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Assessing the Impact of Deficit Irrigation Levels on Wheat Growth, Yield, and Water Use Efficiency in Semi-Arid Regions

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Abstract

Water scarcity is a major constraint to agricultural productivity in semi-arid regions, where optimizing irrigation practices is essential for sustainable crop production. This study investigates the impact of deficit irrigation levels on the growth, yield, and water use efficiency (WUE) of wheat (*Triticum aestivum* L.). A field experiment was conducted during two consecutive growing seasons under four irrigation regimes corresponding to 100%, 80%, 60%, and 40% of crop evapotranspiration (ETc).

Growth parameters such as plant height, leaf area index, and biomass accumulation were measured at different growth stages, while grain yield and water use efficiency were determined at harvest. Results indicated that full irrigation (100% ETc) produced the highest yield, but moderate deficit irrigation at 80% ETc maintained comparable yields with significantly improved WUE. Severe water stress (60% and 40% ETc) reduced growth and yield drastically, although WUE increased due to lower water consumption. The findings suggest that applying 80% of ETc can balance productivity and water conservation, making it an optimal strategy for wheat cultivation in water-limited environments.

The study underscores the importance of adopting efficient irrigation management to enhance resilience against water shortages and ensure sustainable agricultural production in semi-arid regions. The study concludes that improving harvesting efficiency requires adjusting both harvesting speed and cutting angle within optimal limits that maximize grain yield while minimizing field and energy losses. It recommends adopting a moderate harvesting speed combined with a suitable cutting angle as a technical option that can enhance harvesting efficiency, reduce operating costs, and promote agricultural production sustainability.

Keywords: Harvesting speed, cutting angle, harvesting efficiency, wheat harvester, grain loss, grain breakage, energy efficiency.

Introduction

Water scarcity is increasingly recognized as a critical constraint for agricultural production in many semi-arid and arid regions of the world. As global population, climate change, and competing demands for water escalate, efficient use of irrigation water becomes essential for sustaining food security [1]. In semi-arid zones, where rainfall is unreliable and evapotranspiration rates are high, the challenge is not merely to supply water, but to supply it in optimized amounts that maximize crop yield per unit water used—known as water use efficiency (WUE) [1].

Wheat (Triticum aestivum L.) is a staple crop that occupies large areas in semi-arid regions. However, wheat is sensitive to water stress, particularly during certain critical growth stages (such as jointing, booting, flowering), and yield loss can be substantial under inappropriate irrigation regimes [2; 3]. Deficit irrigation, where water is supplied below full crop water requirements (often expressed as a percentage of crop evapotranspiration, ETc), has been studied as a promising strategy to balance yield and water savings [1; "Optimizing wheat productivity …" study in Pakistan, 2025).

[1] conducted field experiments in the Awash Basin of Ethiopia under semi-arid conditions. They compared five irrigation levels: 100%, 85%, 70%, 55%, and 40% of ETc. They found that while full irrigation (100% ETc) gave the highest grain yield (~5,085 kg/ha), the 70% ETc treatment gave the highest water use efficiency (~1.42 kg m^{-3}), with relatively modest yield reduction compared to full irrigation [1], p. [for example] "Grain yield" section). This suggests that moderate deficit irrigation may optimize both yield and water efficiency in resource-limited environments.

Similarly, a study in Pakistan ("Optimizing wheat productivity …", 2025) evaluated wheat under four irrigation treatments: 100%, 80%, 60%, and 40% of crop evapotranspiration (ETc). over three seasons (2019-2022). They observed that the biomass and grain yields declined progressively with increasing water deficit. However, water use efficiency based on biomass and grain yield remained similar under 100%, 80%, and 60% ETc, but dropped sharply under 40%. Notably, the 80% ETc regime achieved a balance—sufficient yield with improved resource efficiency (Pakistan study, 2025, "Abstract" section).

Root growth dynamics and soil water extraction are also central to understanding how deficit irrigation affects wheat performance. [2] investigated root distribution under different irrigation volumes in a winter wheat crop in a semi-arid area. They found that deficit-regulated irrigation promoted deeper root penetration and delayed root senescence, which helped stabilize yield and improve WUE under constraints of reduced water supply [2], p. [Introduction, Root-Growth Dynamics section]).

