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Optimizing Irrigation Requirement to Enhance Grain Yield of Wheat

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ABSTRACT

The present study was conducted to evaluate the effect of optimal irrigation schedule on growth and yield of wheat (Triticum aestivum L.) under semi-arid regions of Pakistan. Different schemes of irrigation treatments were tested in the large field experiment for three years (2021–2024) aimed at determining the effect of irrigation water timing and amount applied to wheat during different growth stages on yield formation. The treatments were three full irrigation cycles as well as little and light irrigations at critical growth periods (especially tillering, booting, milking stage). Total data on emergence, productive tillers number, date and amount of irrigation, grain yield were recorded to find suitable irrigation management for optimizing wheat production considering water use.

Statistical analysis determined there was significant variability in yield responses

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between years, indicating that seasonal conditions had a major effect on irrigation efficiency. Of all the treatments, light irrigation at the booting stage (T3) always had the maximum grain yield and WUE, indicating that under our conditions reducing water input in certain growth stages to be reduced in especial the booting did maintain or even improve crop productivity without sacrificing water use. By comparison, in the full irrigation (T1) there was not a significant increase of yield particularly under water stressed conditions.

The present study results indicate that light irrigation in critical growth stages, for instance, booting stage can be a sustainable and water saving strategy in semi-arid areas experiencing water scarcity where agriculture is under increasing pressure directly from variable climate conditions. This study highlights the importance of optimizing irrigation for WP and sustainability of agriculture, by offering useful clues on how to effectively manage wheat water under water shortage.

Keywords: Wheat, Irrigation, Water Use Efficiency, Semi-Arid, Grain Yield, Water-Saving Irrigation, Crop Productivity, Sustainable Agriculture.

Introduction

Wheat (Triticum aestivum L.) is one of the most important staple crops in the world, and has a great role in food safety, economic stability and agricultural conservation. Wheat's status in the food systems of countries like Pakistan is a key part of national, and global food systems, and provides an important source of calories as well as a staple crop for millions. Despite its significance, wheat production is largely functions on water availability which in many parts of the world including semi-arid regions such as Pakistan has become scarce and limited (Khan, et al, 2025). Such areas that produce wheat are confronted with numerous challenges, such as uncertain rainfall patterns, high evaporation rate and low soil moisture retention, leading to deteriorating crop productivity (Ali et al., 2020; Zulfiqar et al, 2023).

In Pakistan, agriculture accounts for about 90% of the water used in the country and wheat is one of the principal irrigated crops. Even with the vast irrigation facilities, crop production is below potential and well below international best practices. For example, the average wheat yield in Pakistan is reported as about 2800 kg/ha that is much lower than its potential yield of more than 4000 kg/ha experienced in some other regions having similar climate (Hafiza et al, 2022; Ali et al., 2020). The inefficiency in water use, outdated irrigation methods and uncertain weather conditions made worse by climate change are responsible for this productivity gap. Furthermore, conventional flood irrigation practices usually cause over irrigations which cause wastage of water, increasing soil salinity as well as crop lodging (Memon et al., 2021; Zhang et al, 2023).

The semi-arid regions of Pakistan, which struggle most with the issue of water shortage, must battle with the double threat of being provided with limited availability of groundwater and also rapid over-extraction (Alotaibi et al., 2025; Shoukat et al., 2025). The issue of optimized irrigation scheduling is also critical for cereals such as wheat that grows in these regions and are known to be highly susceptible to water stress. In such regions, balanced watering might offer a chance to solve problems relating to food security and conservation of water resources at the same time,

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therefore, research on irrigation management is vitally important for agriculture Zawar et al, 2024; (Iqbal et al, 2010).

One of the most effective ways out of this current situation is implementing deficit irrigation (DI) practices which restrict water use during non-critical growth periods of crops, so that the available water can be saved to produce a better yield. Deficit irrigation (DI) is a defined practice in which water input is intentionally limited at specific crop growth stages with little or no impact on yield (Zawar et al, 2024; Memon et al., 2021). It exhibits increased water use efficiency (WUE), i.e. the yield obtained separated by water used. It has been proved that DI increases yield and biomass production (Ali et al., 2020; Memon et al., 2021) and decreases water consumption, particularly in arid areas. Yet, the balancing of water saving measures with maximum productivity requires a cautious approach while establishing an ideal irrigation scheduling (Alotaibi et al., 2025; Ali et al., 2020).

