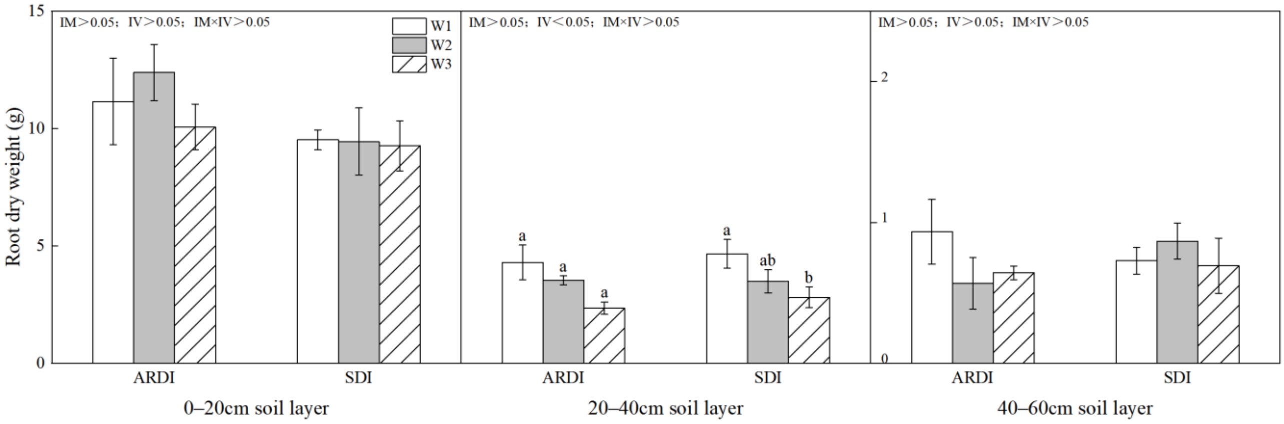

Figure 12. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the root dry weight of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Lowercase letters in the figure denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

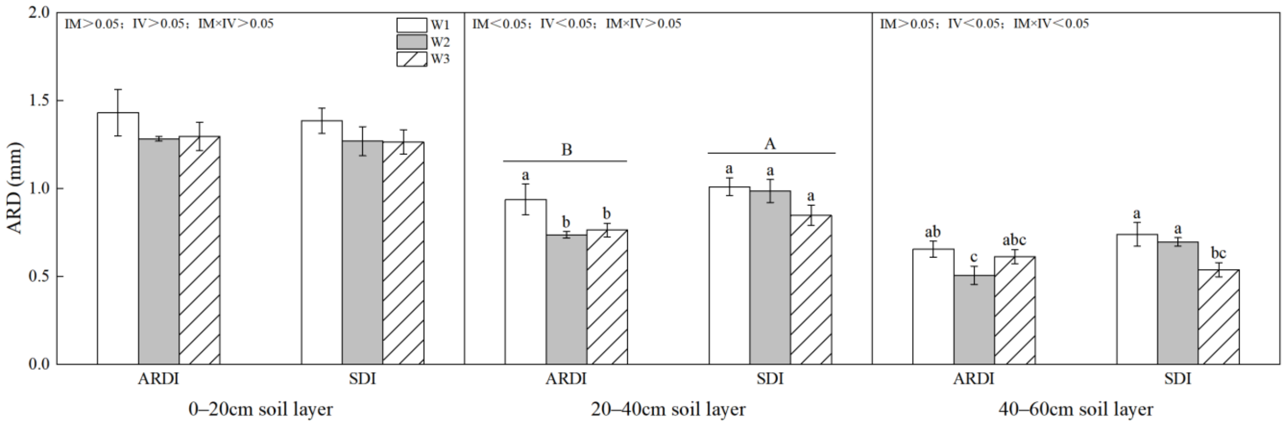

Figure 13. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the average root diameter of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

The effects of irrigation method and irrigation gradient on the average volume of alfalfa roots are shown in Figure 14. The interaction between the two significantly affected the average root volume at a depth of 40–60 cm ($p < 0.05$); the irrigation method did not significantly affect the average root volume in any soil layer ($p > 0.05$), while the irrigation gradient significantly affected the average root volume at depths of 20–40 cm and 40–60 cm ($p < 0.05$). In the 0–20 cm soil layer, neither the irrigation method nor the gradient significantly affected the average root volume ($p > 0.05$). At the 20–40 cm depth, there was no significant difference in average root volume among different water supply gradients under ARDI treatment ($p > 0.05$), while under SDI treatment, the average root volume significantly decreased with the reduction in water supply ($p < 0.05$). At the 40–60 cm depth, ARDI treatment significantly increased the average root volume at the W3 irrigation level compared to SDI treatment ($p < 0.05$).

