A Review of Deficit Irrigation Strategy Applied on the Citrus Orchards

Esther Dzigbogi[a], Shijiang Zhu[b*], Joash Kwasi Ataakorerkpa[c]

[a]College of hydraulic and environmental engineering, China Three Gorges University, Yichang 443002, China
[b*]Engineering Research Center of Eco-Environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University, Yichang 443002, China
[c]Department of Physics Education, University of Education, Winneba, Ghana

***Corresponding Author:** Shijiang Zhu
*Email: zhusjiang@aliyun.com

Abstract: Citrus production is a vital component of global agriculture, yet it faces significant challenges due to increasing water scarcity exacerbated by climate change. Deficit irrigation (DI) strategies, such as Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD), have emerged as effective water-saving techniques to optimize water-use efficiency while maintaining acceptable yields and fruit quality in citrus orchards. RDI involves applying controlled water stress during less sensitive growth stages, such as early fruit development or post-harvest, to reduce water consumption without compromising productivity. PRD alternates irrigation between rootzone sections, inducing mild stress to enhance water use efficiency and fruit quality. Both strategies offer benefits, including improved fruit sugar content, color, and drought resilience, but their implementation requires precise timing, advanced irrigation infrastructure, and continuous monitoring. Challenges such as variability in soil types, economic barriers, and the need for farmer education highlight the importance of targeted research and policy support. This review underscores the potential of DI strategies to promote sustainable citrus production in water-limited regions while addressing the practical and economic constraints faced by growers.

Keywords: Deficit irrigation, Citrus orchards, Regulated Deficit Irrigation (RDI), Partial Rootzone Drying (PRD), Sustainable agriculture, Fruit quality, Irrigation management.

Introduction

Citrus production is a cornerstone of global agriculture, significantly contributing to the economies of many countries, particularly in subtropical and tropical regions. Citrus fruits, including oranges, lemons, limes, grapefruits, and tangerines, are highly valued for their nutritional content, particularly their high levels of vitamin C, antioxidants, and dietary fiber [1]. The global demand for citrus fruits has been steadily increasing due to their widespread use in fresh consumption, juice production, and as ingredients in various food products. The cultivation of citrus is, however, highly dependent on climatic conditions and water availability. Citrus trees are perennial crops that require consistent and adequate water supply to achieve optimal growth, fruit yield, and quality. Water stress whether from drought or inadequate irrigation can reduce fruit size, lower yields, and compromise quality, thereby affecting marketability and profitability [2]. As climate change exacerbates water scarcity in many citrus-growing regions, the need for efficient water management strategies becomes increasingly critical.

Water is a fundamental resource for agricultural production, and its efficient management is essential for sustainable farming practices. Agriculture accounts for approximately 70% of global freshwater withdrawals, making it the largest consumer of water resources [3]. In the context of citrus production, water management is particularly crucial due to the crop's sensitivity to water stress and its long growing season, which often coincides with periods of limited rainfall. Effective water management in citrus orchards involves balancing the water requirements of the trees with the available water supply. Over-irrigation can lead to waterlogging, nutrient leaching, and increased susceptibility to diseases, while under-irrigation can result in water stress, reduced yields, and poor fruit quality [4].Therefore, optimizing irrigation practices is essential to ensure the sustainability of citrus production, especially in regions facing water scarcity.

Various irrigation strategies have been developed and applied in citrus orchards to optimize water use and improve crop productivity. These strategies range from traditional methods, such as flood irrigation, to more advanced techniques, including drip irrigation, micro-sprinklers, and subsurface irrigation. The choice of irrigation method depends on factors such as soil type, climate, water availability, and economic considerations. *Flood Irrigation:* This traditional method involves flooding the orchard with water, allowing it to infiltrate the soil. While simple and low-cost, flood irrigation is often inefficient, with significant water losses due to evaporation and runoff [5]. *Drip Irrigation:* Drip irrigation delivers water directly to the root zone of the trees through a network of tubes and emitters. This method is highly efficient, reducing water losses and allowing for precise control of water application. Drip irrigation is particularly suitable for citrus orchards, as it minimizes water contact with the foliage, reducing the risk of fungal diseases [6]. *Micro-Sprinklers:* Micro-sprinklers distribute water in a fine spray over a small area, providing uniform coverage and reducing water loss. This method is effective in maintaining soil moisture levels and can be adapted to different orchard layouts [7]. *Subsurface Irrigation:* Subsurface irrigation involves delivering water below the soil surface, directly to the root zone. This method minimizes evaporation and runoff, making it highly efficient. However, it requires careful management to prevent clogging and ensure uniform water distribution [8].