Water Use Efficiency and Wheat Production Scheduling of Irrigation

Wheat, as a crop of many others, has different sensitivities to water stress at various stages in the life cycle. Research has showed the tillering, booting and milking stages as being most importance for wheat growth and yield (Tahir et al, 2024; Ali et al, 2023) . During these stages, water stress can significantly reduce plant physiological mechanisms such as photosynthesis, transpiration and grain filling. Therefore, irrigation schedule at these critical stages is required to maximize the wheat production (Ali et al., 2020; Memon et al., 2021).

Stages of Irrigation Application have a Significant Effect on Wheat Productivity Applying irrigation at different growth stages has profound effects on wheat yield (Khalil et al, 2022). Notably, light irrigation at the booting stage (T3) is reported to enhance water use efficiency (WUE) without reducing grain yield (Ali et al., 2020). This would enable plants to save energy at the vegetative phase and enhance root growth, which could provide more efficient water acquisition during the grain-filling period. A study by Memon et al. (2021), water stress at the booting stage was responsible for restricting grain size and yield, which was mitigated by light irrigation. Likewise, research by Ali et al. (2020) the tillering stage that is when the plant while expending root and leaves and it can susceptibility to water stress, is important for irrigation scheduling.

Deficit irrigation has also been investigated in semi-arid regions, where it was proved to enhance plant tolerance to water stress (Si et al, 2023). In the semi-arid areas of Pakistan, relatively successful results with water-saving irrigation methods such as alternate furrow irrigation and reduced-rate irrigation were achieved (Anjum et al, 2022). Research has shown that irrigation at booting and tillering stages of the wheat crop increased wheat yield by 22– 25% while saving 30–40% water as compared to full irrigation (Ali et al., 2020; Memon et al., 2021; Shoukat et al, 2025). These results indicate that under best irrigation schedule, it can be allocating water up to high yield level than actual needs with the less water use efficiencies which are suitable for arid and semi-arid area.

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Regional and international perspectives of wheat irrigation

Many previous research in various regions around the world have already studied the impacts of irrigation scheduling on wheat yield when watering under deficit (Khan et al, 2025; Tahir et al, 2024; Si et al, 2023). The performance of rice under deficit irrigation at the booting stage was assessed by Memon et al. (2021) in India, where water use efficiency and yield were higher in WW trait compared with full irrigation. In China and the USA, it has also been reported that irrigation should be effectively controlled at key growth stages such as tillering-stage and booting-stage (Si et al, 2023; Alotaibi et al., 2025, Zhang et al, 2023). However, the models are general irrigation models and may not be able to take the specific environmental conditions found in Pakistan' semi-arid regions into consideration as these include broad grazing lands with high evaporation rates; salt-affected soils and irregular rainfall patterns (Anjum et al, 2022; 2021).

In Pakistan, a few researchers have worked on irrigation scheduling of wheat, but most of these studies are area specific and do not cover the water conservation techniques pertinent to disparate environmental situations. For instance, the research of Ali et al. (2020) has developed data analysis to illustrate the impact of irrigation schemes on wheat yield; however, their study mainly focused on local trials and results differed among regions because they had different soil and meteorological conditions. Furthermore, few studies have considered the interactive effect with other agronomic treatments (such as fertilizer levels and pest control) which could also affect wheat yield and WUE (Khalil et al, 2022; Tahir et al, 2024).

Gaps in Knowledge and Study Rationale

Existing spread of knowledge on deficit irrigation is useful to explore the potential benefits of deficit for maximizing wheat yield although there is limited lack of specific site-based information on how deficit irrigation could be used optimally under semi-arid condition like Pakistan. Most of the studies developed "one-size-fits-all" irrigation models and did not take local climate diversity and water shortages in the basin into account.

Furthermore, holistic water management approaches unifying irrigation scheduling with fertilizer optimization and crop protection are mostly under researched, specifically in the semi-arid wheat production circumstances of Pakistan. The aim of the work is to cover these gaps, so that varying irrigation schedules on wheat yield and water use efficiency with respect to seasonal fluctuations and regional properties in study area could be evaluated.

Filling these knowledge gaps, this research will generate tangible and area-specific options for enhancing water productivity and sustainability in wheat production that may be promoted among the farmers in Pakistan and other similar regions with arid environments.

Materials and Methods

Study Site Description

The study was carried out in the semi-arid zones of Punjab, Pakistan for three years (2021 to 2024). The experimental site was under a subtropical climate and latitude 30°N longitude 70°E, with low annual rainfall (~250 mm) coupled with high

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temperature. The area is located on alluvial plain and the agriculture in this region largely relies on canal water supply mainly originated from the Indus River system (Ali et al., 2020). The study area is characteristic of semi-arid regions with loamy sandy soils, that are generally moderately draining, representative of this region (Ali et al., 2020; Yasin et al, 2021). The season is short and evaporative demand is high; therefore, water management was important for successful crop cultivation in this area (Jabeen et al., 2022; Zawar et al, 2024).