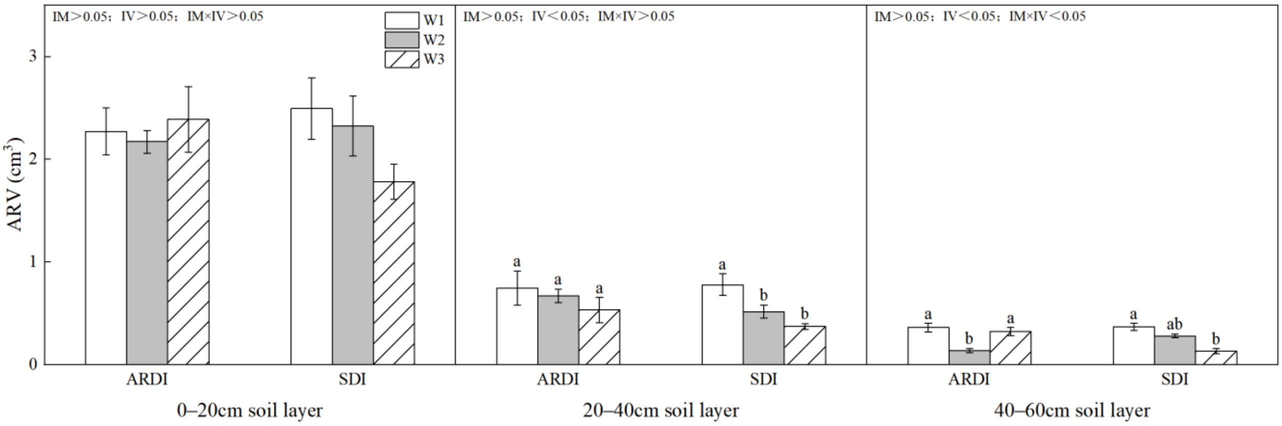

Figure 14. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the average root volume of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Lowercase letters in the figure denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

The effects of irrigation method and irrigation gradient on the root length density (RLD) of alfalfa roots are shown in Figure 15. The interaction between the two significantly affected RLD in the 0–20 cm and 20–40 cm soil layers ($p < 0.05$), and the irrigation method significantly affected RLD in the 40–60 cm soil layer ($p < 0.05$). In the 0–20 cm soil layer, the highest RLD under ARDI treatment was at the W2 irrigation level, significantly higher than the other treatments and irrigation levels ($p < 0.05$), with no significant difference in RLD across irrigation levels under SDI treatment ($p > 0.05$). In the 20–40 cm soil layer, the highest RLD under ARDI treatment was at the W2 level, significantly higher than the other treatments and levels ($p < 0.05$), with no significant difference in RLD across irrigation levels under SDI treatment ($p > 0.05$). In the 40–60 cm soil layer, ARDI significantly increased alfalfa root RLD compared to SDI ($p < 0.05$).

The effects of irrigation method and irrigation gradient on the specific root length (SRL) of alfalfa roots are shown in Figure 16. The interaction between the two and the irrigation gradient did not significantly affect SRL in any soil layer ($p > 0.05$), and the irrigation method significantly affected SRL in the 20–40 cm and 40–60 cm soil layers ($p < 0.05$). In the 0–20 cm soil layer, neither irrigation method nor gradient significantly affected SRL ($p > 0.05$); in the 20–40 cm and 40–60 cm soil layers, ARDI significantly increased alfalfa SRL compared to SDI ($p < 0.05$), and the highest SRL under ARDI treatment was at the W2 irrigation level.

The effects of irrigation method and irrigation gradient on the specific surface area (SSA) of alfalfa roots are shown in Figure 17. The interaction between the two significantly affected the SSA of alfalfa roots in the 0–20 cm soil layer ($p < 0.05$), and the irrigation method significantly affected the SSA in the 20–40 cm and 40–60 cm soil layers ($p < 0.05$), while the irrigation gradient did not significantly affect SSA in any soil layer ($p > 0.05$). In the 0–20 cm soil layer, the highest SSA under ARDI treatment was at the W2 irrigation level, significantly higher than the same level under SDI ($p < 0.05$). Under ARDI treatment, SSA significantly increased with the reduction in water supply ($p < 0.05$), while under SDI treatment, there was no significant difference in SSA across irrigation levels ($p > 0.05$); in the

20–40 cm and 40–60 cm soil layers, ARDI significantly increased alfalfa root SSA compared to SDI ($p < 0.05$).

