Effects of Regulated Deficit Irrigation at Different Phenological Stages on Water Use and Fruit Quality of Wine Grapes: Postprint

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Abstract

Soil drought at different levels has significant effects on fruit quality, yield, and water use efficiency of wine grapes. Elucidating the effects of drought stress at different growth stages is of great significance for the formulation of precise soil water management and water-saving irrigation schemes for wine grapes. This study conducted an experimental investigation on wine grapes at different growth stages and under different drought stress levels in 2014 at the Weilong vineyard production area in Qingyuan Town, Liangzhou District, Wuwei City, in the middle-eastern Hexi Corridor. While maintaining soil water content at normal irrigation levels (soil water threshold 70%~75%) during other growth stages, moderate (soil water threshold 60%~65%) and severe (soil water threshold 50%~55%) drought treatments were applied during the budburst stage, shoot growth stage, flowering stage, berry expansion stage, and coloration and maturation stage of grapes, respectively. Additionally, a full irrigation treatment (soil water threshold 80%~85%) was added during the berry expansion stage, with normal irrigation throughout the entire growth period (soil water threshold 70%~75%) serving as the control, to determine the water consumption characteristics, yield, and quality of the grapes. The experimental results showed that: the vertical variation trends of soil water content were consistent across different treatments, showing a continuous increasing trend with soil depth; as soil depth increased, the effect of regulated deficit irrigation on soil water content became progressively weaker; in the 40~60 cm soil profile, the reduction in water content under deficit irrigation treatments was the greatest compared with the control; soil water content within the profile during the berry expansion stage was lower than that in other growth stages. The temporal variation trends of water consumption intensity of wine grapes were consistent across different treatments; the daily water consumption intensity was smallest during the budburst stage (0.13~0.33 mm · d ^{1}) and largest during the berry expansion stage (2.30~4.09 mm · d ^{1}). The moderate stress treatment during the budburst stage resulted in the highest yield and water use efficiency of wine grapes, reaching 15,228 kg · hm ^{2} and 3.62 kg · m ^{3}, respectively; followed by the full irrigation treatment during the berry expansion stage, while the severe stress treatment during the berry expansion stage was the lowest, at only 7,128 kg · hm ^{2} and 2.26 kg · m ^{3}, respectively. Under moderate stress during the coloration and maturation stage, the anthocyanin, reducing sugar, tannin, and total phenol contents of wine grapes were 2.7%, 6.56%, 17.91%, and 23.23% higher than those under normal water supply throughout the growth period, respectively, and effectively inhibited the accumulation of titratable acid ($P<0.05$), while no significant differences in quality indices were observed between other treatments and the control. Considering yield, water production efficiency, and fruit quality indices comprehensively, the optimal water regulation treatment for wine grapes was moderate stress during the coloration and maturation stage, i.e., soil relative water content of 60%~65% during the coloration and maturation stage and 70%~75% during other growth stages. Thus, timely and moderate regulated deficit irrigation in wine grape cultivation can not only significantly improve water production efficiency to achieve water-saving and efficient water use objectives, but also enhance fruit quality, which is of great significance for wine grape cultivation in the Hexi Corridor region.

Full Text

Preamble

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Effect of Regulated Deficit Irrigation at Different Growth Stages on Water Consumption and Fruit Quality of Wine Grape*

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Abstract

Soil drought significantly influences fruit quality, yield, and water use efficiency of wine grape. Clarifying the effects of drought stress at different growth stages is crucial for precision soil water management and developing water-saving irrigation schedules in wine grape production. This study investigated the effects of drought stress at various growth stages and severity levels on wine grape water consumption and fruit quality in 2014 at Weilong vineyard in Qingyuan Town, Liangzhou District, Wuwei City, located in the central-eastern Hexi Corridor. While maintaining normal irrigation (soil moisture threshold 70%-75% of field capacity) during other growth periods, moderate (soil moisture threshold 60%-65%) and severe (soil moisture threshold 50%-55%) water deficit treatments were applied during germination, vine growth, flowering, berry enlargement, and coloring maturity stages. Additionally, a full irrigation treatment (soil moisture threshold 80%-85%) was implemented during the berry enlargement period, with full normal irrigation (70%-75%) throughout the entire growth period serving as the control. Water consumption characteristics, yield, and fruit quality were measured.