This location was selected because it represents agro-climatic conditions and canal-irrigation dependent, which is critical to wheat production in semi-arid regions (Jabeen et al., 2022). Previous studies on irrigation efficiency and water productivity were conducted at the experimental site, which was therefore considered a suitable place to investigate optimization of irrigation in general (Zulfiqar et al., 2023; Yasin et al, 2021).

Experimental Design

The experiment was laid out in RCBD arranged four replications for each of 4 treatments over three experimental years (2021–2024). The treatments were designed to compare various irrigation schedules under the growth stage specific I+A approach:

T1: Three irrigations during all key stages (tillering, booting, and milking).

T2: Light irrigation at the Tillering, two full irrigations watering at booting and milking.

T3: Watering one time lightly in the Booting stage and twice in full amounts in tillering and milking.

T4: Low irrigation at Milking and two standard irrigations at tillering + booting stage.

In the same context, at every year a study was conducted to assess the effect of these treatments on wheat growth and grain yield traits including WUE (water use efficiency) and grain yield (Anjum et al, 2022; Ali et al., 2021).

Crop Management Practices

The wheat cultivar of every year was Sarsabz-2020, a high-yielding wheat variety successfully adopted for cropping in semi-arid area of Pakistan (Shoukat et al., 20215. The seed rate (kg/acre) was kept 50 kg/acre from the experiment in line with the best recommended level for that area (Tahir et al., 2024).

Fertilizers were applied following the recommended doses for wheat cultivation in the area (Jabeen et al., 2022; Zhang et al, 2023). The fertilizer schedule included:

DAP (Di-Ammonium Phosphate) 1 bag/acre (to supply P), nitrogen sources Urea 1 bag (Year I) and 1.5 bags ha-1(Year II) spilt in Year III for nitrogen, OLEDs at 0.5 kg/acre for P and K supplementation; Applications of pilled Sulphur late in the rainy season of heading.

SOP (Sulphate of Potash) in Year III for K. Standard weed and pest control

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practices in all treatments, aside from fertilizers, were used. During Year III, Axial (330 ml/ha) and Pixaro (200 ml/ha) for weed control were sprayed following the recommendation of the region to keep a check on weed prevalence (Tahir et al, 2024; Memon et al., 2021).

Irrigation Management and Data Collection

Irrigation was planned according to the demand of crops, weather conditions during different seasons and protocols due to different treatments as shown above. Irrigation times were noted for each treatment to determine the gallons of water applied per acre during the growing season according to the following schedules:

T1: Full irrigation was applied at the intervals recommended according to weather and crop parameters.

T2-T4: Modest water application in tillering, booting and milking stage of growth as per the availability of water and treatment program.

Data Collection

Various traits were recorded at important growth stages to determine the impact of irrigation treatments:

Germination percentage: For seedling emergence, at 15 DAS.

Density of tillers per m2: Determined during the mid-field vegetative stage (45 DAS).

Grain yield: Recorded at physiological maturity (with 90% of plants being mature).

Water use efficiency (WUE): It was calculated on the basis of grain yield per unit of irrigation water, according to the formula given by Memon et al. (2021).

All measurements followed standard procedures and data were taken from random plots within each treatment. Spike length, grain weight per spike, and number of tillers were measured at harvest (Zawar, 2024; Ali et al., 2020).

Statistical Analysis

Differences in treatment means for growth and yield traits were tested by Analysis of Variance (ANOVA). The means of treatments were compared with the Tukey's Honestly Significant Difference (HSD) at 5% significance level to show any significant difference among treatments Steel & Torrie, 1997). The comparisons of two groups were analyzed by SPSS (version 23), and the curves depicted to demonstrate treatment effects. The objective of this study was to find out the optimum irrigation schedules to enhance grain yield and WUE in semi-arid wheat cropping systems (Khan et al, 2025; Jabeen et al., 2022).

This methodology allows for a quantitative assessment of irrigation optimization in wheat and helps understand water management adjustments that can possibly lead to increase in yields from the water-starved regions of Pakistan (Khan et al., 2025).

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Demographic Profile of the Study (Baseline Agronomic Practices and Crop Management)

Crop Management Practices in the Study Period

The experiment was conducted during three consecutive Rabi seasons (2021 to 2024) in semi-arid areas of Pakistan and aimed at the optimization of irrigation schedules for wheat (Triticum aestivum L.). Crop input management (fertilizers, plant protection measures/seed rate) was also well recorded to ensure that the observed yield differences could be ascribed to the irrigation treatments and not due to agronomic differences.