Deficit irrigation (DI) is a water management strategy that involves applying less water than the full crop water requirement, with the aim of optimizing water use efficiency while maintaining acceptable levels of crop yield and quality [9]. The principle behind deficit irrigation is to intentionally subject the crop to controlled water stress during specific growth stages when it is less sensitive to water deficits, thereby reducing overall water consumption without significantly impacting yield or fruit quality. In citrus orchards, deficit irrigation can be applied during periods of low water demand, such as the early stages of fruit development or after harvest. By carefully timing the water stress, growers can induce physiological responses in the trees that enhance water use efficiency, such as reduced vegetative growth and improved fruit quality [10]. However, the success of deficit irrigation depends on a thorough understanding of the crop's water requirements and stress tolerance, as well as careful monitoring of soil moisture levels and plant responses. Deficit irrigation is particularly relevant in regions where water resources are limited or where the cost of water is high. It offers a practical solution for maintaining citrus production under water-scarce conditions, while also contributing to the conservation of water resources [11], [12]. However, the implementation of deficit irrigation requires careful planning and management to avoid negative impacts on crop yield and quality. This study has comparative review on the deficit irrigation in the Citrus Orchards and the challenges associated with it.

Literature Review Methodology

To ensure a rigorous and reproducible analysis, this review systematically examined peer-reviewed literature on deficit irrigation in citrus orchards. The selection process prioritized studies that focused specifically on Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD) applications in citrus production; were conducted in major citrus-growing regions facing water scarcity; reported measurable agronomic outcomes (yield, fruit quality, water use efficiency); and employed field experiments or long-term trials. Literature was identified through Scopus, Web of Science, and Google Scholar using keyword combinations including "deficit irrigation," "citrus," "water stress," and "sustainable agriculture." The review particularly emphasized studies from high-impact journals in agricultural water management and frequently cited foundational works. Theoretical models and non-English publications were excluded to maintain focus on empirically validated strategies. This methodological approach ensures the review's findings are both representative of current scientific understanding and directly applicable to real-world citrus production systems facing water constraints.

Deficit Irrigation Strategies

Deficit irrigation (DI) is a water-saving strategy that has gained significant attention in recent years, particularly in regions facing water scarcity. By applying water below full crop requirements, deficit irrigation optimizes water-use efficiency while maintaining acceptable crop yields and quality. This chapter explores the two primary types of deficit irrigation strategies commonly applied in citrus orchards: Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD). Each strategy is discussed in detail, including its principles, implementation, benefits, and limitations, supported by relevant literature and case studies.

Regulated Deficit Irrigation (RDI)

Regulated Deficit Irrigation (RDI) is a precision-based approach that involves reducing water application below the crop's evapotranspiration (ET) demand during growth stages where the crop exhibits lower sensitivity to water stress. In citrus orchards, RDI is typically implemented during phases such as early fruit development or post-harvest, periods when water deficits have minimal impact on fruit size and yield [13]. RDI's principle hinges on crops' physiological response to controlled stress, reducing vegetative growth and improving water-use efficiency without significantly compromising fruit quality. For instance, studies have shown that RDI can enhance fruit sugar content and color, attributes highly valued in the market [14]. However, the success of RDI hinges on precise timing and careful monitoring of soil moisture and plant responses. Over application of stress during critical growth stages, such as flowering or fruit maturation, can lead to yield losses and poor fruit quality [15]. Thus, while RDI offers substantial water savings, its implementation requires a thorough understanding of citrus phenology and local environmental conditions.

Principles of RDI

Regulated Deficit Irrigation (RDI) operates on the principle of applying water stress during specific growth stages when citrus trees are less sensitive to water deficits. This strategy targets periods such as early fruit development or post-harvest, where reduced irrigation does not significantly influence yield or fruit quality [14], [15]. The physiological response of citrus trees to controlled stress includes reduced vegetative growth and improved water use efficiency, which can enhance fruit attributes like sugar content and color [16], [17]. The key to RDI lies in precise timing and monitoring, as misapplication during critical stages like flowering or fruit maturation can lead to adverse effects [18]. By aligning water application with the tree's phenological stages, RDI optimizes water use without compromising productivity as seen in **Figure 1**.

