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Effects of Water Deficit Irrigation on Quality of Pear

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Abstract This study focuses on the effects of moderate deficit irrigation on pear fruit quality and provides a systematic analysis. Based on a review of global pear orchard irrigation patterns and technological developments, it summarizes the implementation methods and outcomes of deficit irrigation under different climatic conditions, cultivar types, and cultivation management practices. Applying moderate water deficit at appropriate growth stages of fruit trees can not only effectively save water resources, but also improve, to some extent, the soluble solid content, sugar–acid ratio, and flavor quality of the fruit, while enhancing storage performance. Deficit irrigation regulates fruit physical traits, chemical composition, and aroma compound formation, and its effects are jointly influenced by multiple factors such as cultivar, rootstock, soil type, and climate conditions. The study proposes suitable irrigation regulation strategies and simple, farmer-friendly technical approaches, emphasizing the importance of coordinated water–fertilizer management and low-cost monitoring methods. Moderate deficit irrigation is a practical technique that balances water saving and quality improvement, and it is of great significance for enhancing resource use efficiency and promoting sustainable development in the pear industry.
Keywords Pear (*Pyrus* spp.); Deficit irrigation; Fruit quality; Water use efficiency; Sustainable agriculture

1 Introduction

Pear (*Pyrus* spp.) is one of the most widely cultivated temperate fruit trees in the world, playing an important role in horticultural production and rural economies in regions such as Europe, China, and South America. As consumers increasingly demand better sensory and nutritional quality, pear growers are not only under pressure to maintain stable yields, but also to improve fruit appearance, texture, flavor, and storage performance. Climate change, more frequent droughts, and competition for limited freshwater resources are making traditional irrigation methods harder to sustain. Agriculture accounts for about 70% of global freshwater withdrawals, and fruit trees are usually irrigated to avoid water stress, especially in semi-arid and arid regions where rainfall is insufficient or unstable (Vélez-Sánchez et al., 2023).

In many major pear-producing areas, current irrigation management mainly relies on supplying all or nearly all crop evapotranspiration (ETc) through surface or subsurface drip irrigation, micro-sprinkler irrigation, furrow irrigation, or flood irrigation. Full irrigation at 100% ETc or maintaining relatively high soil moisture thresholds (such as 80% of field capacity) is commonly used as a reference or “safe” strategy when comparing deficit irrigation treatments (Zhang et al., 2022). The rapid development of pressurized irrigation systems, especially drip irrigation, has greatly improved the precision of water supply. However, in practice, it often leads to “insurance irrigation,” where excessive water is applied to avoid potential yield loss (Vandermaesen et al., 2021). Under conventional management, irrigation amounts are often close to or even exceed ETc in order to maintain vigorous vegetative growth and larger fruit size.

Deficit irrigation refers to the intentional application of water below crop water requirements without causing unacceptable reductions in yield or quality. Regulated deficit irrigation (RDI) is one of the most commonly used approaches in fruit trees. It applies moderate water deficit during phenological stages that are less sensitive to water stress, while maintaining near-full irrigation during critical periods such as rapid fruit enlargement. In pear production, moderate deficit irrigation is usually implemented as applying 50%-80% ETc at specific growth stages, or maintaining soil moisture at about 60%~70% of field capacity, rather than applying it throughout the entire growing season. In some cases, reduced irrigation can even increase soluble solids content and improve storage performance, although fruit size may decrease slightly.

This study reviews the effects of deficit irrigation on pear fruit quality, summarizes global trends in pear cultivation and irrigation practices, and compiles results from different deficit irrigation strategies (including RDI and partial root-zone drying) under various climates, rootstocks, and cultivars. It focuses on how the intensity, timing, and duration of water deficit affect yield components, fruit size distribution, internal quality traits, and postharvest physiological behavior. Based on this, it proposes design principles for deficit irrigation under different production regions and resource conditions, providing a scientific basis for using deficit irrigation as a practical tool to improve sustainability and fruit quality in modern pear production.

2 Implementation of Moderate Deficit Irrigation in Pear Orchards

2.1 Irrigation control methods: soil moisture and irrigation interval

In soil moisture-based regulation, irrigation is triggered when soil water content drops below a preset proportion of field capacity (FC). In subsurface drip irrigation studies on Xinjiang fragrant pear, adjustments to total seasonal irrigation (3 750~6 750 m^3/ha) and emitter burial depth showed that deeper pipe placement combined with a reasonable irrigation amount can reduce excessive wetting of surface soil and better match the wetted zone with the active root layer (Wang et al., 2024).