Moreover, the spatial and temporal patterns of water use, and the sensitivity of yield to water deficits (quantified via yield response factor, K_y), are important considerations. In the Awash Basin study, the yield response factor (K_y) increased as water deficit increased; mild to moderate deficits (85% and 70% ETc) corresponded to relatively lower yield reductions per unit of ETc reduction [1], "Crop water production function" section). The Pakistan study similarly reported K_y values around 1.02 for 80% ETc and 1.25 for 60% ETc, indicating moderate sensitivity (Pakistan study, 2025, "Abstract").

In addition, economic implications of deficit irrigation cannot be ignored. Water saved under reduced irrigation levels could be allocated to expand the cultivated area or invested in other stages of production, potentially offsetting yield reductions [1]. Indeed, Bayisa et al. found that the 70% ETc regimen produced the highest economic profit among deficit irrigation treatments in their study area [1], "Abstract" section).

Despite these promising results, there remain gaps in the literature. First, the optimal deficit irrigation percentage may differ among regions because of differences in climate, soil type, wheat variety, and evapotranspiration rates. What is optimal in Ethiopia's semi-arid Awash Basin or in Pakistan may not be optimal in, for example, Iraq or other similar regions. Second, root behavior under stress, soil moisture stratification, and their interaction with irrigation timing and amount need further elucidation. Third, the effect of deficit irrigation on quality attributes of wheat (protein content, test weight, etc.) is less consistently reported, yet important for market value and nutrition. Finally, long-term effects over multiple seasons under variable climatic conditions are needed to assess sustainability.

Therefore, this study aims to assess the impact of varying deficit irrigation levels (e.g., 100%, 80%, 60%, 40% ETc) on wheat growth (such as leaf area, biomass), final grain yield, and water use efficiency in a semi-arid region. Specific objectives include: (1) determining which deficit level offers the best trade-off between yield and water savings; (2) examining root growth and soil water extraction patterns under different irrigation levels; (3) analyzing yield sensitivity (K_y) to water deficit; and (4) evaluating economic benefits associated with water saved under deficit irrigation. The findings are expected to guide irrigation management decisions in semi-arid agricultural regions striving for sustainable wheat production under water scarcity.

1. Theoretical Framework

1.1. Concept of Deficit Irrigation

Deficit irrigation is a water management strategy that intentionally provides crops with less water than their full evapotranspiration (ETc) requirement to optimize water productivity rather than maximizing yield. The theoretical foundation of this approach lies in the production function of water, which describes the relationship between crop yield and water applied [4]. The concept assumes that mild or moderate water stress during certain growth stages can reduce non-productive water losses (such as evaporation and excessive transpiration) without significantly reducing yield [5].

This framework aligns with the principle of diminishing marginal returns, where the incremental yield gain per additional unit of water decreases after a certain threshold. Thus, the objective shifts from achieving the maximum yield to achieving the maximum economic return per unit of water used [6].

1.2. Crop Water Production Function

The theoretical relationship between yield and water use is represented by the crop water production function (CWPF), originally proposed by [7]. This model quantifies yield response as a function of relative evapotranspiration deficits. The mathematical form is often expressed as:

$$\frac{Y}{Y_{max}} = 1 - K_y(1 - \frac{ET_a}{ET_c})$$

where Y is the actual yield, Ymax is the maximum potential yield, ETa is actual evapotranspiration, ETc is potential evapotranspiration, and Ky is the yield response factor [7].

In this framework, Ky indicates the crop's sensitivity to water deficit. For wheat, Ky typically ranges between 1.0 and 1.25, suggesting moderate sensitivity [4]. A Ky value greater than 1.0 means yield reduction is proportionally larger than ET reduction.

This theoretical relationship guides irrigation scheduling and helps determine the optimal deficit level for maximum water productivity.

1.3. Physiological Basis of Wheat Response to Water Stress

The theoretical understanding of plant response to water stress is rooted in plant-water relations theory, which describes how reduced soil moisture affects physiological processes such as stomatal conductance, photosynthesis, and transpiration [8]. Under deficit irrigation, mild stress can induce physiological adjustments, including increased root-to-shoot ratio, osmotic adjustment, and enhanced water uptake efficiency [9].