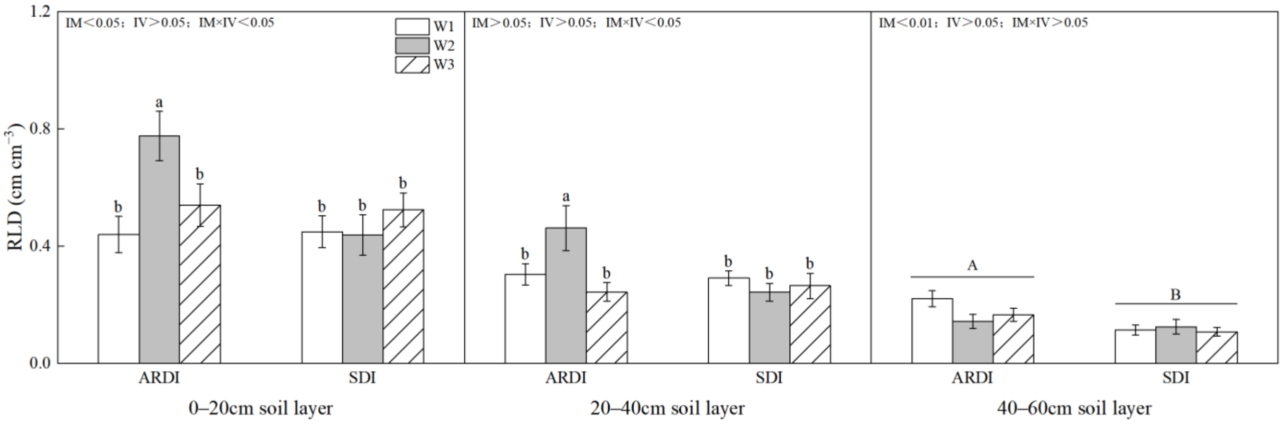

Figure 15. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the root length density of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM $\times$ IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

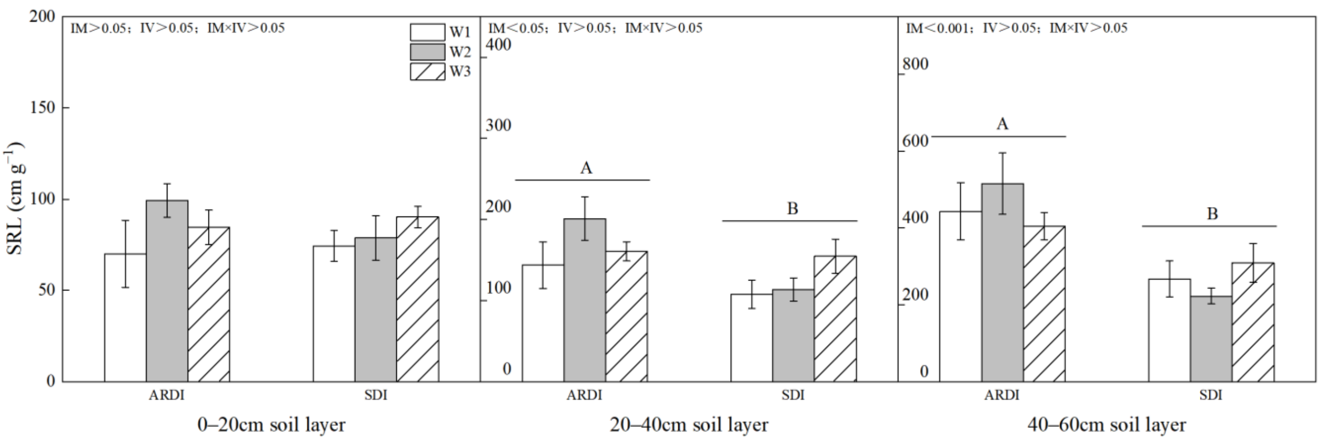

Figure 16. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the specific root length of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05).

