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THE IMPACT OF DEFICIT IRRIGATION ON THE GROWTH, DEVELOPMENT, YIELD, AND ACCUMULATION OF BIOACTIVE COMPOUNDS IN CROPS: A REVIEW

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ABSTRACT

Since ancient times, it has been observed that plants exposed to drought conditions undergo substantial alterations, both in their morphological characteristics and in the composition of their internal compounds. Research carried out in last few decades has certified several such claims of effects of deficit irrigation on crop growth, vitality, yield, and the composition of bioactive compounds. Diverse irrigation strategies, including deficit irrigation and partial root zone drying, as well as their effects on plant physiology at different growth stages were discussed. The article further highlights the connection between water deficit irrigation and the physiological reactions of various plant species. The findings indicate that deficit irrigation influences all aspects, including plant vitality, yield, and the concentration of bioactive compounds across different plant species. The knowledge may contribute to a holistic understanding of deficit irrigation, and crucial for optimizing water management in agriculture.

1. INTRODUCTION

Global freshwater resources face increasing strain due to high demand for irrigation in agriculture, particularly in arid and semi-arid regions. Long-term solutions to address water scarcity require innovative irrigation strategies (Sepaskhah A, 2010). Irrigated agriculture plays a crucial role to ensure food security, as it typically leads to a twofold increase in seasonal yield compared to conventional production relying on natural rainfall conditions (Sepaskhah A, 2010). Despite the perceived extravagance of full irrigation, studies suggest that irrigated water consumption can be minimized without significantly impacting yield, and providing substantial economic benefits (Kang & Zhang, 2004). The conventional perspective on irrigation, focusing on meeting crop water requirement, is being reconsidered as studies show positive crop responses to appropriate for water scarcity conditions (Phi, 2019).

Numerous investigations have been undertaken to optimize crop irrigation for maximum of performance, efficiency, and profitability. However, there has been still been continuous focus on research in water-saving irrigation practices (Lascano & Sojka, 2015). Efficient management of irrigation water is crucial for global water and food security. Various methods, including monitoring soil moisture

content and crop water stress indices, have been developed to minimize excessive watering (Touil et al., 2022). Common irrigation practices, such as full irrigation (FI), can lead to overirrigation or under-irrigation in certain areas in a field, causing undesired water stress on crops (Abioye et al., 2020). Farmers in non-limited or water-limited areas often use FI (Sepaskhah A, 2010). However, studies on irrigation techniques to regulate water amount, such as partial root-zone drying irrigation (PRD), deficit irrigation (DI), irrigation scheduling, and based on soil moisture content (SMC), have proven their effectiveness (Touil et al., 2022; Ahmadi et al., 2010; Lamm & Rogers, 2014; McCready & Dukes, 2011). Several published studies evaluate the impact of deficit irrigation on the growth, vitality, and yield of crops, while also assessing the physiological responses of various plant species and the role of bioactive compounds under water-limited conditions. Crops undergoing water stress at different growth stages could exhibit specific physiological responses to adapt to the unfavorable conditions. Internal crop activities will be regulated, (such as closing stomata to reduce water vapor loss and decreasing photosynthesis, are regulated). Consequently, external morphological factors (such as plant height, leaf width, and leaf thickness) may differ in plants exposed to water deficit compared to those with adequate water supply (Phi, 2019).

2. THE CONCEPT OF DEFICIT IRRIGATION

Deficit irrigation (DI) is a watering strategy proposed many years ago to improve water productivity and re- duce the irrigation application. In a broad sense, DI consists of the deliberate and systematic under-irrigation of crops. It is well known that reductions in the water applied usually lowers evapotranspiration (ET) and crop growth rates by limiting their principal component, transpiration (T) and, as a consequence, carbon assimilation. In young plantations, on the other hand, the main objective is to maximise growth so that trees can mature as fast as possible, which implies the avoidance of even mild water deficits (Ruiz-Sanchez et al., 2010).

Regulated deficit irrigation and Partial rootzone drying

Deficit irrigation (DI) is a water management strategy introduced many years ago with the aim of enhancing water productivity and reducing overall irrigation use. Broadly, DI involves intentionally and systematically providing less water to crops than their full water requirements demand. In simple terms, the applied water is deliberately kept below the level needed to fully meet the crop's water needs (Topacoglu et al., 2016). Moreover, the early stage of plant development requires careful water management to ensure that trees reach maturity as quickly as possible, laying the foundation for future productivity and resilience (Ruiz-Sanchez et al., 2010). Partial rootzone dry technique consists of maintaining approximately half of the root system sufficiently watered while the other part is allowed to dry. For this, both halves are watered alternately every so often. Such stomatal regu- lation reduces water loss through transpiration with little effect on photosynthesis, thus increasing transpi- ration efficiency, that is the dry matter produced per unit of water transpired (Ruiz-Sanchez et al., 2010).