In ET- or Ep-based regulation, irrigation is calculated as a proportion of ETc or Ep, and deficit irrigation is achieved by reducing this proportion or extending irrigation intervals. Young pear trees were irrigated at 70% (T70), 100% (control), and 130% (T130) of the FAO water budget. The T70 treatment reduced water use by 30% while promoting trunk growth and increasing fruit number, indicating that “full irrigation” may actually be excessive (Marsal et al., 2002). Later, the control treatment was reduced to 82% of the original irrigation level during mid-growth (Control-82%), and regulated deficit irrigation was applied at about half of this level during specific fruit development stages.

In regulated deficit irrigation experiments with the “Triunfo de Viena” cultivar, irrigation was reduced to 67% and 55% ETc only during the rapid fruit growth period (about two months), while 100% ETc was maintained at other times. This approach saved 33%~45% water without significant changes in yield or fruit quality (Molina-Ochoa et al., 2016). Under desert climate conditions, both RDI and PRD treatments used the same water amount (50% Ep during slow growth and 80% Ep during rapid expansion), and results showed that plant responses were mainly controlled by irrigation volume rather than irrigation method (Wu et al., 2020).

2.2 Key application periods of moderate deficit irrigation

Pear fruit growth is usually divided into the cell division stage (Stage I), slow growth stage (Stage II), and rapid enlargement or maturation stage (Stage III/IV). Moderate deficit irrigation can be applied at all stages, but the purpose differs.

In Bartlett pear, irrigation was stopped in spring to dry the root zone, followed by regulated deficit irrigation at 23%-46% of evaporation. This significantly reduced vegetative growth (about 52%) without affecting fruit growth. When irrigation was restored to 120% Eps during the rapid growth stage, fruit growth was promoted and yield increased by about 20% (Chalmers et al., 1986). Applying RDI in Stage I can increase flowering and fruit set, while applying it in Stage II can control fruit size. Adjusting irrigation to an intermediate level (Control-82%) helps balance yield and fruit size. In widely spaced mature pear trees, water deficit during Stage II (slow growth stage) has little effect on yield, indicating strong tolerance to moderate stress and making this stage suitable for deficit irrigation.

In studies on pear jujube and other woody fruit trees, the period from bud break to leaf expansion (Stage I) and the fruit maturation stage (Stage IV) are considered key regulation windows. Applying moderate or severe deficit during these stages can increase yield by 9%~32%, reduce water use by up to 17.5%, improve water use efficiency by up to 41%, and enhance fruit firmness, soluble solids, sugar-acid ratio, vitamin C content, and storage performance (Cui et al., 2008; 2009; Guo and Gao, 2023).

2.3 Common irrigation patterns in pear production

Common irrigation patterns in pear orchards mainly include the following. The most widely used is regulated deficit irrigation (RDI), which applies full irrigation during sensitive stages and reduces irrigation to a certain proportion of ETc or Ep during non-sensitive stages. Typical schemes include: 40%-60% Ep in early stages and 80% Ep later; 50% adjusted ETc in Stage I or II for young trees; 60%~80% ETc at specific stages and 100% ETc at other times; or 67%~55% ETc only during the rapid growth stage. Another method is partial root-zone drying (PRD), where irrigation alternates between the two sides of the root system.

At the orchard scale, irrigation patterns are also influenced by irrigation systems and soil moisture thresholds. In northern China, drip irrigation (surface, ring, subsurface, single-line or double-line) is commonly combined with a lower limit of 60%-80% FC, and subsurface double-line drip at 60% FC performs best (Wang et al., 2021). In Xinjiang fragrant pear, 30 cm subsurface drip irrigation with a moderate irrigation amount shows the best performance in yield, water use efficiency, and economic return, while traditional flood irrigation uses more water but has low efficiency (Wang et al., 2024).

In semi-arid regions of Brazil, drip and micro-sprinkler irrigation were tested at 60%~120% ETc, and the highest yield was achieved at about 92% ETc. Both excessive and insufficient water reduced gas exchange and affected carbohydrate metabolism (Gomes et al., 2023). In Kosovo, 50% ETc reduced yield per plant but increased the proportion of high-quality fruit and saved half of the irrigation water (Lepaja et al., 2024).