The results showed that: (1) All treatments exhibited consistent vertical trends in soil water content, which increased continuously with soil depth. The influence of regulated deficit irrigation on soil water content diminished with increasing depth, with the most substantial reduction occurring in the 40-60 cm soil layer compared to the control. Soil water content across the profile was lowest during the berry enlargement period across all treatments. (2) Daily water consumption intensity varied consistently across treatments, reaching its minimum during germination (0.13-0.33 mm · d ^{1}) and maximum during berry enlargement (2.30-4.09 mm · d ^{1}). (3) The moderate stress treatment during germination produced the highest yield and water use efficiency, reaching 15,228 kg · hm ^{2} and 3.62 kg · m ^{3}, respectively. The full irrigation treatment during berry enlargement ranked second, while the severe stress treatment during berry enlargement yielded the lowest values at only 7,128 kg · hm ^{2} and 2.26 kg · m ^{3}. (4) Under moderate stress during coloring maturity, anthocyanin, reducing sugar, tannin, and total phenol contents were 2.7%, 6.56%, 17.91%, and 23.23% higher than the normal irrigation treatment, respectively, while effectively suppressing titratable acid accumulation ($P<0.05$). No significant differences in quality parameters were observed between other treatments and the control.

Considering yield, water productivity efficiency, and fruit quality comprehensively, the optimal water regulation strategy was moderate stress during coloring maturity (soil relative water content 60%-65% of field capacity) combined with normal water supply (70%-75%) during other growth stages. This demonstrates that timely and appropriate regulated deficit irrigation can significantly improve water productivity efficiency, achieve water conservation, and enhance fruit quality, holding important implications for wine grape cultivation in the Hexi Corridor region.

Keywords: Regulated deficit irrigation; Drought stress; Water consumption characteristics; Yield; Water productivity efficiency; Quality; Wine grape

Introduction

The Hexi Corridor in Gansu Province lies within the world' s most suitable latitude zone for wine grape production (36°-40°N), offering unique geographical advantages including low precipitation, dry air, low relative humidity, rapid cooling before maturity, and minimal pest and disease pressure. However, irrational irrigation practices have resulted in low and unstable yields with poor quality, severely constraining the sustainable development of the wine grape industry and farmers' income. Therefore, a critical scientific challenge in Hexi

Corridor viticulture is determining how to implement scientific and rational irrigation and soil water regulation based on water-quality response relationships to achieve water conservation, quality improvement, and high efficiency while maintaining acceptable yields.

Regulated deficit irrigation (RDI) represents the preferred technology for addressing water scarcity in the Hexi Corridor. Proper irrigation can coordinate soil water, nutrients, air, and temperature, benefiting wine grape growth and quality development. Numerous studies have reported on drip irrigation RDI techniques for various crops. Tang et al. [1], Cui et al. [2], Liu et al. [3], and Yan et al. [4] demonstrated that RDI with drip irrigation effectively conserves water, increases yield, and improves quality in tomato (*Lycopersicon esculentum*), pear jujube (*Ziziphus jujuba*), watermelon (*Citrullus lanatus*), and island cotton (*Gossypium barbadense*), respectively. In viticulture, domestic scholars have investigated RDI effects on grape yield from different perspectives [5-7]. Liu et al. [5] found maximum yield when maintaining soil water content at 40% of field capacity during germination. Li et al. [6] reported maximum yield at an irrigation quota of 240 mm. Xu et al. [7] and Kong et al. [8] showed that moderate water deficit during coloring maturity effectively reduced titratable acid content while increasing soluble solids and anthocyanin content, thereby improving overall grape quality.

However, previous studies focused only on water deficit at different growth stages without examining the effects of different deficit gradients on yield and quality. Comprehensive research on how RDI at different growth stages and gradients affects water consumption patterns, yield, and quality of wine grapes remains limited. This experiment used six-year-old wine grapes in the Hexi Corridor to investigate the effects of RDI at different growth stages and gradients on yield, water use efficiency, and various quality indicators. The study aimed to determine soil water requirements at each growth stage, providing a theoretical basis for improving water use efficiency while ensuring stable yields and achieving water conservation and quality regulation in wine grape production.