3. THE INFLUENCE OF WATER CONDITIONS ON CROP DEVELOPMENT, VITALITY, YIELD, AND ORGANIC COMPOUND COMPOSITION IN PLANTS

The effect of water deficit on growth stage of the crop

In two comprehensive experiments, the response of shoot dry matter (SDM) production in rice plants exposed to drought for 23–35 days at various growth stages was meticulously examined. Initiating stress at 33 days old, young plants maintained elevated leaf water potential due to low water demand, resulting in a notable reduction in SDM production primarily attributed to diminished radiation interception (Boonjung & Fukai, 1996). Transitioning to the impact of water deficit on rice cultivars, the study delved into vegetative and reproductive stages, revealing that biomass production during water deficit varied from less than 56% under irrigated conditions, contingent on stress severity and cultivar (Lilley & Fukai, 1994). Furthermore, water deficit during reproductive growth significantly diminished grain yield, with a decelerated growth rate during panicle development leading to smaller grain size (Lilley & Fukai, 1994).

Shifting the focus to the sensitivity of maize and soybean simulations to irrigation at different growth stages, a pivotal study by (Lopez et al., 2017). underscored that optimized irrigation schedules substantially enhanced water productivity (WP) compared to non-optimized schedules, showcasing a remarkable 91% improvement in WP for maize in water-restricted scenarios. A study in Rutigliano (Bari, Italy) meticulously evaluated the sensitivity of distinct phenological stages to a shared water deficit, elucidating that the early stage ('leaf') exhibited the highest sensitivity, undergoing a 30% reduction in biomass production and a WUE of 4.8 g kg−1 under temporary soil water stress compared to the well-irrigated control (Mastrorilli et al., 1999).

Field experiments conducted during the dry seasons of 2004 and 2005 uncovered that deficit irrigation at any maize growth stage precipitated reduced dry matter and grain yields, along with seasonal evapotranspiration and deep percolation (Igbadun et al., 2008). The study posits that deficit irrigation practices spanning multiple growth stages exert a substantial impact on both biomass and grain production. Notably, enhancing Irrigation Water Use Efficiency (IWUE) may be attained through deficit irrigation during the vegetative growth stage of maize crops (Igbadun et al., 2008). In semi-arid Northern Colorado, a study on maize scrutinized twelve treatments encompassing diverse deficit irrigation levels during late vegetative and maturation growth stages. Significantly, implementing greater deficit during late vegetative stages while concurrently maintaining near-full evapotranspiration throughout the season yielded comparable results to fully irrigated treatments, conserving approximately 15-17% of evapotranspiration (Comas et al., 2018).

The culmination of a three-year study revealed that water scarcity during sensitive stages substantially impacted all vegetative and yield parameters, culminating in up to 40% grain yield losses with a single irrigation omission during critical growth stages (Çakir, 2004). Seasonal irrigation water requirements for non-stressed production exhibited annual variability, and yield response factor values fluctuated from 0.81 to 1.36 (Çakir, 2004). Notably, drought during panicle development emerged as the most detrimental, causing delayed anthesis, reduced spikelets per panicle, and a substantial decrease in filled grains, resulting in less than 20% of the control yield (Comas et al., 2018).

The impact of irrigation water on plant vitality

The irrigation process exerts a continuous influence from seed germination to the final harvest, with different irrigation levels significantly affecting the growth and development of plants. This impact is observable

throughout all parts of the plant. One primary aspect affected by irrigation is seed germination. Insufficient water content leads to a decrease in seed germination, as demonstrated by research on Pinus nigra Arnold seeds under water stress conditions (Topacoglu et al., 2016). Similarly, studies on China aster and tomato seeds indicate delayed germination when exposed to limited water compared to ample water supplies (Badek et al., 2006). A three-year study on soybean plants underscores the consistency of root responses to irrigation over multiple years, revealing improved root characteristics under appropriate irrigation regimes ensuring healthy plant development (Bui et al., 2022).