2.4 Indicators for monitoring water deficit

For soil monitoring, gravimetric methods, capacitance sensors, or tensiometers are commonly used, with indicators including volumetric water content, percentage of FC, or soil water potential. In the “Triunfo de Viena” study, combining ETc with soil moisture monitoring achieved water savings of up to 73% while avoiding severe drought (Vélez-Sánchez et al., 2023).

In plants, leaf and stem water potential (Ψleaf, Ψstem) are widely used indicators, usually measured in the early morning or at midday with a pressure chamber. In the Abbé Fetèl cultivar, the 60% ETc treatment significantly reduced water potential and gas exchange, but fruit size was maintained and postharvest soluble solids increased on BA29 rootstock, indicating that moderate decreases in water potential are acceptable (Venturi et al., 2021). Under tropical high-altitude conditions, Ψpdl, Ψstem, Ψpdf, and Ψf showed no significant differences among different RDI treatments (-0.25 to -1.03 MPa) (Vélez-Sánchez et al., 2022). Other indicators include maximum daily trunk shrinkage (MDS) and pressure–volume curve parameters.

3 Effects on Fruit Physical Quality

3.1 Fruit size and single fruit weight

In the cultivar Abbé Fetèl, trees grafted onto the more dwarfing quince rootstock (SYDO) produced significantly smaller fruits under 60% ETc compared to 110% ETc. In contrast, on the more vigorous BA29 rootstock, final fruit size remained essentially unchanged among 110%, 80%, and 60% ETc treatments (Venturi et al., 2021). On both rootstocks, moderate irrigation reduction increased fruit dry matter content, indicating that water inflow through the xylem (and also the phloem under stronger deficit) was reduced, leading to lower fruit water content, while carbohydrate supply did not decrease proportionally.

Under field conditions, in ‘Conference’, complete irrigation was stopped for 3 weeks at the beginning of the second growth stage, followed by deficit irrigation at only 20% ETc during the remaining period. This reduced fruit size at harvest but improved internal quality. Thinning under deficit conditions partially restored fruit size and fresh-market yield (López et al., 2011). In postharvest deficit irrigation (DI) studies of ‘Conference’, stopping irrigation after harvest for 3~4 consecutive seasons did not cause a sustained reduction in fruit size in subsequent years. In some years, a “carry-over effect” was observed, where fruit number decreased but individual fruit size increased. This reflects changes in crop load rather than a direct limitation of fruit growth by water stress (Marsal et al., 2011).

In ‘Triunfo de Viena’ grown in high-altitude tropical regions, even when irrigation was greatly reduced to 25% ETc or completely stopped during the rapid fruit growth stage, fresh weight and diameter at harvest did not significantly decrease compared to 100% ETc (Bayona-Penagos et al., 2017).

3.2 Fruit firmness and texture characteristics

In Abbé Fetèl, deficit irrigation at 60% ETc significantly reduced shoot and leaf water potential as well as gas exchange, but did not consistently reduce firmness at harvest. Storage performance depended on rootstock type: on the more dwarfing SYDO, firmness was more affected by irrigation, while on BA29, reduced irrigation mainly increased soluble solids after 6 months of storage at 1 °C, with only slight fruit size reduction (Venturi et al., 2021).

At a more microscopic level, the effect of RDI on stone cells (a key factor determining the gritty texture of pear flesh) has also been studied. In potted ‘Williams’ (‘Bartlett’), RDI at about 15% of the control applied from 32 to 60 days after flowering (late stage I) showed, through microscopic image analysis, no significant differences in stone cell area, size, or spatial distribution between RDI and full irrigation at the end of stage I or at harvest (Peco et al., 2023) (Figure 1).