However, severe stress can lead to decreased leaf area index, reduced chlorophyll concentration, and impaired grain filling [10]. These responses underpin the theoretical balance between conserving water and maintaining sufficient physiological activity to sustain yield. Thus, the optimal deficit level lies where stress improves water efficiency without crossing the physiological threshold of yield loss.

1.4. Concept of Water Use Efficiency (WUE)

Water Use Efficiency (WUE) is the cornerstone of deficit irrigation theory. It can be defined as the ratio of grain yield (Y) to the total water consumed by the crop (ETa). The theoretical framework of WUE is linked to the law of conservation of mass and energy in soil-plant-atmosphere systems, emphasizing that the same water input can yield varying productivity depending on management efficiency and plant adaptation [11].

The WUE concept can also be divided into three hierarchical components:

•Agronomic WUE: Yield per unit of total water applied.

•Physiological WUE: Biomass produced per unit transpiration.

•Irrigation WUE: Yield per unit of irrigation water supplied [12].

Deficit irrigation theoretically increases WUE by minimizing non-beneficial evaporation and forcing plants to use available water more efficiently. However, beyond a threshold, stress can reduce WUE due to impaired photosynthetic activity. Therefore, this theory supports a trade-off model where moderate deficits enhance WUE, while severe deficits decrease it [5].

1.5. Sustainable Water Management Theory

The broader theoretical perspective of this research is rooted in sustainability theory, particularly the Integrated Water Resources Management (IWRM) framework. This theory emphasizes the equitable, efficient, and sustainable use of water resources [13]. Under conditions of scarcity, deficit irrigation becomes a sustainable alternative, enabling higher productivity per drop of water and supporting long-term environmental resilience [14].

This approach aligns with climate-resilient agriculture theory, which advocates adaptive strategies to maintain productivity under changing climatic conditions [15]. By integrating these principles, the study connects the micro-level physiological and agronomic responses of wheat to macro-level water management strategies that promote sustainability and resilience in semi-arid regions.

1.6. Conceptual Model of the Study

Based on these theoretical foundations, the conceptual model of this research can be summarized as follows:

1. Independent variable: Irrigation level (% of ETc).

2. Mediating variables: Soil moisture, plant physiological response (leaf area, stomatal conductance), and biomass accumulation.

3. Dependent variables: Wheat yield and water use efficiency.

The theoretical relationship posits that as irrigation level decreases from full to moderate deficit, WUE improves up to an optimal point, beyond which yield and physiological processes decline sharply. This conceptual framework integrates agronomic theory (CWPF), physiological theory (plant-water relations), and sustainability principles (IWRM) to explain the expected outcomes.

2. Literature Review

Deficit irrigation is an agricultural water management strategy that applies water below the full crop evapotranspiration (ETc) requirement to optimize water productivity rather than maximize yield. It is widely implemented in semi-arid and arid regions where water resources are limited [5]. The primary goals of deficit irrigation are to enhance water use efficiency (WUE), reduce non-productive water losses, and maintain acceptable crop yields under water-limited conditions. Studies indicate that deficit irrigation can improve water productivity by up to 6–7%, although grain yield may decrease slightly under severe stress [11]. This strategy is grounded in the principle of diminishing returns, where each additional unit of water contributes progressively less to yield, emphasizing efficiency over maximum production [6].

Several studies have investigated the effects of deficit irrigation on wheat (Triticum aestivum L.) growth. Moderate water stress can stimulate deeper root growth and enhance water uptake from deeper soil layers, thereby stabilizing yield under limited water supply [2]. Field experiments in Pakistan and Ethiopia reported that wheat grown under 70–80% of ETc exhibited improved root distribution and physiological adaptations, including increased root-to-shoot ratio and delayed senescence, which allowed the plants to maintain sufficient biomass accumulation despite reduced irrigation [1]. These findings underscore the importance of strategic deficit irrigation during non-critical growth stages to optimize crop development while conserving water.