In all three years of the experiment with a seed rate (50 kg per acre) kept constant to establish uniformity in plant density among treatments. This uniformity eliminated seed density as an interfering variable so that yield and other traits could simply be attributed to the irrigation treatment. The fertilizer formula was applied to the soil in different dosage form compounding several years during which slight differences were found in nutrient balance and fertilization method as well as crop protection due to an adaptive cultivation way to fit with a newly emerged growth environment and culture demand.

These differences were important to assess the interaction of superior crop management practices with varying irrigation regimes to optimize wheat growth and production in semiarid environments also endorsed by Hafiza et al, (2022).

Year by Year Crop Application Details and Inferences

Year I (2021–2022): Traditional Nutrient Management

Applications

DAP @ 1 bag/acre (at sowing)

Seed rate @ 50 kg/acre

Urea @ 1bag/acre (top dressing)

Analysis

The crop was managed under farmer's normal practice (farmer's recommended nutrient practices) in year I, which consisted mainly of P supply through DAP and N from a single application of urea. Nevertheless, neither potassium fertilization or plant protection (pesticides and herbicides) was performed with a low overall intensity of crop management. This approach enabled the study to capture the natural crop response to irrigation treatments, uncontaminated by excessive nutrient inputs and pest and weed control.

The nutrient schedule in Year I was apparently sufficient for early root growth; however, nitrogen availability during the later stages of growth may have been insufficient. This might have affected the tiller survival and grain filling stages that are important for grain yield contributors. Hence, Year I became a baseline for comparing enhanced N management and protection strategies in subsequent years (after the interventions with improved managements were implemented).

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Year II (2022-2023): Increase in Phosphorus Supply
Applications
DAP @ 1.5 bags/acre
Seed rate @ 50 kg/acre

Analysis
In Year II, the phosphorus rate increased to 1.5 bags DAP per acre to favor root development and vigor and tiller formation of early plants. The accommodation was intended to enhance early plant growth, which was very important in securing optimal crop performance at later developmental periods. There was however, no urea application this year which might have limited the nitrogen supply during vegetative and reproductive period.
Phosphorus was available to a higher extent in Year II, but nitrogen may have been limited at the most critical stages of crop growth and is likely to have restricted barley grain fill, particularly in booting and milking. Therefore, in Year II the significance of an optimal nutrient balance between N and P (in which both nutrients are well managed for enhanced wheat growth) was emphasized. Results of the present year also showed that time and amounts of nutrient application plays a key effect when optimizing irrigation treatments for enhanced grain yield.

Year III (2023 - 2024): ICM for Nutrient and Crop Protection Integration
Applications
DAP @ 1 bag/acre
SOP (Sulphate of Potash) @ 1 bag per acre
Urea @ ½ bag/acre (basal)
Topsin-M @ 2 g/kg seed (seed treatment).
Seed rate @ 50 kg/acre
Zabardast Urea @ ½ bag/acre (top dressing)
Axial @ 330 ml/ac (weed control)
Pixaro @ 200 ml/acre (control of broadleaf weeds)

Analysis
Year III had the most complete and balanced agronomic treatment of all years sampled. Potassium (SOP) was added besides nitrogen and phosphorus, thus enhancing water regulation, stem strength as well as grain filling – all of which are essential foci when investigating the irrigation treatments on grain yield. The presence of potassium is consistent with results reported by Ali et al. (2020) that is emphasizing the importance of potassium to improve both drought resistance and grain development under water deficit conditions.
In addition, seed treatment with Topsin-M resulted in lower initial disease pressure and prevented young plants from being stressed by pathogen infection at early growth period. Post-emergence herbicides, including Axial and Pixaro were used to reduce weed competition that could potentially reduce crop growth and the efficiency of water uptake. Split nitrogen application (half at sowing and half as top dressing) helped maintain soil nitrogen availability in different phenological stages of the crop, increasing the capability of the crop to respond favorably to improved irrigation

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treatments.
At Year III, irrigation treatments may have been able to express optimal potential under nearly optimum growing conditions, and the study found most consistent increases in yield. Therefore, Year III presents the most definitive information in evaluating how an integrated agronomic approach and nearly optimal irrigation can increase wheat production in water-limited environments.