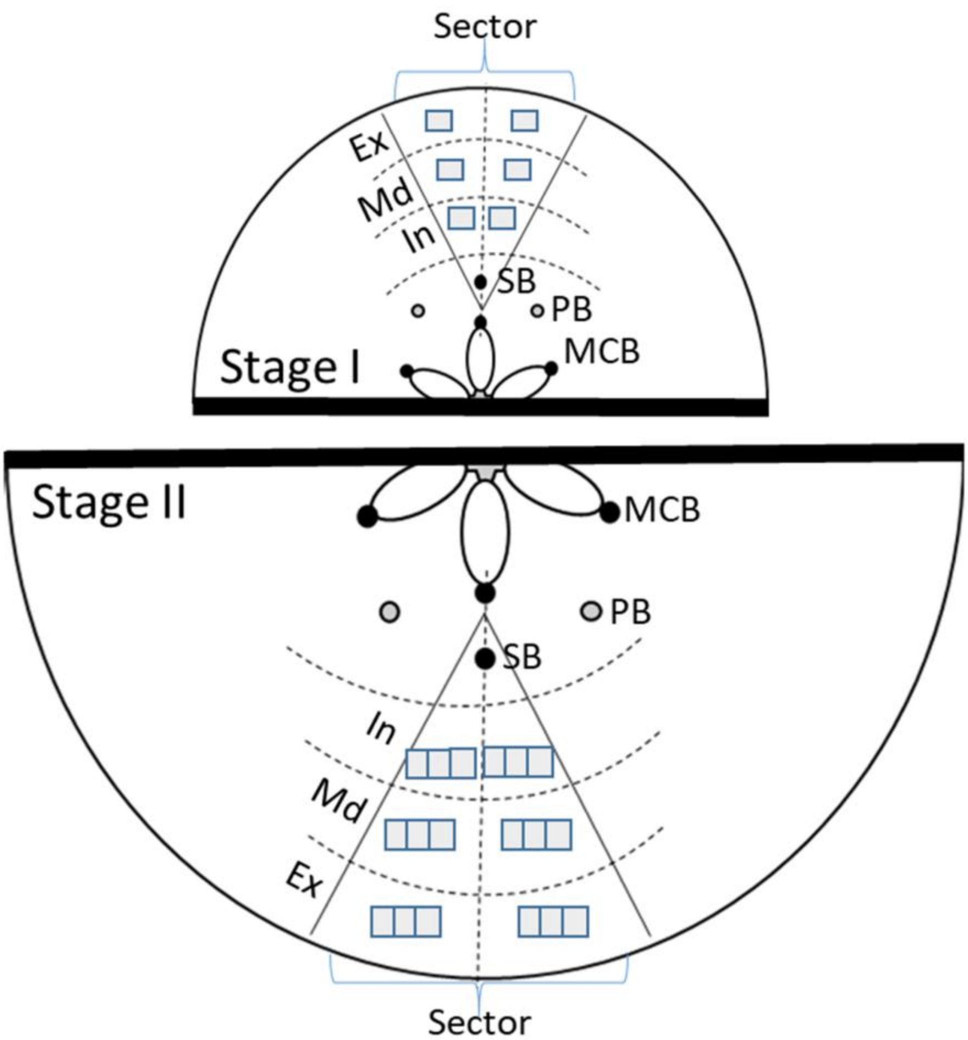

Figure 1 Scheme for the analysis of pear fruit cells in sections of Stages I (upper) and II (lower). Wedge-shaped sectors were cut from central transverse fruit slices, each extending from a sepal bundle (SB) to the fruit exterior, and processed for histological study. For measurements, the sector was visually divided into two halves and three concentrically oriented zones: Ex (Exterior), Md (Middle), and In (Interior). The squares within each zone represent the number of microscope image areas (0.06 cm2) captured and analyzed (two images per zone for Stage I; six per zone for Stage II). SB: sepal bundle, PB: petal bundle, and MCB: median carpelary bundle (Adopted from Peco et al., 2023)

3.3 Peel coloration and external appearance

In 'Triunfo de Viena', applying 74%~60% and 48%~27% ETc during the rapid fruit growth stage resulted in no significant differences at harvest in peel chlorophyll, carotenoid content, or overall color index compared with 100% ETc (Vélez-Sánchez et al., 2021).

By regulating vegetative growth, deficit irrigation can indirectly improve external appearance. For example, in 'Bartlett' under the Tatura system, applying RDI at 46% Eps during vigorous vegetative growth reduced shoot and structural growth without affecting fruit growth. This may improve light distribution within the canopy, thereby enhancing color uniformity and reducing russeting, although color parameters were not directly measured in that study (Mitchell et al., 1984).

3.4 Effects on fruit uniformity and commercial grading

In high-altitude tropical 'Triunfo de Viena', under postharvest deficit treatments of 25% and 0% ETc, the largest diameter and volume were observed in the fully irrigated treatment 2 days after harvest. However, subsequent evaluations did not show a decline of fruit below market standards, and all quality parameters remained within commercially acceptable ranges (Bayona-Penagos et al., 2017).