3.6. Principal Component Analysis

To analyze the various characteristics of alfalfa under different irrigation methods and gradients, principal component analysis (PCA) was conducted on 17 variables: plant height, stem diameter, fresh forage yield, dry forage yield, crude protein content, neutral detergent fiber, acid detergent fiber, relative feed value, water transpiration, irrigation water productivity, crop water productivity, average root diameter, root dry weight, root length density, specific root length, specific surface area, and average root volume. From this analysis, four principal components were selected based on eigenvalues greater than 1.2. The variance contribution rates of these four principal components were 32.614%, 26.326%, 12.392%, and 10.949%, respectively. The cumulative contribution rate of these four components was 82.281%, which represents the vast majority of the information on alfalfa's production performance, nutritional quality, water use efficiency, and root distribution. The eigenvectors were calculated based on the eigenvalues and variance contribution rates of each principal component, as shown in Table 3. These eigenvectors serve as the factor coefficients for constructing the function expressions of each principal component:

$$F_1 = 0.405X_1 + 0.371X_2 + 0.395X_3 + 0.402X_4 + 0.237X_5 - 0.211X_6 - 0.112X_7 - 0.189X_8 + 0.153X_9 + 0.146X_{10} + 0.256X_{11} - 0.063X_{12} + 0.068X_{13} + 0.171X_{14} + 0.182X_{15} + 0.187X_{16} + 0.124X_{17}$$

$$F_2 = -0.069X_1 + 0.024X_2 + 0.078X_3 - 0.009X_4 - 0.274X_5 + 0.276X_6 + 0.264X_7 + 0.277X_8 - 0.293X_9 + 0.334X_{10} + 0.206X_{11} - 0.382X_{12} - 0.147X_{13} + 0.217X_{14} + 0.317X_{15} + 0.306X_{16} - 0.208X_{17}$$

$$F_3 = 0.045X_1 + 0.067X_2 + 0.130X_3 + 0.138X_4 - 0.030X_5 + 0.296X_6 + 0.187X_7 + 0.245X_8 - 0.172X_9 + 0.293X_{10} + 0.236X_{11} + 0.338X_{12} + 0.467X_{13} + 0.110X_{14} - 0.373X_{15} - 0.332X_{16} + 0.087X_{17}$$

$$F_4 = 0.015X_1 + 0.051X_2 + 0.013X_3 - 0.078X_4 + 0.215X_5 + 0.166X_6 + 0.207X_7 + 0.334X_8 + 0.416X_9 - 0.262X_{10} - 0.405X_{11} - 0.007X_{12} + 0.347X_{13} + 0.419X_{14} + 0.125X_{15} + 0.206X_{16} - 0.056X_{17}$$