Deficit irrigation affects both grain yield and WUE. Research shows that applying 80% of ETc often achieves a balance between yield retention and improved WUE [1]. Full irrigation (100% ETc) usually produces the highest yield but consumes more water per unit of output, whereas severe water stress (≤60% ETc) reduces both growth and yield, despite slight increases in WUE due to reduced water consumption (Pakistan study, 2025: Abstract). The yield response factor (Ky), which quantifies crop sensitivity to water deficit, typically ranges from 1.0 to 1.25 for wheat, indicating moderate sensitivity [4]. These theoretical and empirical results provide a foundation for optimizing deficit irrigation strategies in semi-arid regions.

Deficit irrigation also influences nutrient absorption, particularly nitrogen uptake. Water stress can reduce nutrient mobility and availability in the root zone, limiting overall growth and productivity [3]. Studies in Egypt demonstrated that wheat under moderate deficit irrigation (70–80% ETc) maintained adequate nitrogen uptake to sustain physiological processes, whereas severe stress significantly decreased nitrogen assimilation and final grain yield [3]. These results highlight the need to integrate water and nutrient management in semi-arid agricultural systems.

In addition to yield, deficit irrigation affects wheat grain quality. Moderate water stress can enhance grain protein content and improve the nutritional value of the final product [10]. For example, field trials have shown that wheat subjected to 80% ETc had slightly higher protein content than fully irrigated crops while maintaining acceptable grain size and weight. Therefore, deficit irrigation can simultaneously optimize water use and improve grain quality when carefully managed.

Deficit irrigation is also a key strategy in sustainable water management. By reducing water consumption while maintaining adequate yield, it contributes to the long-term conservation of water resources in semi-arid regions [14]. Integrating deficit irrigation with climate-resilient agricultural practices allows farmers to adapt to changing precipitation patterns and increasing competition for water resources [15]. These sustainable practices support both environmental and economic goals by improving water productivity and reducing the pressure on scarce water supplies.

In summary, the research gap can be articulated as follows:

1. Region-Specific Optimization: most studies (e.g., [1; 2] focus on specific regions such as Ethiopia, Pakistan, or Egypt. There is limited research on the optimal deficit irrigation levels for wheat in other semi-arid regions, such as Iraq or the Middle East, where climatic conditions, soil types, and wheat varieties differ.

2. Critical Growth Stage Sensitivity: While general effects of deficit irrigation are reported, many studies do not precisely quantify water stress impacts during specific wheat growth stages (e.g., tillering, booting, flowering), A detailed understanding of stage-specific irrigation scheduling is lacking, which is crucial for maximizing yield and WUE.

3. Root Dynamics Under Deficit Irrigation: [2] and other studies indicate changes in root growth patterns under moderate water stress. There is limited research on long-term root adaptation mechanisms and how these affect water uptake efficiency and resilience under multiple growing seasons.

4. Integration of Water and Nutrient Management: Deficit irrigation can influence nutrient uptake, particularly nitrogen [3], Few studies have simultaneously evaluated irrigation and fertilizer strategies, leaving uncertainty on how combined management can optimize yield and quality under water-limited conditions.

5. Grain Quality Under Water Stress: Some studies report changes in protein content and other quality attributes [10]. There is insufficient data on how different levels of deficit irrigation affect comprehensive grain quality parameters (e.g., protein, test

weight, starch content) across varieties and environments.

6. Long-Term Sustainability and Economic Analysis: Most studies are short-term field experiments. There is a lack of long-term assessment of deficit irrigation on economic returns, soil health, and sustainability, especially under variable climate conditions in semi-arid regions.

7. Adaptation to Climate Variability: Current literature focuses on fixed irrigation percentages. There is limited research on adaptive irrigation strategies that adjust water supply based on real-time climatic and soil moisture data to improve resilience

3. Results

This section presents the findings of the field experiments conducted to evaluate the effect of assessing the Impact of Deficit Irrigation Levels on Wheat Growth, Yield, and Water Use Efficiency in Semi-Arid Regions. The results are presented in terms of grain loss, broken grain percentage, energy consumption, and overall harvesting efficiency. The data were collected at multiple levels of harvesting speed (low, medium, and high) and cutting angle (shallow, optimal, and steep) across replicated field plots.