In contrast, when continuous deficit was applied throughout the entire growing season, some trade-offs occurred. In field trials in Kosovo, compared with 100% ETc drip irrigation, a simplified 50% ETc treatment reduced yield per tree by about 38%, but improved fruit grading quality: 92.30% of fruits reached the extra class under 50% ETc, compared to 85.41% under full irrigation (Lepaja et al., 2024). Average fruit diameter and length did not differ significantly between treatments, indicating that the higher proportion of top-grade fruit was mainly due to improved uniformity, shape, or peel quality rather than larger fruit size.

4 Effects on Fruit Chemical Quality

4.1 Soluble solids content (ssc) and sugar accumulation

In pears and other woody fruit trees, mild to moderate deficit irrigation generally increases SSC and enhances sugar concentration. This may result from reduced fruit water content leading to solute concentration, or from restricted water inflow while maintaining or even increasing carbohydrate supply, or a combination of both.

In sparsely planted mature pear orchards in Xinjiang, regulated deficit irrigation (RDI) at 40%~60% of pan evaporation (Ep) applied during the cell division stage or slow fruit expansion stage significantly increased total soluble sugar content compared with full-season irrigation at 80% Ep. Meanwhile, fruit growth and yield were maintained or even improved under some treatments (Wu et al., 2013). In 'Conference' pear, applying deficit irrigation (0% followed by 20% ETc) during stage II increased SSC at harvest and after storage, and combining deficit irrigation with fruit thinning further enhanced SSC (López et al., 2011).

The mechanisms may include increased dry matter content under stress, osmotic adjustment promoting sugar accumulation, and reduced energy consumption for fruit growth, which lowers sugar use in glycolysis (Bai et al., 2022; Toumi et al., 2022). These findings are consistent with observations in Abbé Fetèl and mature pears, indicating that moderate water deficit generally increases sugar concentration and potential sweetness, especially after storage in climacteric cultivars.

4.2 Organic acids and sugar-acid balance

Direct measurements in 'Williams' pear showed that irrigation (adequate water supply) reduced malic acid, citric acid, fumaric acid, and shikimic acid contents, and also decreased SSC. In contrast, non-irrigated fruits had higher sugar and acid contents, indicating that water limitation concentrates primary metabolites, including organic acids (Hudina and Stampar, 2005).

In 'Conference' pear, moderate preharvest deficit irrigation during stage II increased titratable acidity at harvest and maintained higher levels during storage. Together with higher SSC, this resulted in a richer and more complex flavor (López et al., 2011). Postharvest deficit (irrigation stopped while maintaining stem water potential above about -1.5 MPa) generally had little effect on acidity, although in one season SSC slightly increased while acidity remained unchanged (Marsal et al., 2011).

In pear-jujube, regulated deficit irrigation applied during the germination stage and fruit maturation stage increased SSC, vitamin C, and the sugar-acid ratio, while only slightly reducing fruit water content (Cui et al., 2008).

4.3 Changes in flavor and texture quality

In ‘Conference’ pear, preharvest stage II deficit treatment (no irrigation followed by 20% ETc) increased firmness, SSC, and acidity at harvest. This higher SSC/TA combination corresponds to a more complex and pronounced flavor. These advantages were maintained during storage, and fruit thinning under deficit conditions further increased SSC and promoted ripening, allowing earlier harvest of high-flavor fruit (López et al., 2011).

In ‘Williams’ pear, continuous irrigation increased fruit size but reduced SSC, monosaccharides, and organic acids. In contrast, non-irrigated fruits were smaller but had stronger flavor and higher sweetness (Hudina and Stampar, 2005).

4.4 Effects on aroma-related compounds

In ‘Triunfo de Viena’, the effects of irrigation levels at 100%, 74%, and 48% ETc during the rapid fruit expansion stage (with full irrigation at other stages) on aroma were evaluated. Moderate RDI had no significant effect on firmness, SSC, acidity, pigments, or phenolic compounds at harvest, and yield was similar to the control, but it altered the temporal dynamics of volatile compound release during ripening (Vélez et al., 2019).

Esters are the main components of pear aroma and showed a continuous increase during the climacteric stage under all treatments. Under moderate water limitation, RDI maintained or slightly increased ester formation without causing off-flavors, provided that the deficit occurred at less water-sensitive growth stages and did not exceed the stress threshold.