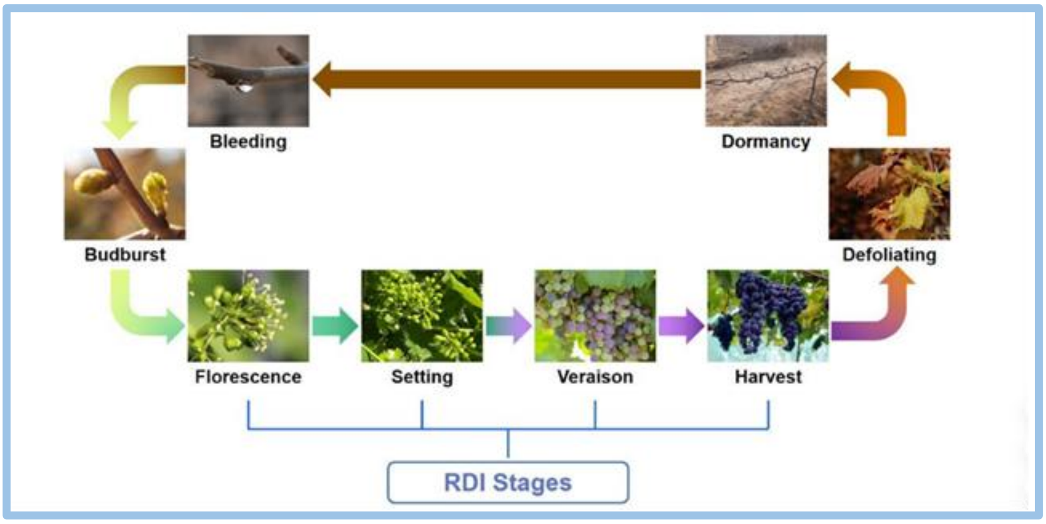

Figure 1. Phenological stage suitable for RDI treatment [13]

Benefits of RDI

RDI offers several advantages for citrus orchards, particularly in water-scarce regions. By reducing irrigation during less sensitive growth phases, it achieves significant water savings while maintaining acceptable yield levels [19]. Studies have shown that RDI can improve fruit quality, including higher sugar concentrations and better color development, which are critical for marketability [20]. Additionally, RDI can mitigate excessive vegetative growth, directing more energy toward fruit production and reducing pruning costs [21]. The strategy also aligns with sustainable agriculture goals by minimizing water waste and reducing the environmental impact of over-irrigation. These benefits make RDI a valuable tool for citrus growers seeking to balance water conservation with economic viability.

Challenges of RDI

Despite its advantages, RDI presents several challenges that require careful management. The success of RDI depends on accurate knowledge of citrus phenology and local environmental conditions, as misjudging the timing or severity of water stress can lead to yield losses or poor fruit quality [5]. Soil variability, particularly in sandy soils with low water-holding capacity, complicates irrigation scheduling and necessitates frequent adjustments [14]. Additionally, the need for continuous monitoring of soil moisture and plant responses can increase labor and resource demands, which may be a barrier for small-scale growers [1]. Addressing these challenges requires targeted research, farmer training, and the development of user-friendly tools to support precise irrigation management.

Partial Rootzone Drying (PRD)

Partial Rootzone Drying (PRD) is an innovative DI technique that alternates irrigation between different sections of the rootzone, thereby maintaining partial hydration while inducing controlled stress. In citrus orchards, PRD is executed by irrigating one side of the rootzone while allowing the opposite side to dry, typically on a 7–14-day cycle [14] as presented in **Figure 2**. This method capitalizes on the plant's ability to regulate water uptake and stomatal conductance, which can lead to reduced water consumption without drastic yield penalties [22]. PRD has been shown to improve water use efficiency and fruit quality, particularly in terms of acidity and soluble solids content. However, PRD presents challenges, including the need for specialized irrigation infrastructure and the risk of uneven stress distribution if not managed properly. Additionally, long-term effects of PRD on root development and soil health require further investigation. Despite these challenges, PRD remains a promising strategy for citrus growers in water-limited regions.