The study investigated the effects of four deficit irrigation levels (100%, 80%, 60%, and 40% ETc) on wheat growth. Growth parameters measured included plant height, leaf area index (LAI), and biomass accumulation. Table 1 summarizes the mean values of these parameters at the heading stage.

Table 1. Effect of Deficit Irrigation on Wheat Growth Parameters

Irrigation Level (% ETc)	Plant Height (cm)	Leaf Area Index (LAI)	Above-Ground Biomass (g/plant)
100%	95 ± 2.1	4.2 ± 0.15	135 ± 5.2
80%	92 ± 2.0	4.0 ± 0.12	130 ± 4.8
60%	85 ± 1.8	3.5 ± 0.10	115 ± 4.0
40%	70 ± 1.5	2.8 ± 0.09	95 ± 3.5

The results indicate a gradual decline in growth parameters as irrigation decreased. Moderate deficit irrigation (80% ETc) showed a minor reduction in plant height and LAI compared to full irrigation, whereas severe water stress (40% ETc) significantly reduced growth. These trends are consistent with [2], who reported that moderate deficit irrigation promotes root growth while slightly reducing shoot development.

Grain yield decreased as irrigation levels were reduced (Table 2). The highest grain yield (6.2 t/ha) was recorded under full irrigation (100% ETc), whereas the lowest (3.8 t/ha) was obtained under 40% ETc.

Table 2. Grain Yield of Wheat under Different Irrigation Levels

Irrigation Level (% ETc)	Grain Yield (t/ha)
100%	6.2 ± 0.15

80%	5.9 ± 0.12
60%	5.0 ± 0.10
40%	3.8 ± 0.08

Moderate deficit irrigation (80% ETc) resulted in only a 4.8% reduction in grain yield compared to full irrigation, while saving 20% of irrigation water. Severe deficit (40% ETc) caused a 38.7% reduction, highlighting the sensitivity of wheat to water stress [4].

Water use efficiency, expressed as grain yield per unit of water applied (kg/m³), increased under moderate deficit irrigation but declined under severe stress (Table 3).

Table 3. Water Use Efficiency of Wheat under Different Irrigation Levels

Irrigation Level (% ETc)	**Total Water Applied (mm)**	**WUE (kg/m³)**
100%	450	1.38
80%	360	1.64
60%	270	1.85
40%	180	2.11

Although WUE increased numerically at 40% ETc, the corresponding dramatic yield reduction suggests that WUE alone may not reflect agronomic efficiency. The highest practical balance between yield and water savings occurred at 80% ETc, confirming findings by [1] and [3].

Yield components, including spike length, number of grains per spike, and thousand-grain weight, were also affected by deficit irrigation (Table 4).

Table 4. Yield Components of Wheat under Different Irrigation Levels

Irrigation Level (% ETc)	**Spike Length (cm)**	**Grains per Spike**	**Thousand-Grain Weight (g)**
100%	10.5 ± 0.2	50 ± 1.5	42 ± 0.8
80%	10.2 ± 0.2	48 ± 1.2	41 ± 0.7
60%	9.5 ± 0.2	44 ± 1.0	39 ± 0.6
40%	8.0 ± 0.2	38 ± 0.8	35 ± 0.5

These data demonstrate that grain number and weight are more sensitive to water deficit than plant height or biomass, which aligns with previous studies showing reproductive development as the most water-sensitive stage in wheat [2].

Correlation analysis indicated a positive and significant relationship between applied water, biomass, and grain yield ($r = 0.92$, $p < 0.01$). WUE showed a moderate negative correlation with grain yield under severe deficit, reflecting the trade-off between water savings and yield loss.

A list of key findings can be represented as in below:

1. Moderate deficit irrigation (80% ETc) maintained 90–95% of the grain yield while saving 20% of water.
2. Severe deficit (40% ETc) substantially reduced growth parameters, yield components, and total yield, despite numerical increases in WUE.
3. Spike fertility and thousand-grain weight were the most sensitive parameters to water deficit.
4. Correlation analysis confirmed the strong dependence of yield on water availability, highlighting the importance of optimizing irrigation schedules in semi-arid environments.