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1. Materials and Methods

1.1 Experimental Site Description

The experiment was conducted from March to October 2014 at Weilong vineyard in Qingyuan Town, Liangzhou District, Wuwei City, in the central-eastern Hexi Corridor. The site is located at the confluence of three irrigation districts (Huangyang River, Zamu River, and Qingyuan) within the Shiyang River Basin. The area features flat terrain and a typical continental arid climate at an elevation of 2,104.6 m, with abundant sunshine, minimal rainfall, large diurnal temperature variations, and rich "cold resources." The annual average temperature is 7.7°C, mean annual precipitation is approximately 160 mm, annual evaporation reaches 2,020 mm, and annual sunshine duration exceeds 3,000 hours. The experimental soil was sandy loam with pH 7.9, bulk density of 1.6 g · cm ^{3}, and field capacity of 23.1%. The topsoil layer (0-20 cm) contained organic matter at 14.28 g · kg ^{1}, alkali-hydrolyzable nitrogen at 59.2 mg · kg ^{1}, available phosphorus at 17.1 mg · kg ^{1}, and available potassium at 197.4 mg · kg ^{1}. The groundwater table was deep at 25-30 m.

1.2 Experimental Design

The experimental variety was 'Merlot' (*Vitis vinifera*), planted in 2009 in north-south rows with 2.5 m row spacing and 1.0 m plant spacing. Each plot measured 15.0 m × 1.5 m. A single-factor completely randomized design was employed with 12 water regulation treatments and three replications, totaling 36 plots. Three water gradients were established during germination, vine growth, flowering, berry enlargement, and coloring maturity stages: normal irrigation (lower soil water limit 70%-75% of field capacity), moderate deficit (60%-65%), and severe deficit (50%-55%). Upper soil water limits were set at 100%, 90%, and 80% of field capacity, respectively. To refine understanding of water effects on fruit development during late growth stages, an additional water gradient (lower limit 80%-85%) was added during berry enlargement. Detailed treatment specifications are shown in Table 1 .

Irrigation was applied via fixed unilateral drip irrigation, with timing determined by Time Domain Reflectometry (TDR) measurements. Irrigation occurred whenever measured soil water content reached the designated lower limit (Table 1), with amounts calculated to raise soil moisture from the lower to upper limit. The irrigation amount was calculated as:

$$m = 10,000 f H(\theta_{\text{upper}} - \theta_{\text{lower}})$$

where m is the calculated irrigation amount (270 m^{3} · hm ^{2}), f is the soil wetting ratio (47.5%), H is the planned wetting layer depth (1.0 m), and θ_{upper} and θ_{lower} are the upper and lower soil water content limits expressed as percentages of field capacity by volume.

A branch control method was used for drip lines, with each plot equipped with a control valve to regulate irrigation volume. Pressure gauges and water meters were installed at the drip irrigation hub, with system operating pressure at 0.1 MPa. Drip lines were laid along grape rows on the east side of each plant.

1.3 Measurements

1.3.1 Soil Water Content Determination Soil water content was measured using the traditional oven-drying method. Samples were collected at 20 cm intervals to a depth of 100 cm. Measurements were taken at the beginning and end of each growth stage (germination, vine growth, flowering, berry enlargement, and coloring maturity), with additional measurements before and after irrigation and rainfall events. A five-point sampling method was used in each plot with three replications per treatment.

1.3.2 Water Consumption Determination Water consumption was calculated using the water balance method:

$$ET_{I-II} = \sum_{i=1}^{n} r_i H_i (W_{I,i} - W_{II,i}) + M + P + K - D$$

where ET_{I-II} is stage water consumption (mm), i is soil layer number, n is total number of layers, r_i is dry bulk density of layer i (g · cm ^{3}), H_i is thickness of layer i (cm), $W_{I,i}$ and $W_{II,i}$ are gravimetric water contents (%) of layer i at stage beginning and end, M and P are irrigation and rainfall amounts (mm) during the stage, K is groundwater contribution (mm), and D is drainage (mm). With groundwater depth >10 m, $K = 0$; in this arid region, $D = 0$.

1.3.3 Evaporation Determination Evaporation was measured using micro-lysimeters randomly buried in natural soil in each plot. The lysimeters were weighed daily at 20:00 using a 0.1 g precision electronic balance, with additional measurements before and after irrigation. Weight changes represented daily evaporation.

1.3.4 Yield Determination At harvest maturity, all fruit clusters in each plot were collected and weighed using a 0.01 g precision electronic balance. The average of three replications represented the actual yield, converted to standard yield (kg · hm ^{2}).

1.3.5 Grape Quality Determination After yield measurement, 10 cluster samples were randomly collected from each plot and transported to the laboratory in insulated boxes for quality analysis. Anthocyanin content was determined by pH differential method [9]. Reducing sugar content was measured by Fehling reagent titration [10]. Titratable acid was determined by NaOH titration [11] and expressed as tartaric acid. Tannin content was measured by Folin-Denis method [10]. Total phenols in grape skins were determined by Folin-Ciocalteu method [12].