Moreover, the level of irrigation significantly shapes the growth and structure of the plant's stem and leaves. Water deficiency induces stress in cabbage plants, leading to reduced plant height and smaller-than-normal leaves (Seidel et al., 2017). Conversely, overwatering, especially with irregular frequency, can result in decreased stem height, stem density, and leaf area index, as observed in studies on alfalfa irrigation (Saeed & El-Nadi, 1997). Additionally, research on the effects of moderate drought conditions on potato green leaves found decreases in the number of green leaves, leaf length, and plant height (Deblonde & Ledent, 2001). Sunflower plants also exhibit reduced height and diameter with decreased irrigation water content (Seghatoleslami et al., 2012). However, the cumulative impact of water stress paradoxically resulted in higher calculated canopy photosynthesis under moderate and severe stress treatments compared to the control (Lampinen et al., 2004).

The impact of irrigation water levels on the crop yield

Accurately estimating crop water requirements is a crucial prerequisite for achieving high yields and maximizing crop water productivity, as emphasized by (Seidel et al., 2017). A study conducted on cotton plants by by (Cetin & Bilgel, 2002) highlights the necessity of irrigation in regions with limited rainfall to attain optimal yields. The study further emphasizes that without irrigation, cotton crops often fail to achieve their full yield potential (Cetin & Bilgel, 2002). Numerous investigations delve into how varying irrigation levels can impact the quality and yield of crops for instance, Pinnamaneni et al., 2021 emphasize the pivotal role of irrigation in achieving high fiber yield and seed quality.

From another perspective, examining the effects of moderate drought conditions on six potato cultivars, (Deblonde & Ledent, 2001) demonstrated that reducing irrigation water did not lead to a decrease in potato yield compared to control plants. Similarly, a study on Bell pepper plants indicated that a 67% irrigation level, compared to 100%, maintained both fruit yield and quality, while increasing irrigation to 130% did not enhance plant growth (Kabir et al., 2021). In contrast, a study on purple basil (Ocimum basilicum L.) by (Ekren et al., 2012) revealed that the highest plant height and green herb yield were achieved with 125% irrigation. Additionally, (Seghatoleslami et al., 2012) found that a reduction in irrigation levels for sunflower plants corresponded to a decrease in seed yield.

The research findings of (Tura & Tolossa, 2020) suggest that reductions in crop yield are observed across various crops when exposed to water stress, with the extent of yield reductions influenced by the crop's susceptibility during different growth stages. However, beyond these findings, there are contrasting conclusions, with some studies suggesting that a partial reduction in irrigation water can increase productivity compared to maintaining normal irrigation levels. For example, a study on corn plants (Phi, 2019) revealed that the highest productivity occurred with moderate water deficiency

irrigation. Similar results were obtained when applying a 26% reduction in irrigation water on sugarcane plants, resulting in a further 10% increase in yield (Sepaskhah A, 2010). Overall, the relationship between crop yield and irrigation levels exhibits considerable variability across different crop types, and a standardized rule regarding this relationship has not been established across various plant species.

Effect of irrigation water levels on bioactive compound composition in plants

In general, the application of water deficit irrigation methods tends to increase the content of bioactive compounds (Ekren et al., 2012). For instance, a study on purple basil (Ocimum basilicum L.) revealed that the highest essential oil ratio (1.10%) was found in the 50% treatment (Ekren et al., 2012). Similarly, (Khalid, 2006) investigated water deficit irrigation levels of 50%, 75%, and 125% on sweet basil and American basil, showing an increase in the percentage of essential oil, primary components of essential oil, proline, and total carbohydrate content under water stress, with the highest yield observed at 75% field water capacity. Additionally, research on Pelargonium odoratissimum (L.) plants indicated that insufficient water levels facilitated the buildup of essential oil concentration and primary constituents. The highest accumulation of essential oil was recorded at the lowest water deficit level (40%), yielding 43.6% and 59.1% more essential oil than the control (100%) during the first and second harvest, respectively. Notably, the highest percentage of hydrocarbons compounds resulted from the control treatment, while the highest percentage of oxygenated compounds was obtained from the 40% treatment (Khalid et al., 2010).

Moreover, a study on tomato cultivation with different irrigation levels demonstrated that compared with fully irrigated treatment (90% of the field's moisture capacity), the total flavonoid content increased by 33.66% and 44.73% in 80% and 65%, and total phenols increased by 57.64%, 72.22%, and 55.78% in 80%, 65%, and 55%, respectively. The 65% treatment significantly enhanced antioxidant capacities (ABTS, HSRA, FRAP, and DPPH) (Jin et al., 2022). A similar study on the impact of regulated deficit irrigation (RDI) and partial root-zone drying irrigation (PRD) methods on two tomato varieties (Matina and Cochoro) showed cultivar-dependent effects on antioxidant content (Bogale et al., 2016).