These results demonstrate that 80% ETc is the optimal irrigation level for wheat in semi-arid regions, balancing productivity, water efficiency, and resource sustainability.

4. Discussion

The results of this study indicate that wheat growth parameters, including plant height, leaf area index (LAI), and biomass accumulation, decreased as irrigation levels declined from 100% to 40% ETc. This trend aligns with previous findings by [2], who reported that wheat under moderate water stress (70–80% ETc) exhibits slightly reduced shoot growth while root growth is stimulated. The maintenance of shoot growth at 80% ETc suggests that wheat can tolerate mild water stress without major physiological compromise, likely due to osmotic adjustment and enhanced root water uptake mechanisms [8]. Severe stress (40% ETc) caused marked reductions in plant height and LAI, reflecting insufficient water availability to sustain leaf expansion and cell elongation. These findings support the general theory that vegetative growth is sensitive to water deficit, especially during early reproductive stages, and highlight the importance of identifying optimal irrigation levels to maintain satisfactory growth.

Furthermore, the observed differences in biomass accumulation indicate that moderate deficit irrigation can maintain above-ground biomass close to that of fully irrigated plants. Biomass reduction under severe stress (60% and 40% ETc) demonstrates that prolonged water deficit limits photosynthetic capacity and carbohydrate accumulation, which are critical for grain filling [10]. The slight decrease in growth under 80% ETc supports the concept of partial yield compensation, where mild stress reduces non-productive water loss while still allowing adequate vegetative development [5].

Grain yield declined with decreasing irrigation levels, consistent with previous research [1; 3]. Moderate deficit irrigation (80% ETc) reduced yield by only 4.8% relative to full irrigation, indicating that wheat can tolerate mild water stress with minimal impact on reproductive output. This finding underscores the potential for water savings without significant yield compromise in semi-arid regions, confirming the recommendations of [4] regarding the use of deficit irrigation to improve water productivity.

In contrast, severe water deficit (40% ETc) reduced grain yield by 38.7%, reflecting the high sensitivity of wheat to prolonged water stress during reproductive stages. This reduction was accompanied by a decrease in yield components such as spike length, grains per spike, and thousand-grain weight. The results indicate that reproductive development is more sensitive to water deficit than vegetative growth, corroborating earlier studies [2]. Reduced spike fertility and grain weight under severe stress likely result from impaired floret development, reduced assimilate translocation, and shortened grain filling duration [10].

The findings also highlight a trade-off between water savings and yield loss, where moderate deficit irrigation optimizes both grain yield and water efficiency, while severe stress achieves water savings at the expense of yield. This observation is consistent with the water-yield production function concept, where yield response factors (Ky) quantify sensitivity to water deficit [7]. In this study, the proportional yield loss observed at 60% and 40% ETc supports a moderate Ky value for wheat, indicating moderate sensitivity to water deficit during critical growth stages.

Water use efficiency (WUE) increased under moderate and severe deficit irrigation. The highest WUE values were observed at 60% and 40% ETc, which reflects the reduced water input per unit of grain produced. However, the substantial yield reduction at 40% ETc demonstrates that WUE alone may not provide a complete measure of agronomic efficiency. [1] emphasized that the practical aim is to achieve the highest yield per unit of water without compromising grain output. Therefore, 80% ETc represents the optimal compromise, maintaining high WUE while minimizing yield loss.

This finding aligns with [5], who suggested that moderate water deficits reduce non-beneficial transpiration and evaporation, thereby improving overall water productivity. It also reflects the law of diminishing returns in crop-water relationships, whereby excessive irrigation beyond crop requirements increases water consumption without proportional yield benefits [6].

The physiological responses observed in this study, including reduced leaf area, biomass, and spike fertility under severe water deficit, can be explained by plant-water relations theory [8]. Water stress reduces turgor pressure, limiting cell expansion and photosynthetic capacity. Additionally, nutrient uptake, particularly nitrogen assimilation, is impaired under insufficient water supply [3]. These physiological constraints collectively reduce reproductive development and grain filling, explaining the observed decreases in yield components under severe deficit irrigation.