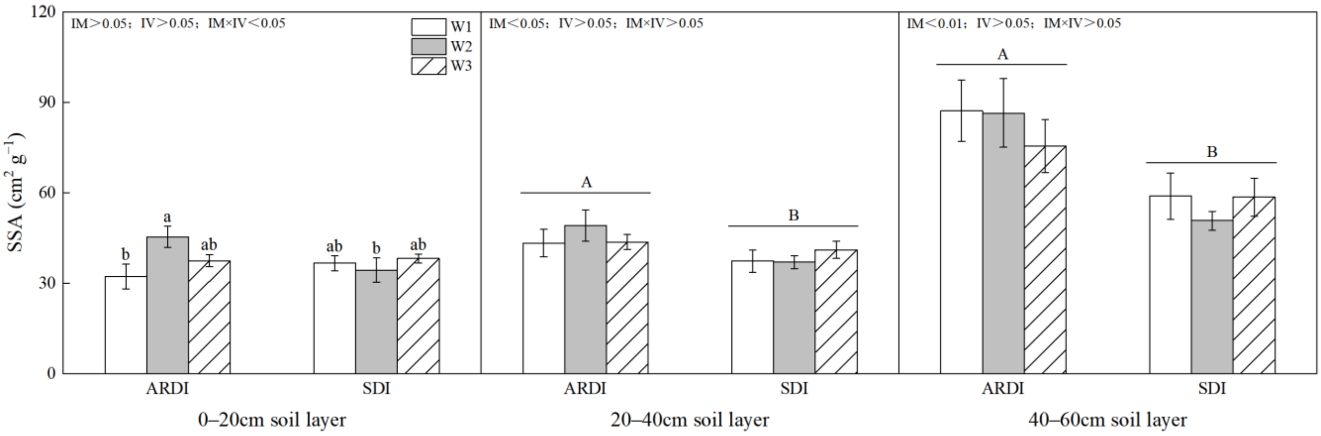

Figure 17. The effects of irrigation methods (alternate partial root-zone irrigation and subsurface drip irrigation) and irrigation volumes (W1, W2, and W3) on the specific surface area of two-year-old alfalfa roots in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers, with all values representing the mean of replicated trials accompanied by the standard error. Capital letters in the figure indicate significant differences between irrigation methods (IM < 0.05), while lowercase letters denote significant differences between irrigation volumes within each irrigation method group (IV < 0.05). In figures where the interaction between irrigation method and volume is significant (IM × IV < 0.05), lowercase letters indicate significant differences among variables based on simple effects analysis ($p < 0.05$).

A comprehensive evaluation model was constructed using the variance contribution rates of the four selected principal components as weighting coefficients: $Y = 0.326F_1 + 0.263F_2 + 0.124F_3 + 0.109F_4$, as shown in Figure 18. The comprehensive scores under different irrigation methods and irrigation gradients are shown in Table 4, ranked as ARDI2 > ARDI1 > ARDI3 > SDI3 > SDI1 > SDI2. Under the comprehensive consideration of alfalfa's productive performance, nutritional quality, water productivity, and root distribution, the W2 water supply gradient under the ARDI irrigation method achieved the highest comprehensive score.

Table 3. Eigenvectors of each index in each principal component.

Program	Eigenvector			
	PCA1	**PCA2**	**PCA3**	**PCA4**
Plant height	0.405	−0.069	0.045	0.015
Stem diameter	0.371	0.024	0.067	0.051
Yield	0.395	0.078	0.130	0.013
Hay yield	0.402	−0.009	0.138	−0.078
CP	0.237	−0.274	−0.030	0.215
NDF	−0.211	0.276	0.296	0.166
ADF	−0.112	0.264	0.187	0.207
RFV	−0.189	0.277	0.245	0.334
ETa	0.153	−0.293	−0.172	0.416
WP_I	0.146	0.334	0.293	−0.262
WP_C	0.256	0.206	0.236	−0.405
Average root diameter	−0.063	−0.382	0.338	−0.007
Root dry weight	0.068	−0.147	0.467	0.347
RLD	0.171	0.217	0.110	0.419
SRL	0.182	0.317	−0.373	0.125
SSA	0.187	0.306	−0.332	0.206
Average volume of roots	0.124	−0.208	0.087	−0.056
Eigenvalue	5.544	4.475	2.107	1.861
Contributions	32.614	26.326	12.392	10.949
Cumulative contribution	32.614	58.940	71.332	82.281

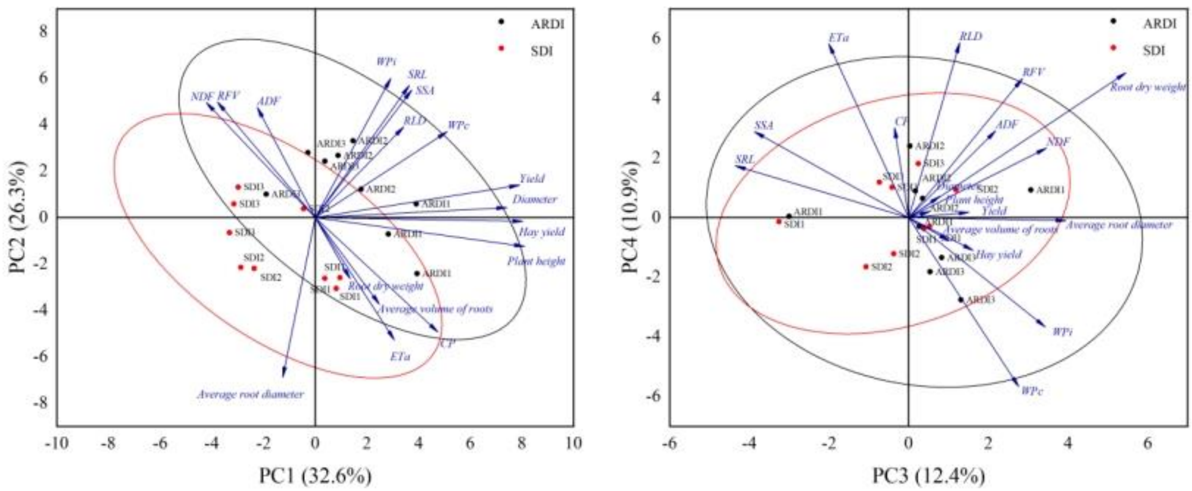

Figure 18. Principal component analysis.