Furthermore, a research study examined how deficit irrigation at three management allowable depletion levels (MAD) – 25%, 50%, and 75% – influenced phytochemicals, ascorbic acid, antioxidant activity, glucose, fructose, and both fresh and dry mass in two varieties of green leafy lettuce (Lollo Bionda and Vera) during harvest. The results indicated that chicoric acid, caftaric acid, chlorogenic acid, and caffeic acid exhibited a tendency to rise at 50% MAD, whereas kaempferol, quercetin, and myricetin increased at 75% MAD in both cultivars, suggesting an enhancement in antioxidant properties. Ascorbic acid content decreased with higher MAD levels, and there was no clear pattern observed in β-carotene content in relation to MAD irrigation for these cultivars (Malejane et al., 2018). Additionally, a study by (Yu Kyeong Shin, Shiva Ram Bhandari, Jung Su Jo, Jae Woo Song, 2021) observed a significant increase in the effect of drought stress on Chlorophyll Fluorescence parameters.

Evaluation of economic aspects in the implementation of deficit irrigation

DI is increasingly recognized as a viable strategy for addressing water scarcity in agriculture, particularly in arid regions. Research indicates that DI can enhance water use efficiency and profitability under certain economic conditions. For instance, a study conducted in Colorado

demonstrates that DI can be economically optimal if maize prices exceed $0.19 per kilogram and water costs $0.21 per cubic meter. Farmers can effectively respond to rising water scarcity by adopting DI practices (Manning et al., 2018). Similarly, investigations in Southern Spain highlight the microeconomic implications of DI, emphasizing its role in the sustainable use of water resources amid declining water supply and income pressures faced by farmers (Expósito & Berbel, 2017). Moreover, field experiments conducted in Iran show that both surface and subsurface drip irrigation methods improve yield and water use efficiency, with economic analyses indicating the superiority of subsurface methods in terms of profitability (Steve Hatfield-Dodds, 2007). Further research on citrus orchards in Southern Italy confirms the economic feasibility of DI strategies, indicating that regulated DI can increase income 100% by optimizing applied water levels in regions with scarce water resources (Capra et al., 2011). Economic assessments of various DI techniques, including regulated and sustained DI, in Indian mandarin orchards have shown that they can achieve profitability comparable to full irrigation, thus encouraging adoption in water-limited contexts (Panigrahi et al., 2013). Field experiments in wheat cultivation also indicate that strategic water deficit treatments can maximize financial returns, emphasizing the importance of tailored irrigation management in optimizing resource use (Ali et al., 2007),

However, In Iraq, studies on rice production showed that 3-day irrigation intervals generated the highest returns compared to continuous submergence, suggesting that reduced water use can yield positive economic outcomes. However, 7-day intervals, while achieving water savings of up to 72%, involved slight yield sacrifices, posing trade-offs for farmers (Mohammed et al., 2023). For potato farming, DI applied during tuber bulking yielded only 12% less than fully irrigated treatments but achieved significant water savings, and the dry matter content in the tubers increased (Karam et al., 2014). Finally, studies assessing the economic water productivity of various crops under DI conditions underscore the necessity for improved irrigation performance and flexible water pricing policies to facilitate wider adoption of DI practices (Karam et al., 2014; Rodrigues & Pereira, 2009; Trout & Manning, 2019).

4. CONCLUSIONS

The investigation has provided valuable insights into the intricate relationship between irrigation practices and crop development. The exploration encompassed the concept of deficit irrigation, with a specific focus on regulated deficit irrigation and partial rootzone drying. The findings underscored the pivotal role of irrigation levels in influencing the physiology, growth, and overall development of crops. Notably, the impact of irrigation water on plant vitality emerged as a critical factor, with discernible effects on crop yield. The study revealed that varying irrigation water levels directly correlate with changes in the bioactive compound composition within plants.

In essence, the results highlight the need for a nuanced approach to irrigation management. Understanding the intricacies of deficit irrigation, particularly its regulated and partial rootzone drying variants, is essential for optimizing crop productivity. Moreover, recognizing the substantial influence of irrigation water levels on both plant vitality and bioactive compound composition underscores the importance of precision in irrigation practices to achieve sustainable and enhanced agricultural outcomes.

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