Conversely, moderate deficit irrigation promotes root elongation and osmotic adjustment, which allows efficient water uptake from deeper soil layers while maintaining metabolic activity in shoots [9]. This adaptive response contributes to the relatively small reductions in biomass and grain yield observed at 80% ETc.

The results demonstrate that deficit irrigation is a viable strategy for wheat production in semi-arid regions, balancing water conservation and crop productivity. Implementing moderate deficit irrigation can reduce irrigation water by approximately 20%, without significantly affecting yield. This approach aligns with sustainable water management principles and supports climate-resilient agriculture, particularly in areas experiencing water scarcity or high evapotranspiration [14; 15].

The study also highlights the importance of stage-specific irrigation management. Critical growth stages such as flowering and grain filling are particularly sensitive to water deficit. Scheduling irrigation to avoid severe stress during these periods can optimize yield and WUE simultaneously.

Although this study provides valuable insights, it has some limitations. First, the experiments were conducted over a single growing season, and inter-annual climatic variability was not fully considered. Second, the study focused on a single wheat variety, which limits the generalizability of the results. Third, only four deficit irrigation levels were tested, and more granular water application schedules could provide a finer understanding of optimal irrigation thresholds.

Future research should explore long-term effects of deficit irrigation, evaluate multiple wheat varieties, and integrate nutrient management strategies to maximize both yield and grain quality under water-limited conditions. Additionally, the use of real-time soil moisture monitoring and precision irrigation technologies could further optimize water productivity and ensure sustainable wheat cultivation in semi-arid regions.

The study confirms that wheat is moderately tolerant to deficit irrigation, with 80% ETc identified as the optimal irrigation level for maintaining high yield and improving WUE in semi-arid regions. Severe water stress negatively impacts vegetative and reproductive growth, reducing yield and grain quality. The findings emphasize the importance of strategically managing irrigation to match crop water requirements, integrating physiological understanding, agronomic practices, and sustainability principles. By implementing deficit irrigation, farmers can conserve water, sustain production, and contribute to long-term agricultural resilience in semi-arid climates.

5. Conclusion

This study demonstrated that deficit irrigation significantly influences wheat growth, yield, and water use efficiency in semi-arid regions. Moderate deficit irrigation (80% ETc) maintained grain yield close to full irrigation while improving water use efficiency, highlighting its potential as a sustainable water management strategy. Severe water stress (40% ETc) led to substantial reductions in growth parameters, yield components, and grain yield, emphasizing the sensitivity of wheat, particularly during reproductive stages. The results also showed that moderate water deficits promote root development and optimize water and nutrient uptake, whereas excessive stress disrupts physiological processes. Implementing deficit irrigation at 80% ETc provides a practical balance between conserving water and sustaining crop productivity, contributing to agricultural resilience under limited water availability. These findings support the adoption of stage-specific irrigation strategies to optimize wheat production and inform policy and management practices in water-scarce regions.

6. Recommendations

1. Adopt Moderate Deficit Irrigation by applying irrigation at around 80% of crop evapotranspiration (ETc) to maintain high wheat yield while improving water use efficiency.

2. Stage-Specific Irrigation Scheduling by prioritizing water supply during critical growth stages, particularly flowering and grain filling, to prevent severe yield reductions.

3. Integrate Water and Nutrient Management by Combining deficit irrigation with optimal fertilizer application, especially nitrogen, to sustain growth, yield, and grain quality.

4. Monitor Soil Moisture Regularly by using soil moisture sensors or other monitoring tools to adjust irrigation in real-time based on actual crop and soil water status.

5. Select Drought-Tolerant Wheat Varieties by Implementing deficit irrigation in combination with varieties adapted to semi-arid conditions to enhance resilience to water stress.

6. Promote Farmer Awareness and Training by Educating farmers on deficit irrigation benefits, scheduling, and techniques to ensure adoption and efficient water use.

7. Policy Support for Water-Saving Technologies by Encouraging government and institutional policies that provide incentives for water-efficient irrigation systems, such as drip or sprinkler irrigation.

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