Table 4. Comprehensive score table.

Treaments	*F1*	*F2*	*F3*	*F4*	*Y*
ARDI1	1.512	−0.398	0.074	0.167	0.415
ARDI2	0.583	1.138	0.125	0.963	0.610
ARDI3	−0.256	0.985	0.614	−1.444	0.094
SDI1	0.303	−1.301	−0.542	−0.196	−0.332
SDI2	−0.806	−0.622	−0.060	−0.472	−0.485
SDI3	−1.337	0.198	−0.211	0.982	−0.303

4. Discussion

Numerous studies have indicated that the adoption of APRI can significantly reduce the transpiration rate of crops while maintaining a high level of photosynthesis, thereby enhancing the instantaneous water use efficiency of crop leaves. This is one of the key factors that explain why APRI can sustain stable crop yields or only slightly reduce them despite a reduction in water supply [23,24]. However, since this study applies APRI on the basis of SDI, which has already reduced the irrigation volume and ineffective evaporation of water compared to traditional irrigation methods [25], it is more convincing to evaluate whether ARDI, with increased initial investment, has more potential for water saving than SDI under the same water supply standards. The plant height and stem diameter of alfalfa contribute to the accumulation of biomass and are direct reflections of productive performance [26]; they are also two sensitive indicators of plant water status [27]. In this study, ARDI significantly improved the plant height and stem diameter of alfalfa compared to SDI during full irrigation and mild deficit irrigation. Between 2022 and 2023, the alfalfa under mild deficit irrigation with ARDI maintained its height without significant reduction compared to the fully irrigated SDI treatment, even with a 25% reduction in water supply. Under two irrigation methods, both the plant height and stem thickness of alfalfa were significantly reduced at 50% water deficit compared to full irrigation; however, alfalfa under ARDI treatment still had advantages in plant height and stem thickness when compared to SDI. This indicates that under the same irrigation quota, alfalfa grown with the ARDI irrigation strategy has advantages in plant height and stem diameter and that ARDI, when combined with mild water deficit, does not significantly affect the height and stem diameter utilized by the alfalfa plants over multiple years. Some studies suggest that APRI, through repeated cycles of drying and rewatering, alternately wets and dries the crop root zone soil in both time and space, thereby stimulating a compensatory growth effect in the crop's root system. This not only accelerates root metabolism and induces the formation of new roots and root hair development but also enhances root vitality. It cleverly avoids the growth inhibition caused by prolonged drought, ultimately enhancing the absorption and utilization of soil moisture and nutrients [28–30]. In this study, ARDI did not significantly affect the alfalfa root dry weight, ARD, or ARV compared to SDI. However, ARDI significantly increased the root length density (RLD) of alfalfa at 40–60 cm depth and significantly increased the specific root length (SRL) and specific surface area (SSA) of alfalfa roots at 20–60 cm depth compared to SDI, peaking at 75% water deficit. The phased wet–dry environment alternation created by the ARDI irrigation method and appropriate water deficit strategy has promoted changes in the growth and distribution of alfalfa roots [31]. Compared to SDI, the roots and soil under ARDI treatment have a larger contact area, which can ensure the nutrients and water needed for the growth and development of the above-ground parts [32]. Fresh and dry forage yields are important indicators of economic and application value, as well as important reflections of growth and development status [33]. In the four harvests of alfalfa from 2022 to 2023, ARDI significantly increased the fresh and dry forage yields of each harvest and the annual yields over the two years compared to SDI. Under the ARDI irrigation method, the fresh and dry forage yields of alfalfa under mild deficit did not significantly decrease except for the initial harvest of the establishment year. Over the two-year production process of alfalfa, the annual dry forage yield of alfalfa with the ARDI irrigation strategy was 23.2%, 25.8%, and 33.8% higher than that of the SDI irrigation strategy at various moisture gradients, respectively. ARDI significantly enhances the productive performance of alfalfa compared to SDI under the same water supply. Research by Zhang Jing et al. suggests that APRI promotes the development of lateral roots in alfalfa plants, stimulates the production of more rhizome buds, and increases plant height, thereby achieving a greater biomass distribution to roots and stems [34]. This is broadly consistent with the results of this study, where ARDI, compared to SDI of the same irrigation volume, improves the productive performance of alfalfa by increasing the root contact area and plant height.