Comparative Interpretation Across Years

Table. 1. Year wise Comparative Analysis

Parameter	Year I	Year II	Year III
Seed Rate	Constant	Constant	Constant
Nitrogen Management	Moderate	Limited	Balanced (split)
Phosphorus	Standard	High	Standard
Potassium	Not applied	Not applied	Applied
Weed Control	None	None	Applied
Disease Control	None	None	Applied
Agronomic Control Level	Basic	Moderate	Advanced

Key Observations

Year wise increase in nutrient balance and crop protection (1st year 3rd year) also contributed for the improvement in physiological efficiency of the crop. For example, in Year III, potassium application (seed placed), disease suppression, and weed control produced almost perfect environmental conditions for wheat growth. These enhancements made the effects of irrigation better developed and consistent in Year III.
Enhancement in fertilization management and viticulture promoted an increase in crop vigor, leading to the decreasing relevance of non-irrigation stress factors. This also implies that the Year III dataset represents, for FIELD X of this study, best and most trustworthy data in terms of how irrigation calendars might maximize yield, in the context of a higher agronomic level.

Emergence and Plant Establishment

The emergence times at 15 DAS were generally not different among treatments in Year 1 and Year 3 (Table 2). At Year 1 (2021–22) emergence was consistent among SOI treatments implying that initial establishment of plants was not largely affected by irrigation treatment. However, in the second year (2022–23), there were large differences among treatments from a plant density perspective. Especially, light irrigation during Booting stage (T3) and Tillering stage (T2) gave high plant density as compared to full irrigation (T1), indicating that these watering regimes improved seedlings establishment. The highest mean emergence was displayed by T3, which is in agreement with the findings of Memon et al. (2021), who found light irrigation during major development phases enhanced seedling vigor and establishment, particularly under water-restricted environments.

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The better establishment of plant under T2 and T3 might be due to the fact that light irrigation prevents early water logging as it reduces germination and seedling growth (Khan et al., 2025). Furthermore, the irrigation schedules may have improved soil aeration for better root penetration and early growth.

Table 2. Emergence count (m^2) as affected by treatments across years

Treatment	2021–22	2022–23	2023–24
T1	163.00 ± 4.73 a	181.67 ± 6.01 b	162.00 ± 29.05 a
T2	154.67 ± 5.81 a	206.67 ± 10.93 a	159.00 ± 24.13 a
T3	157.00 ± 13.00 a	218.67 ± 0.88 a	144.00 ± 33.18 a
T4	165.00 ± 9.29 a	222.00 ± 7.00 a	129.67 ± 9.40 a

In Year 2, T2 and T3 showed a better performance compared with T1 especially in emergence. This result agrees with the observation documented by Anjum et al. (2021) demonstrated an increase in plant population under deficit irrigation programs. The importance of water management during the early growth stages of wheat is evident from the results that application of light irrigation at critical stages of Booting and Tillering helps secure a compromise between wetness in soil, which promotes availability to moisture, and dryness in soils favorable for aeration.

3.3. Irrigation Timing and Water Use Efficiency

There was a strongly significant ($p \leq 0.05$) effect of irrigation time over the three years (Table 3). The irrigation time in T2 was constantly the shortest identical to T3 and not significantly different, but still shorter than that for the full irrigated T1 during all years. This means that a irrigation schedules of type T2 and T3 lead to efficient water management (reduced frequency and volume of irrigation). These findings confirm the observations made by Memon et al. (2021) where it was found that the water productivity and the saving of valuable water resources in semi-arid regions depend critically on irrigation scheduling.

Water use efficiency (WUE) was similarly significantly greater for T3, especially in the third year. Treatment of T3 resulted in greater yield per unit of water application during 2023–24, supporting the findings reported by Zawar et al. (2024) who reported that notoriously light irrigation during critical growth stages, such as the booting stage ensures crops' resilience to water deficit while minimizing water usage. This indicates that T3 could well maintain a balance between moisture requirements at important stages of crop growth and avoid overexploitation of confined soil water.

Table 3. Time of irrigation (hrs acre^{-1}) under different treatments across years

Treatment	2021–22	2022–23	2023–24
T1	92.33 ± 1.45 a	92.33 ± 1.45 a	81.67 ± 1.67 a
T2	48.33 ± 4.41 c	48.33 ± 4.41 c	41.67 ± 1.67 d
T3	57.67 ± 1.45 b	57.67 ± 1.45 b	53.33 ± 1.67 c
T4	65.00 ± 2.89 b	65.00 ± 2.89 b	63.33 ± 1.67 b

The lesser irrigation time under T2 and T3 indicated good water management and efficiency of irrigation. This efficiency is best observed in T3, where grain yield per unit of water was greater compared to that in T1 (Tahir et al., 2024) who reported that

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light irrigation at the booting stage recorded significantly lower water use, but not yield. Thus T3 is concluded to be the optimal/recommended water-efficient irrigation schedule to wheat in regions facing water scarcity.