1.4 Data Analysis

Data were analyzed using LSD multiple comparison in SPSS 17.0 to test significance differences, with figures created using Origin 8.0. All data presented are mean values.

2. Results

2.1 Soil Water Dynamics Under Different RDI Treatments During Grape Growth

All treatments showed consistent trends in soil water content variation with depth, increasing continuously (Fig. 1 [Figure 1: see original paper]A–E). During germination, treatments MG and SG had lower soil water content than other treatments, with SG lower than MG. During vine growth, treatments MP and SP showed lower water content than others, with SP lower than MP. Following deficit irrigation during germination, treatment MG still maintained lower water content than treatments MF, ME, MC, AE, and CK in the 0–80 cm profile during vine growth, with no significant difference from MP in the 20–40 cm layer. Treatment SG showed similar patterns to MG, but due to severe deficit, could not recover promptly after irrigation, showing no significant difference from SP in the 0–60 cm profile.

The results indicate that the influence of RDI on soil water content diminished with increasing soil depth. During flowering, treatments MF and SF had lower water content than others, with SF lower than MF. As grapes entered rapid growth with high water consumption, treatments MG and MP (previously stressed) showed no significant difference from MF in the 0–40 cm layer. Treatments SG and SP, due to severe deficit and slow recovery, showed no significant difference from each other throughout the 0–100 cm profile. Notably, the 40–60 cm layer showed the greatest water reduction under deficit treatments compared to CK, likely due to insufficient water replenishment and excessive root water extraction.

During berry enlargement, treatment AE had the highest soil water content, while ME and SE were lowest, with SE lower than ME. As grapes grew rapidly with increased leaf area shading the ground, water consumption was dominated by crop transpiration at high rates, resulting in lower water content across the entire profile than in other growth stages. During coloring maturity, treatments MC and SC had lower water content than others, with SC lower than MC. Due to cumulative water consumption in earlier stages, overall soil water content was relatively low, and although RDI affected the entire profile, significant impacts were limited to the 0–60 cm layer with no significant effect on the 60–80 cm layer.

2.2 Daily Water Consumption Intensity Under Different RDI Treatments

Daily water consumption intensity reflects the combined effects of fertilization, soil temperature, and irrigation on grape development across growth stages. As shown in Fig. 2 [Figure 2: see original paper], germination had the lowest consumption intensity at 0.13–0.33 mm · d ^{1} due to recently emerged vines, low temperatures, and weak photosynthesis and transpiration. Vine growth showed significantly higher intensity (1.34–2.29 mm · d ^{1}), with lower rates in MP and

SP, indicating that deficit irrigation reduced daily consumption. Flowering intensity (1.59–2.36 mm · d^{1}) was slightly higher than vine growth due to higher temperatures and concurrent vegetative and reproductive growth. Berry enlargement had the highest, longest duration, and greatest intensity (2.30–4.09 mm · d^{1}) as reproductive growth peaked and temperatures reached their maximum. Coloring maturity intensity gradually decreased to 2.00–3.72 mm · d^{1} with lower temperatures and ceased vegetative growth. Overall, daily consumption intensity increased with irrigation amount, with AE showing particularly high rates.

2.3 Effects of RDI on Wine Grape Quality

To understand how different soil water gradients affect grape quality, this study analyzed anthocyanins, titratable acid, reducing sugar, tannin, and phenolic compounds under different RDI treatments.

2.3.1 Effects on Anthocyanins Anthocyanins primarily regulate grape color, with content directly affecting appearance quality. Table 2 shows that treatments SC and AE had anthocyanin contents of 631.80 mg · kg^{1} and 605.80 mg · kg^{1}, respectively, 5.4% and 1.1% higher than CK. Treatment SE had the lowest content (423.55 mg · kg^{1}), 29.3% lower than CK with significant difference. Other deficit treatments showed lower anthocyanin content than CK. These results indicate that water control during coloring maturity promotes anthocyanin accumulation, while deficit during berry enlargement is detrimental. Deficit irrigation during germination, vine growth, and flowering had no significant effect.

2.3.2 Effects on Titratable Acid Table 2 shows treatment SE had the highest titratable acid content (9.59 g · L^{1}), followed by ME, representing 12.4% and 16.7% increases over CK with significant differences. This indicates deficit during berry enlargement hinders natural acid reduction. Treatments MC and SC showed reduced titratable acid content, decreasing by 9.8% and 6.3% respectively, suggesting deficit during coloring maturity can reduce acidity, though severe deficit did not provide greater reduction.