Crude protein content, acid detergent fiber, and neutral detergent fiber levels are significant indicators for assessing the quality of alfalfa, and relative feed value is an internationally recognized evaluation criterion for the nutritive value of roughage [35]. Studies by Staniak and Harasim, Kou, et al. have shown that water deficit can enhance the nutritional quality of alfalfa by reducing the levels of NDF and ADF and by increasing the CP content [36,37]. However, in this study, under both irrigation methods, there was insufficient evidence of a consistent pattern to suggest that water stress could increase the CP content and decrease the NDF and ADF contents of alfalfa to enhance its nutritional quality, which is similar to the findings of Testa [38]. The possible reason might be that there is a threshold in the effect of water supply on the CP, NDF, and ADF levels of alfalfa, and under the premise that the SDI has already reduced the irrigation volume relative to conventional irrigation, further reduction in irrigation volume has a minimal effect on improving the nutritional quality of alfalfa.

The study indicates that under APRI, the crop roots are constantly in an alternating wet–dry environment. Roots on the dry side are stimulated to produce chemical signaling substances such as abscisic acid, which are then transported from the roots to the leaves through the xylem. Upon sensing drought signals, the leaves partially close their stomata, reducing stomatal conductance and transpiration rate, thus diminishing luxurious transpiration to achieve the objective of drought resistance [39,40]. In this study, the ETa of each cut of alfalfa under full ARDI irrigation and 75% water deficit treatment, as well as the AETa for the years 2022 and 2023, showed no significant difference compared to the same irrigation volume under SDI. The reason for this is that ARDI affected the distribution of alfalfa roots, leading to improved production performance, which allowed alfalfa under the ARDI irrigation regime to accumulate more above-ground biomass without a significant increase in ETa compared to the SDI treatment, essentially due to PRD reducing the transpiration rate of alfalfa. Under the W3 water gradient, where the improvement in production performance was smaller, ARDI treatment significantly reduced the alfalfa AETa compared to SDI treatment, corroborating this finding. Over the course of two years of alfalfa production, except for the first cutting in 2022, the WP_I and WP_C for each subsequent cutting, as well as the AWP_I and AWP_C for the years 2022 and 2023, were significantly higher under ARDI treatment than under SDI. This increase trended upwards with the gradient of water deficit adjustment, which can be attributed to the enhancement of alfalfa production performance by ARDI. The combined effect of the improvement in production performance due to ARDI's influence on the alfalfa root distribution and the reduction in alfalfa transpiration under the alternating dry and wet conditions of the root environment results in ARDI irrigation having higher water productivity.

ARDI is of significant importance for enhancing water use efficiency and productivity and improving the quality of crop production in arid regions. While previous research has delved into the theory and technological improvements of APRI, the physiological and molecular mechanisms underlying specific crop water-saving remain largely unknown. Further in-depth studies should be conducted to establish a solid foundation for the widespread application of this irrigation technology in arid and semi-arid regions.

5. Conclusions

The ARDI treatment, compared to the equivalent irrigation volume of SDI, can improve the root distribution and characteristics of alfalfa as well as enhance its productivity and water use efficiency, with the optimal water deficit parameter being 75%. Under this treatment, the root distribution and characteristics of alfalfa are improved, laying the foundation for the uptake of nutrients and water required for the accumulation of above-ground biomass of alfalfa, maintaining stable nutritional quality and enhancing productivity over multiple years of alfalfa production. Compared to fully irrigated SDI, it still achieves a 6.6% increase in total dry hay yield over two years while saving 25% of water. Moreover, it improves the water use efficiency of alfalfa over multiple years of production by reducing its own evapotranspiration and enhancing its productivity. In summary, ARDI can achieve water savings while maintaining high-quality, high-yield alfalfa. Combined with mild water deficit, it has greater water-saving potential than traditional SDI, making it a new water-saving irrigation strategy suitable for the multi-year production of alfalfa in arid and semi-arid regions. The results of this study provide partial data references and a theoretical basis for achieving high-quality and high-yield alfalfa in water-scarce pastoral areas and have a wide range of application prospects in the forage production field of arid and semi-arid regions in the future.

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