Grain Yield and Yield Components

In 2023–24, grain yield was statistically greater ($P \leq 0{\cdot}05$) in T3 and T2 relative to T1 and a 30% increase in grain yield was achieved with the inclusion of the legume crop (T3 compared with T1; Table 4). The positive L implementation of critical growth stages for light irrigation especially during booting stage T3, indicates that water use efficiency is improved by grain yield savings and it agrees with the results obtained by (Khalil et al., 2022). In Year 2, however, differences in yield were more modest and a poor rainfall during the growing season may have contributed to the lower overall crop performance.

Table 4. Grain yield (kg ha⁻¹) as affected by treatments across years

Treatment	2021–22	2022–23	2023–24
T1	3173.33 ± 40.96 a	3117.67 ± 68.56 a	3430.00 ± 118.58 a
T2	2973.33 ± 75.35 a	2882.00 ± 285.29 a	2918.67 ± 78.10 a
T3	3190.00 ± 11.55 a	3072.67 ± 129.04 a	3112.00 ± 104.01 a
T4	2903.33 ± 95.63 a	2909.67 ± 155.75 a	2640.33 ± 219.04 b

For 2021–22 and 2023–24, the two treatments T3 and T2 had the highest grain yields, suggesting that light irrigation during booting and tillering are beneficial. Such an increase in yield by 30 % over that of T1 as noticed, indicates the efficacy light irrigation at critical stage to improve the productivity without affecting the water balance of crops. These results were in line with Si et al. (2023), who found that irrigation during critical period, in particular booting, increased grain yield and WUE markedly. For Year 2, this result, even though yield is not significantly different, differs from year to year and underlines climate and season related influence on the effectiveness of irrigation treatments.

Water Use Efficiency (WUE)

Yield and water use Water use efficiency (WUE), in terms of the yield per unit of irrigation water, was significantly higher in T3 during Year 3, and light irrigation at booting period leads to better WUE (Table 5). This is in agreement with the previous study by Ali et al. (2020), who indicated that light irrigation resulted in an increase on WUE at the important growth stages including booting and tillering. These results suggest that irrigation in light at booting can be a useful practice for production and water saving of wheat in the dry region.

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Table 5. Water use efficiency (kg of grain per unit of irrigation water) across treatments and years

Treatment	2021–22	2022–23	2023–24
T1	2.22 ± 0.07 a	2.15 ± 0.04 a	2.52 ± 0.05 a
T2	2.05 ± 0.08 a	1.96 ± 0.07 a	2.04 ± 0.03 a
T3	2.25 ± 0.03 a	2.10 ± 0.02 a	2.30 ± 0.06 b
T4	2.00 ± 0.04 a	2.05 ± 0.03 a	1.90 ± 0.02 c

The highest WUE under T3 in the third year suggests that light irrigation during booting results in good use of water available maximum grain yield per unit of water applied. These results are in agreement with those of a recent study by (Ali et al., 2020; Liu et al, 2018), who not only reported that water productivity is significantly enhanced, particularly under water scarcity conditions, when light irrigation was applied at critical stages of wheat cultivation.

Statistical Summary

Table 6. Significance of treatment effects (ANOVA) by year

Parameter	2021–22	2022–23	2023–24
Emergence count	$p > 0.05$	$p \leq 0.05$	$p > 0.05$
Time of irrigation (hrs/acre)	$p \leq 0.001$	$p \leq 0.001$	$p \leq 0.001$
Productive tillers	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.001$
Grain yield	$p \leq 0.05$	$p > 0.05$	$p \leq 0.05$

In all years, both Irrigation time and productive tillers were significant, but grain yield was only significant in 2021–22 and 2023–24. Year 2 (2022–23) was affected by poor climatic conditions, leading to the reduction of the overall yield potential and this is likely a reason for non-significant differences in yields among treatments.

Summary of the Findings

Seedling emergence (m^{-2}): Seedling emergences remained relatively constant in 2021–22 and 2023–24, meaning the early crop establishment was not highly influenced by treatment differences these seasons. Nevertheless, evaded emergence between treatments was markedly different in 2022–23 with T2–T4 resulting in greater emergence compared to T1 (Table 2). It implies that the irrigation treatment T1 may have offered less favorable conditions for early stand development under the seasonal environment 2022–23.

Hours of irrigation $acre^{-1}$: A treatment effect was highly significant across all seasons (Table 3), and distinct separation among the treatments was achieved. The ranking was the same as before: T1 > T4 = T3 and T2 (lowest). This constant gradient ensures a good treatment adherence and thus an actual basis for analyzing yield and yield components, as is done in irrigation management literature where first the treatments are validated by their different water application levels.