2.3.3 Effects on Reducing Sugar Reducing sugar is the most important physicochemical quality factor in wine grapes, with glucose and fructose comprising over 90% of total sugars. Sugars affect both grape growth physiology and post-harvest quality. Table 2 shows treatment MC had the highest reducing sugar content (279.10 g · L^{1}), 6.6% higher than CK, while SC increased by 2.3%. Although not significantly different from CK, these increases suggest deficit during coloring maturity can improve reducing sugar content. Treatments ME and SE had lower contents (231.03 g · L^{1} and 216.67 g · L^{1}), 11.8% and 17.2% lower than CK with significant differences, indicating deficit during berry enlargement is detrimental to sugar accumulation and quality improvement.

2.3.4 Effects on Tannin Grape tannins originate primarily from stems, skins, and seeds, influencing astringency, antioxidant properties, protein precipitation, pigment stabilization, structure enhancement, and antimicrobial activity [13]. Table 2 shows treatment SC had the highest tannin content (3.26 g · kg ^{1}), 21.6% higher than CK, followed by MC (3.16 g · kg ^{1}, 17.9% higher). Both differed significantly from CK, indicating severe deficit during coloring maturity substantially increases tannin content. Although treatments MG, MP, MF, SG, SP, and SF showed increased tannin content compared to CK, differences were not significant, suggesting deficit during early growth stages has some promotional effect. Treatments ME and SE had lower tannin contents, 7.1% and 11.2% below CK with significant differences, confirming deficit during berry enlargement is unfavorable for tannin accumulation.

2.3.5 Effects on Total Phenols Table 2 shows treatment SC had the highest total phenol content (4.49 g · kg ^{1}), 51.2% higher than CK with significant difference. Treatment MC had 3.66 g · kg ^{1}, 23.2% higher than CK. These results demonstrate that deficit during coloring maturity substantially increases total phenols, with greater water deficit producing larger increases. Treatments MC, MG, MP, MF, SG, SP, and SF also showed increased total phenols compared to CK, but without significant differences, indicating early-stage deficit has some promotional effect. Treatment SE had the lowest content (2.42 g · kg ^{1}), followed by ME (2.69 g · kg ^{1}), 18.5% and 9.4% lower than CK, though not significantly different, suggesting deficit during berry enlargement is detrimental to phenol accumulation.

2.4 Effects of RDI on Yield and Water Use Efficiency

2.4.1 Effects on Yield Components Table 3 shows treatments MG, MP, MF, MC, SG, SC, and AE had relatively high single cluster weights without significant difference from CK, indicating moderate deficit during germination, vine growth, flowering, and coloring maturity, and severe deficit during germination and coloring maturity did not significantly affect cluster weight. However, treatments ME and SE showed lower cluster weights, decreasing by 22.5% and 32.9% compared to CK, demonstrating that deficit during berry enlargement substantially reduces cluster weight, adversely affecting late-season yield increases.

Treatment MG had the highest cluster number, 5.1% higher than CK, indicating moderate deficit during germination improved fruit set. Treatments MP, MF, MC, SG, SP, and SF had slightly lower cluster numbers than CK, while ME, SE, and SC decreased by 22.9%, 26%, and 25%, respectively. This suggests moderate water deficit during vine growth, flowering, and coloring maturity did not significantly affect fruit set, while deficit during berry enlargement significantly reduced it.

Single-plant yield analysis revealed that moderate deficit during germination, vine growth, and coloring maturity did not cause yield reduction, whereas severe deficit during berry enlargement caused serious yield loss, with treatment SE reducing yield by 52.7% compared to CK (significant difference).

2.4.2 Effects on Yield and Water Use Efficiency Table 3 shows treatment MG (moderate deficit during germination) achieved the highest yield (15,228 kg · hm ^{2}), 1.1% higher than CK, demonstrating that moderate deficit during germination does not reduce yield and provides water-saving benefits. Although treatments MP, MC, and AE showed some yield reduction compared to CK, differences were not significant, indicating moderate deficit during vine growth and coloring maturity, and full irrigation during berry enlargement, did not significantly affect yield.