5 Yield–Quality Relationship under Moderate Deficit Conditions

5.1 Changes in total yield and yield stability

In ‘Yali’ pear, both early and late RDI significantly suppressed vegetative growth and reduced irrigation water use. However, over two consecutive growing seasons, there were no significant differences in fruit yield at harvest or average single fruit weight compared with the control. This indicates that yield remains stable when stress is applied from bud break to 25 days after full bloom (pullulation-25 DAFB) or during the last month before harvest (Cheng et al., 2012).

Responses of roots and canopy also support yield stability. In mature ‘Sinkiang’ pear, moderate RDI (60% Ep) during the early fruit development stage had no effect on final yield compared with full irrigation. Although more severe or longer deficits altered fine root distribution, they did not produce clear positive or negative effects on yield (Wu et al., 2021).

In pear–jujube systems, applying light to moderate water deficit at the bud stage or maturity stage increased yield by 13%~32% or kept it similar to full irrigation, while reducing irrigation water use by up to 18% (Cui et al., 2008; 2009).

5.2 Balance between yield reduction and quality improvement

In ‘Yali’ pear, late-season RDI improved SSC, sugar content, and dry matter without reducing yield (Cheng et al., 2012).

For ‘Triunfo de Viena’, applying RDI during the rapid fruit growth stage maintained yield and standard quality traits, with the main effect being water saving. Even under stronger deficits at this stage (25% ETc or no irrigation), yield still did not decrease (Moreno-Hernández et al., 2017).

5.3 Suitable deficit thresholds in production practice

Appropriate deficit thresholds for pear come from pear trials and broader studies on woody fruit trees. For ‘Triunfo de Viena’, applying RDI at 60%~74% ETc (and even 48% ETc in wet years) during the rapid fruit growth stage can achieve 26%~73% seasonal water savings without affecting yield or quality (Moreno-Hernández et al., 2017).

Results from 'Yali' pear show that under deep soil conditions, completely stopping irrigation (close to 0% ETc) from bud break to 25 days after flowering or during the last month before harvest is feasible, as long as the stress period is limited and followed by sufficient rewatering. These strategies improved WUE and late-stage quality without reducing yield (Cheng et al., 2012).

From a broader perspective, a meta-analysis of woody fruit trees (including pear) shows that mild deficit irrigation at 80%~100% of full irrigation maximizes yield and water productivity (WP). It is best applied during the first and second growth stages (bud break to leaf expansion, and flowering to fruit set), which can increase WP by about 2%~9% while reducing yield risk (Wen et al., 2023). More severe seasonal deficits (below 60% of full irrigation) increase the risk of yield reduction, but may still be reasonable when water resources are extremely limited or when fruit quality has a high price premium.

6 Differences in Cultivars and Growth Conditions

6.1 Differences in responses among common pear cultars

The European pear cultivar "Triunfo de Viena," grown in high-altitude tropical regions of Colombia, shows strong tolerance to regulated deficit irrigation (RDI) during the rapid fruit growth stage. Across different years, reducing irrigation to 74%~60% or even 48%~27% of ETc did not significantly affect fruit number, average weight, size distribution, yield, or key quality traits (firmness, sugars, organic acids, pigments, and phenolic compounds), while saving up to about 73% of water (Vélez-Sánchez et al., 2021). Even under more severe conditions (such as 25% ETc or no irrigation during rapid fruit growth), no significant differences in yield and quality were observed for this cultivar.

In contrast, the late-maturing European pear cultivar "Abbé Fetél" under Mediterranean climate conditions is more sensitive to seasonal water deficit. After storage, fruits on BA29 rootstock showed higher soluble solids at 60% ETc, while fruit firmness on SYDO rootstock was more sensitive to irrigation level. This indicates that tree vigor and scion–rootstock combinations play an important role in regulating stress resistance and fruit quality (Venturi et al., 2021).

Asian pear types show different response patterns. For white pear (*Pyrus* bretschneideri 'Sinkiangensis'), applying moderate deficit irrigation at 60% of pan evaporation (Ep) during the early cell division stage (Stage 1) or Stage 1+2 reduces fine root length density, but has no significant effect on final yield compared with full irrigation. This suggests that the whole plant still has strong recovery ability even when roots are temporarily restricted. More severe early stress (40% Ep) causes clear changes in root distribution and can even increase final yield when applied only in Stage 1, indicating a specific compensation mechanism when early vegetative growth is controlled (Wu et al., 2021) (Table 1).