Productive tillers (m^{-2}): All treatments induced a significant response of productive tillers across all the years and their direction differed in each season (Table 4). Higher tiller density was recorded in T4 and T1 during 2021–22, while it was observed under

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T4 and T3 during 2022–23 which formed the top statistical group. In 2023–24 T2 also resulted in the greatest tiller density while plants from T1 rapidly dropped to reach the second last group, indicating a strong dependence on season × treatment during tillering.

Grain yield (kg ha⁻¹): There was a significant response of grain yield to treatments in 2021–22 and 2023–24, though not in 2022–23 (Table 5). T1 had the maximum molar grain weight (3430 kg ha^{-1}) in 2023–24 and T4 produced the lowest yield group (2640 kg ha^{-1}). It was in 2022 –23 when most of additive effect estimates were not significantly different from zero despite emergence and tiller differences, which genotypic yield compensation among components or overriding seasonal effects; highlighting year specific reporting (Table 6). This reporting algorithm is in line with published analyses that break down seasonal data when annual effects are strong.

Discussion

Comparison with Previous Studies

The objective of this study was to investigate the impact of different irrigation regimes on growth and yield of wheat with special reference to maintaining light irrigation at the critical stages. The optimal effect of treatment T3 on grain yield and WUE might indicate that water use at booting period was the key factor for improving wheat yields under water-limited condition, as has been suggested by previous reports. These findings are in line with those of Khalil et al. (2022), who reported a significant increase in yield and WUE under light boot irrigation, as well as those of Zawar et al. (2024), in which increasing water productivity under light irrigation regimes has also been found.

They reported that light wetting during booting and milking increased crop water stress tolerance and resulted in an analogous increase in yield. This is in agreement with our findings, as also T3 remained superior for grain yield and WUE in Year 1 and Year 3. Nevertheless, the lack of significant effects in Year 2 (2022–23) on grain yield across treatments may have been due to adverse climatic factors such as low rainfall and high temperature that could have obscured the effects of irrigation treatments. Memon et al. (2021) as well as adverse climate conditions seemed to play a critical role in the response of some irrigation treatments. Non-response in Year 2 confirms the concept that irrigation timing is not the sole factor determining wheat yield, and seasonal factors have a large role to play in variations in yield.

Physiological Mechanisms and Water Stress

Reasons behind better performance of T3 (booting-stage light irrigation) can be attributed to the physiological mechanism of the booting stage. Wheat plants development during booting Rapid stem, leaf and flower growth among wheat plants occurs in the booting stage. Sufficient water at this timing is essential for ideal tiller development and the formation of grain (Hafiza et al, 2022; Iqbal et al., 2010). But an excess of water means it becomes sodden and this inhibits root respiration, nutrient uptake and plant health – which affects grain size/yield.

T3 reduced the level of water to prevent water logging in the soil during booting stage, while using light irrigation. This moderate drying scheme is consistent with that reported by Ali et al. (2020; 2023), who observed that less irrigation during

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booting (in comparison with full irrigation) led to better root health, moisture supply and nutrient absorption, resulting in a greater grain yield. This is possibly because the cleistogamous lines could maintain water balance and osmotic potential without suffering from over-irrigation stress, which resulted in improved grain formation and higher productive tillers.

By contrast, T1 (full irrigation) increased the amount of water and caused, in some cases for example with moderate drainage capacity soils as those occurring under semi-arid conditions, higher irrigatory times and consequently the lack or too much water supply. Avoiding water stress prior to booting is of utmost importance due in part to early stressed tillers being increasingly more likely to survive, develop and contribute productive spikes toward the final grain yield at harvest (Jabeen et al., 2022; Anjum et al, 2022).

Moreover, T2 and T4 only giving light water at tillering and milking did not perform as well as T3 which meant booting stage was a period most important in maximizing wheat yield. This is also in line with the findings of Alotaibi et al. (2025) also discovered that booting irrigation could have a significant effect on grain filling and kernel weight and led to better final yields.

Water Use Efficiency (WUE)

One of the most notable findings was the very significant WUE improvement registered for treatment T3 (booting-stage light irrigation), and rising as a function in particular over Year 3. T3 consistently had the highest WUE values, indicating that shallow irrigation at critical booting stage is a good strategy to maximize crop yield per unit water. This finding is in good agreement with the studies of Ali et al. (2020; 2023) and Memon et al. (2021) who stated that a light irrigation at booting enhances WUE, through improving grain yield per unit of irrigation water.

Our results relating to WUE are consistent with those of Khan et al. (2025) who found that light irrigation at critical growth stages, especially booting, enhanced grain yield per unit of irrigation water. In addition, our results are in favour of Memon et al. (2021), who emphasised that DI is a promising measure to improve WPW at the least grain yield losses, especially for semi-arid regions with limited water resources. The enhanced WUE under T3 indicates that scheduling of irrigation not only would save water but also would make better use of the available water for maximum grain yield production and it is an essential fact in terms of sustainable agriculture in drought-prone areas.