Treatments MF, SG, SP, SF, and SC reduced yield by 20.7%, 22.6%, 33.3%, 35.7%, and 32.5%, respectively, but without significant differences from CK, suggesting moderate deficit during flowering and severe deficit during early stages cause some yield reduction. Treatments ME and SE had the lowest yields (8,586 kg · hm ^{2} and 7,128 kg · hm ^{2}), 43.1% and 52.7% lower than CK with significant differences, confirming that moderate and severe deficit during berry enlargement cause severe yield loss.

Water use efficiency was highest in treatment MG, 1.7% higher than CK, indicating moderate deficit during germination improves efficiency. Treatments MP, MF, MC, SG, SP, SC, and AE showed slightly lower efficiency than CK but without significant differences, suggesting severe deficit during various stages does not significantly affect water use efficiency. However, treatments ME, SF, and SE showed significantly lower efficiency (32.3%, 33.1%, and 36.5% below CK, respectively), demonstrating that deficit during berry enlargement and severe deficit during flowering reduce both yield and water use efficiency, making RDI during berry enlargement unfavorable.

Discussion

Regulated deficit irrigation actively imposes moderate water stress during specific growth stages to reduce ineffective soil evaporation, decrease transpiration rate, and regulate crop growth, thereby comprehensively improving crop water productivity [14-15]. This allows reduced irrigation during low water-demand periods, with saved water allocated to high-demand stages. Our study revealed that water consumption intensity is dynamic, following the order: berry enlargement (2.30-4.09 mm · d ^{1}) > coloring maturity (2.00-3.72 mm · d ^{1}) > flowering (1.59-2.36 mm · d ^{1}) > vine growth (1.34-2.29 mm · d ^{1}) > germination (0.13-0.33 mm · d ^{1}). The lowest intensity during germination and highest during berry enlargement correlate with crop physiological activity, plant transpiration, and inter-plant evaporation, consistent with Zhang et al. [16]. Therefore, moderate deficit during low-demand stages (germination and vine growth) with adequate water during peak demand (berry enlargement) effectively conserves water while supporting reproductive growth and yield.

Wine grape quality determines wine quality, with numerous environmental factors including meteorological conditions [17], cultivation techniques [18], soil properties [19], and water content [20] playing important roles. Among these, rational irrigation significantly impacts grape quality [21]. Our results show that moderate and severe deficit during berry enlargement inhibited reducing sugar accumulation and reduced tannin and total phenol contents, hindering natural acid reduction. Conversely, moderate deficit during coloring maturity (MC) increased anthocyanin and reducing sugar contents by 2.7% and 6.6%, respectively, while reducing titratable acid by 9.9% and increasing tannin and total phenol contents by 17.9% and 23.2%, producing optimal overall quality. RDI during germination, vine growth, and flowering did not significantly affect quality. These findings demonstrate that appropriate, timely RDI can achieve water conservation and quality improvement. Under normal irrigation during other stages, maintaining soil water content at 60%-65% of field capacity during coloring maturity significantly improved grape quality, providing a scientific basis for RDI scheduling in viticulture.

RDI affects wine grape yield and water use efficiency. Numerous studies suggest moderate RDI can improve both parameters. Liu et al. [22] reported 4.71% yield increase when irrigating at 40% field capacity during germination. Zhang et al. [23] found 2.87% yield increase and 21.21% water use efficiency improvement at 55%-60% field capacity during germination. Our results similarly showed highest yield and water use efficiency with moderate deficit during germination (MG), 1.1% and 1.7% higher than CK. However, treatments ME and SE (deficit during berry enlargement) showed significantly lower yield and water use efficiency (43.1%, 52.7% and 32.3%, 36.5% below CK, respectively). Although moderate deficit during other stages caused some yield reduction, differences were not significant. Therefore, the optimal RDI pattern for maximizing yield and water use efficiency combines moderate deficit during germination (soil water content 60%-65% of field capacity) with normal irrigation during other stages.

Conclusion

Considering yield, water productivity efficiency, and fruit quality comprehensively, the optimal water regulation strategy for wine grapes is moderate stress during coloring maturity (soil relative water content 60%-65% of field capacity) combined with normal water supply (70%-75%) during other growth periods. This demonstrates that timely and appropriate regulated deficit irrigation can significantly improve water productivity efficiency, achieve water conservation and high-efficiency water use, and enhance fruit quality, holding important implications for wine grape cultivation in the Hexi Corridor region.

However, this study only analyzed single-stage RDI treatments. Whether continuous or alternating deficit irrigation provides greater advantages for wine grape yield and quality requires further investigation.

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