Studies on other pear cultivars further show differences in water use and stress sensitivity. In South African orchards, seasonal transpiration of "Packham's Triumph" and "Forelle" was 539 mm and 733 mm, respectively. This is related to the higher leaf area index and longer growth period of "Forelle," reflecting differences in water demand among genotypes (Dzikiti et al., 2024).

6.2 Effects of soil conditions and climate

Soil profile and climate conditions largely determine the safe range of deficit irrigation. Water limitation is more obvious in semi-arid and arid climates, and plant responses are stronger. In the semi-arid middle São Francisco River region of Brazil, pear trees under both drip and microsprinkler irrigation were negatively affected by either insufficient or excessive water. This was shown by reduced gas exchange and abnormal synthesis and accumulation of carbohydrates, amino acids, and proteins in leaves. Yield reached its maximum at 91.8% ETc, indicating that under high evaporative demand and shallow or moderately deep soils, the room for deficit regulation is limited (Gomes et al., 2023).

Soil texture and water-holding capacity interact with climate to influence deficit irrigation effects. In coarse-textured or salinity-prone soils in desert or continental regions, deficit irrigation may lead to salt accumulation due to reduced leaching. In peach studies, saline water under deficit irrigation increased soil salinity along the drip line, but rainfall and sandy soils helped stabilize salinity at the end of the season (Toumi et al., 2024). Similar processes may limit long-term deficit irrigation in pear orchards, requiring monitoring of soil electrical conductivity and periodic leaching.

Table 1 Yield, fruit quality, and shoot length of each treatment (Adopted from Wu et al., 2021)

Year	Treatment	Yield (t/ha)	Total Soluble Solid Content (%)	Soluble Sugar Content (%)	Fruit Volume (cm3)	Final Shoot Length (cm)	Shoot Length in Late May (cm)
2009	MRDI-1	18.9 ab	12.3 b	8.14 c	94 a	27.5 b	25.6 b
	SRDI-1	21.5 a	12.5 ab	8.82 a	100 a	25.9 bc	23.6 bc
	MRDI-1+2	18.1 bc	12.0 bc	7.97 c	103 a	26.0 b	24.9 bc
	SRDI-1+2	15.8 c	13.1 a	8.61 b	96 a	24.0 c	22.3 c
	Control	18.6 b	11.5 c	6.93 d	98 a	32.4 a	30.2 a
2010	MRDI-1	21.2 ab	12.8 b	8.08 a	116 a	25.4 b	23.1 b
	SRDI-1	23.6 a	13.8 a	8.05 a	123 a	23.9 c	21.9 b
	MRDI-1+2	20.6 b	13.6 a	7.71 bc	113 a	24.3 bc	22.6 b
	SRDI-1+2	17.2 c	13.9 a	7.99 ab	122 a	22.5 c	21.0 b
	Control	19.8 b	13.6 a	7.63 c	114 a	31.3 a	29.1 a

Note: Different letters within the same column indicate significant differences at the $p < 0.05$ level. MRDI-1 and SRDI-1 were applied with moderate and severe water stress, respectively, during Stage 1 (0~30 DAB), and fully irrigated during other stages; MRDI-1+2 and SRDI-1+2 were applied with moderate and severe water stress, respectively, during Stage 1+2 (0-86 DAB), and fully irrigated during other stages. The shoot lengths in late May were measured on 20 and 21 May in 2009 and 2010, respectively; the final shoot lengths were measured on 4 September and 29 August in 2009 and 2010, respectively (Adopted from Wu et al., 2021)

In the Bukhara region of Uzbekistan, dwarf high-density orchards of "Williams," "Abbot," and "Carmen" under drip irrigation reduced water use by half while increasing yield per tree to 1.6 kg. This shows that proper planting density and canopy management can help reduce climate and soil limitations (Yunusov et al., 2023). In the Dukagjini Plain of Kosovo, irrigation at 100% and 50% ETc resulted in yields of 8.33 kg and 5.10 kg per tree, respectively, but the 50% ETc treatment produced a higher proportion of high-quality fruits. This indicates that climate-soil-water interactions significantly affect both yield and fruit grading (Lepaja et al., 2024).