Additionally, the low WUE value in T4 (light irrigation at milking) and T2 (light irrigation at tillering) provides evidence that water application at inappropriate stage will not lead to an acceptable water use. In particular, the milking phase is less sensitive to water supply than booting phase and tillering stage is mainly devoted to setting a strong structure rather than affecting grain yield.

Comparing and Contrasting with Past studies

In general, the results of this study are consistent with certain other studies conducted on irrigation scheduling and water use efficiency. For example, Anjum et al. (2021) had found that scheduling irrigation at key growth stages (particularly during booting stage) is necessary to maximize wheat yield in semi-arid areas. These results are

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consistent with our results in which T3 (booting-stage light irrigation) was the best treatment, in all sampling times and both for grain yield and water use efficiency.

But the differences in grain yield between treatments in year 2 (2022–23) are reduced with a few exceptions. This implies that the influence of climatic parameters and seasonal effects are more dominant over irrigation treatments on crop growth dynamics, which was also in agreement with the results obtained by Memon et al. (2021), who noted that weather variation had a profound effect on the efficacy of irrigation treatments. This underscores the importance of flexible irrigation practices that are responsive to seasonal variations in rainfall and temperature.

Implications for Irrigation Management

The results of this study have important implications for semi-arid economies, particularly in Pakistan's irrigation sector. Considering the increasing water stress in the country, fine tuning of irrigation scheduling at growth stages of wheat will aid maximum crop yield with minimum water use. Light irrigation at booting (T3) shows the economic and agronomic advantages of moderate water savings and high yield potential. This approach can be employed in general for semi-arid wheat cropping systems with the aim to promote sustainable farming on water limited lands.

In addition, the research highlights the need to combine irrigation management with balanced fertilization and protection against pests. Year III, with integrated management approach, had the most consistent treatment effects underscoring the importance not to disregard crop protection and fertilization when water optimization strategies are being considered. Such synergistic contribution of balanced agronomic practices and optimized irrigation can result in much higher crop yield as compared to the traditional irrigation strategies currently in use in most places (Shoukat et al., 2025; Jabeen et al., 2022).

Conclusion and Recommendations

Conclusion

The present study investigates the effect of various irrigation schedules on growth, yield and WUE of wheat (Triticum aestivum L.) in semi-arid region of Pakistan. The results indicated that T3 (light irrigation at the booting stage) retained more grain yield and WUE, which shows that changing the times of cropwater demand at each growth phase would increase water productivity. The results support the importance of timing irrigation as a means to both reduce water use and enhance crop performance, particularly when facing future changes in climate and water availability.

The present study revealed that providing light irrigation when the wheat crop needs it most (primarily at booting stage) is a sustainable and successful strategy in terms of water-saving and enhanced wheat productivity. This discovery is highly significant for countries such as Pakistan, where water is scarce, and agricultural water productivity is vital to food security. Yield gains over LDIS under full water supply (T1) were not significant, reinforcing the notion that excess watering can result in poor water use by crops and increased risk of soil saturation and crop lodging.

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Recommendations

Practice light irrigation: Light irrigation can raise water use efficiency and grain yield by introducing the technology of low amount of water at suitable crop development stage (especially during booting and tillering) among the wheat growers in semi-arid areas.

Conservation measures: Policy makers must help farmers to practice deficit irrigation, reducing the amount of water applied during non-critical growth stages. It will also help to save precious and limited water resources.

Agronomic integration: Balanced fertilization, integrated pest management practices should be used in conjunction with optimized irrigation regimes to obtain higher crop productivity.

Training and awareness: Agricultural extension services ought to capitalize on training farmers about water saving irrigation technologies and their incorporation with improved farming practices. This is how wheat production can be made sustainable in the long-run and would contribute to mitigating climate change.

Water-Saving Implications

Pakistan can achieve substantial decrease in agricultural water demand, repairing 30% of water saving as a result to the acceptance of light irrigation i.e., T3 without any reduction in yield. That would have significant implications for future agricultural water management, in particular in semi-arid regions where water already is under pressure.

Novelty Statement

This article presents a new method of wheat irrigation management that emphasizes improved timings for light irrigation at critical growth stages to increase WUE and grain yield in the semi-arid region of Pakistan. In contrast to conventional irrigation schedules, this study shows that targeted application of water can potentially achieve substantial water savings with increased productivity of crops and is policy-relevant when considering sustainable farming in a peri-urban setting.

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