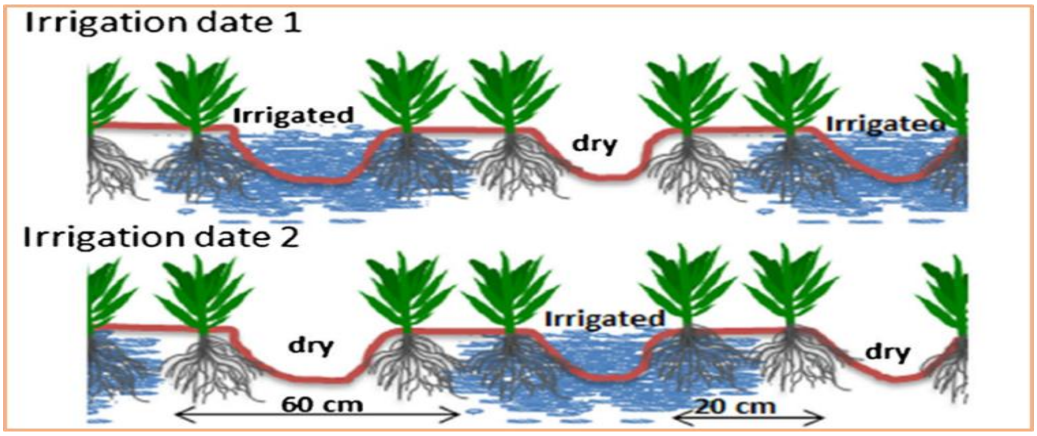

Figure 2. Partial root-zone irrigation [14].

Principles of PRD

Partial Rootzone Drying (PRD) is an innovative deficit irrigation technique that alternates water application between different sections of the rootzone. In citrus orchards, PRD involves irrigating one side of the rootzone while allowing the opposite side to dry, typically on a 7–14-day cycle [14]. This method leverages the plant's ability to regulate stomatal conductance and water uptake, inducing mild stress that reduces water consumption without severely impacting yield. PRD stimulates hormonal responses, such as increased abscise acid production, which enhances water use efficiency and can improve fruit quality parameters like acidity and soluble solids content [15], [23]. The success of PRD relies on proper irrigation system design and consistent monitoring to ensure uniform stress distribution.

Benefits of PRD

PRD offers several benefits for citrus production, particularly in regions with limited water resources. By maintaining partial rootzone hydration, PRD reduces overall water use while minimizing yield penalties [14]. Studies have demonstrated that PRD can enhance fruit quality, including higher sugar levels and improved flavor profiles, which are desirable for both fresh markets and processing [23]. The technique also promotes deeper root growth, which can improve drought resilience over time. Furthermore, PRD aligns with sustainable farming practices by reducing water waste and lowering the risk of nutrient leaching. These advantages make PRD a promising strategy for optimizing water use in citrus orchards.

Challenges of PRD

The implementation of PRD is not without challenges. The technique requires specialized irrigation infrastructure, such as dual-line drip systems, which can be costly to install and maintain [24]. Poorly managed irrigation cycles may cause uneven stress distribution, resulting in inconsistent fruit quality or yields. Additionally, the long-term effects of PRD on root development and soil health remain areas of ongoing research, as repeated drying cycles could alter soil microbial communities or root architecture [24]. Economic barriers, such as the high initial investment for small-scale growers, may also limit widespread adoption [1]. Overcoming these challenges will require further research, technological innovations, and policy support to make PRD more accessible and effective for citrus producers.

Thoughts on Deficit Irrigation in Citrus Orchards

Deficit irrigation (DI) presents a viable solution for sustainable citrus production in water-limited regions, yet its successful adoption depends on addressing key challenges. First, local conditions such as soil type, climate, and citrus variety play a crucial role in DI effectiveness. For instance, sandy soils demand more frequent irrigation adjustments than clay soils, while arid climates may require supplemental practices like mulching to enhance water retention. Second, the implementation of DI relies heavily on technical knowledge, including precise irrigation scheduling and real-time monitoring, which can be a barrier for small-scale growers lacking access to affordable technology or training [1]. Bridging this gap requires targeted farmer education and user-friendly decision-support tools. Finally, economic constraints, such as the high upfront costs of advanced irrigation systems, may limit widespread adoption. Policymakers can facilitate DI uptake through financial incentives, water pricing reforms, and shared-resource models. Future research should optimize DI strategies for diverse growing conditions, while extension programs must ensure practical on-farm application [14]. By addressing these challenges, DI can evolve from a promising concept into a scalable and sustainable practice for citrus growers worldwide.