6.3 Adaptability of moderate deficit irrigation in different regions

Evidence from pear experiments and global meta-analyses of woody fruit trees shows that moderate deficit irrigation has wide adaptability, but optimal thresholds and strategies vary by region and cultivar. For woody fruit trees (including pear), mild deficit irrigation at 80%~100% irrigation level can slightly increase yield (+0.87%) and improve water productivity (+9.77%). Stronger seasonal deficits may reduce yield by about 14%, but still improve water productivity. Deficit irrigation is suitable for regions with annual precipitation over 400 mm and mean annual temperature ≥10 °C, and should be applied mainly during early growth stages to reduce yield risk (Wen et al., 2023).

In high-rainfall or high-altitude tropical regions (such as Sesquilé, Colombia), RDI can be applied at relatively high intensity (even down to 27% ETc or with no irrigation during certain stages) without affecting yield and quality of "Triunfo de Viena." This is because rainfall and deep soils buffer water fluctuations, and the main advantage is significant water saving.

In arid and semi-arid inland regions (such as Xinjiang in China, semi-arid Brazil, and northern desert regions of China), deficit irrigation needs to be more conservative and combined with efficient irrigation methods. In fragrant pear production, subsurface drip irrigation at 30 cm depth combined with a higher irrigation amount (6 750 m^3/ha) can optimize yield, quality, water use efficiency, and economic returns. Subsurface drip irrigation can increase yield by 13%~17% and water productivity by 45%-137%, showing that improving irrigation methods can sometimes be more effective than simply reducing water amount. In semi-arid Brazil, optimal yield is close to full irrigation level (about 92% ETc), indicating limited room for deficit irrigation under high evaporation and shallow soil conditions (Gomes et al., 2023).

7 Conclusion

Moderate deficit irrigation, achieved through fine control of soil moisture at specific phenological stages, can improve multiple quality indicators, including soluble solids content, flavor, nutritional composition, and storage performance, while having limited or acceptable effects on yield. Compared with conventional full irrigation, deficit irrigation helps achieve the dual goals of producing high-quality fruit and improving water use efficiency, which is particularly important in regions facing increasing water scarcity and more frequent droughts due to climate change.

Moderate deficit irrigation generally increases soluble solids content and sugar concentration, improves the sugar–acid ratio, and enhances flavor and aroma. Fruits under deficit treatment often show higher firmness and better texture, lower incidence of physiological disorders, and in many cases higher levels of vitamin C, phenolic compounds, and antioxidant capacity. Although fruit size and total yield may decrease slightly, these losses are usually compensated by better appearance quality, more uniform fruit within the marketable size range, and improved storage and transport tolerance.

Moderate deficit irrigation is a practical water-saving technique that can be integrated into existing orchard management systems with relatively low additional cost. By adjusting irrigation schedules based on soil moisture conditions, evapotranspiration, or plant water status indicators, growers can reduce irrigation water use without reducing, and sometimes even improving, fruit quality. Deficit irrigation can also be combined with optimized fertilization, canopy management, and pruning practices to improve light distribution and source-sink relationships. At the regional scale, promoting deficit irrigation in pear orchards can contribute to sustainable water use, reduce energy consumption for pumping, and lessen environmental impacts caused by over-irrigation and nutrient leaching.

To promote wider application, several recommendations are proposed. First, the level and timing of deficit irrigation should be scientifically determined based on cultivar characteristics, local climate, soil water-holding capacity, and orchard structure, and severe water stress should be avoided during highly sensitive stages such as early fruit development and cell division. Moderate deficit is generally recommended during the middle to late stages of fruit enlargement and, in some cases, the pre-harvest maturation stage, with quantitative thresholds set using soil moisture, stem water potential, or other reliable indicators. Second, simple and low-cost monitoring tools and decision-making methods should be promoted so that deficit irrigation can be applied by both smallholders and large-scale growers. Third, more demonstration orchards and field trials should be established to validate and optimize deficit irrigation strategies under different production conditions, forming region-specific technical guidelines and training materials. Finally, future research should focus on the long-term effects of continuous deficit irrigation on tree vigor, alternate bearing, root development, and soil health, and explore its integration with precision agriculture technologies, so as to fully realize the water-saving and quality-improving potential of moderate deficit irrigation in pear production and support its wider adoption.

Author Contributions

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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