Soil-Specific Efficacy: Resolving Conflicts in Deficit Irrigation Performance

The efficacy of DI strategies varies markedly by soil type, creating adoption challenges. As summarized in **Table 1**, sandy and clay soils exhibit fundamentally different responses to water stress, necessitating tailored approaches.

Table 1. Comparative Analysis of Deficit Irrigation Performance in Sandy vs. Clay

Factor	Sandy Soils Findings	Clay Soils Findings	Conflict Analysis	Practical Implications
Water Retention	Low water-holding capacity requires frequent irrigation adjustments [12]	High water holding capacity maintains moisture longer [24]	DI timing must be soil-adaptive	Sandy: Shorter irrigation intervals
Stress Response	Rapid stress onset improves WUE but risks over-stress [13]	Slower stress development may delay ABA signaling [22]	PRD may be less effective in clays	Sandy: Ideal for PRD
Yield Impact	Yield losses >20% ET_c stress [12]	More tolerant to moderate stress [18]	Universal DI thresholds unreliable	Soil-specific stress thresholds needed
Root Adaptation	Promotes deeper root growth [15]	Lateral root dominance may limit PRD response [24]	Root architecture affects DI success	Sandy: Better for PRD
Nutrient Leaching	High risk due to fast drainage [5]	Low risk but potential salt accumulation [7]	DI impacts nutrient management differently	Sandy: Requires more frequent fertigation

Practical Steps for Policymakers and Growers

To facilitate the widespread adoption of deficit irrigation (DI) strategies in citrus production, concerted efforts from both policymakers and growers are essential. Policymakers should prioritize financial support through subsidies for advanced irrigation infrastructure, such as drip systems and soil moisture sensors, making these technologies more accessible to growers, particularly small-scale farmers. Developing region-specific guidelines through targeted research will help tailor DI techniques to local conditions, accounting for variations in soil types, citrus cultivars, and climate patterns. These findings should be disseminated through farmer training programs and digital platforms, ensuring growers have the knowledge to implement DI effectively. Additionally, water pricing reforms that reward efficient usage and investments in water storage infrastructure can create an enabling environment for sustainable practices. Policymakers should also foster innovation by supporting pilot projects and data-sharing platforms where growers can exchange insights on DI performance.

For growers, adopting DI requires a phased approach, beginning with small-scale trials to assess crop responses before full implementation. Investing in monitoring tools, even basic ones like tensiometers, can significantly improve irrigation precision. Timing is critical growers must apply water stress during less sensitive growth stages, such as post-harvest or early fruit development, while avoiding periods like flowering or fruit maturation. Adapting DI to local conditions is equally important; for instance, sandy soils may require more frequent but reduced irrigation, while arid regions could benefit from complementary practices like mulching. Collaboration is key: joining grower networks or attending extension workshops can provide valuable insights and troubleshooting support.

Ultimately, the successful integration of DI in citrus orchards hinges on a partnership between policymakers and growers. By addressing economic barriers, providing education, and promoting adaptive management, stakeholders can ensure that DI becomes a viable, scalable solution for water conservation in citrus production. The path forward requires localized adaptation, continuous learning, and shared knowledge to balance water sustainability with agricultural productivity.

Conclusion

Deficit irrigation strategies, particularly RDI and PRD, represent innovative approaches to water management in citrus orchards, offering a balance between water conservation and agricultural productivity. These techniques have demonstrated potential in improving water use efficiency and enhancing fruit quality, making them particularly valuable in regions facing water scarcity. However, their success depends on meticulous planning, tailored implementation, and ongoing monitoring to mitigate risks such as yield reduction or uneven stress distribution. Future research should focus on optimizing these strategies for diverse growing conditions and addressing the economic barriers to their adoption. Integrating scientific advancements with practical farming needs will enable deficit irrigation to ensure sustainable citrus production amid growing water constraints. As the global demand for citrus continues to rise, the adoption of efficient water management practices will be critical to securing the future of this vital agricultural sector.

Conflict of interest

The authors declare no conflict of interest.

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