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Modelling the Impact of Regulated Water Management on Growth and Yield Parameters of Wheat (*Triticum aestivum* L.)

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Author's contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Wheat is one of the most important cereal crops providing food to one fifth of the world population. Wheat cultivation faces numerous challenges, including climate change impacts like heat stress and water scarcity, biotic stresses such as diseases and pest and soil degradation. The food security under limited resources and global climate change has become a major challenge for sustainability. Therefore, the present field investigation was conducted in wheat crop during *rabi* 2021-22 at

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Irrigation and Water Management Farm of Department of Soil Science, CSK HPKV, Palampur to study the effect of regulated deficit irrigation on the growth and yield attributes of wheat (*Triticum aestivum* L.). The treatments consisted of selected combination of four deficit levels *viz.* high (50% ET_C), medium (70% ET_C), low (90% ET_C) and free from deficit (100% ET_C) and three phases of application *viz.* phase I (CRI and jointing), phase II (flowering) and phase III (dough stage). A total of eight combinations *viz.* FFF: Free from deficit at all three phases; LLL: Low deficit at all three phases; MMM: Medium deficit at all three phases; FMM: Free from deficit at phase I, Medium at phase II, Medium at phase III; HFM: High at phase I, Free from deficit at phase II, Medium at phase III; MFH: Medium at phase I, Free from deficit at phase II, High at phase III; MFM: Medium at phase I, Free from deficit at phase II, Medium at phase III; HFH: High at phase I, Free from deficit at phase II and High at phase III, were tested under randomized block design, replicated thrice. The soil of the experimental site was silty clay loam in texture, acidic in reaction, medium in organic carbon, available potassium, high in available phosphorus and low in available nitrogen. Results revealed that among all regulated water deficit schemes the low deficit LLL scheme of 90% ET_C application at CRI and jointing, flowering and dough stage resulted in higher plant height (105.4 cm), higher dry matter accumulation (763.1 gm^{-2}), more no. of tillers per meter square (236.4), more no. of ears per meter square (224.0), more no. of grains per ear (38.3), higher 1000 grain weight (42.6 g), higher grain yield (3129 kg ha^{-1}), higher straw yield (4558 kg ha^{-1}), higher values of biological yield (7687 kg ha^{-1}) and harvest index (40.8) that was statistically similar to the wheat cultivation under water deficit free condition at all critical stages of growth (FFF) having values (107.0 cm, 780.3 gm^{-2}, 242.7, 231.0, 39.5, 43.3 (g), 3320 kg ha^{-1}, 4785 kg ha^{-1}, 8105 kg ha^{-1}, 41.0 g for plant height, dry matter accumulation, no. of tillers per meter square, no. of ears per meter square, no. of grains per ear, 1000 grain weight, grain yield, straw yield, biological yield and harvest index, respectively). Any water deficit below 90% ET_C especially a high deficit of 50% ET_C at phase I (CRI and jointing) and phase III (dough) (HFH) resulted in significant decrease in yield.

Keywords: Organic carbon; wheat cultivation; heat stress; water scarcity; biotic stresses.

1. INTRODUCTION

Wheat (*Triticum* spp.), also known as the "golden grain", is critical to global food security, accounting for 20% of total protein and caloric intake (Salaria et al*.,* 2024a). Over 35% of the world's population relies on wheat as a staple diet. It is the primary source of plant-based protein, with a protein content of around 13%, which is higher than that of most major cereals. (Sharma and Sharma, 2025). Globally, wheat is cultivated on 219 million hectares, producing 808.4 million tonnes (FAOSTAT, 2025). However, climate change and resource constraints now threaten wheat sustainability, with over 50% of global wheat farms exposed to recurring drought stress-an issue expected to intensify due to erratic rainfall and rising temperatures.

In India, wheat is the second most important food crop after rice. The country accounts for 13.33% of global wheat production, covering 30.4 million hectares and producing 107.7 million tonnes with an average productivity of 3.46 t/ha (Salaria et al*.,* 2024b; FAOSTAT, 2025). Despite 95.34% of wheat being grown under irrigation, yields remain lower than global leaders due to factors such as poor seed quality, imbalanced fertilization, and suboptimal water and land management. Terminal heat stress is an emerging concern, further affecting productivity. Scientific studies have advocated decreasing trends of rainfall and increase in maximum and minimum temperatures in mountain state of Himachal Pradesh and increase in temperature has reflected an increase in crop water requirements for future 1, 2, and 3^{o}C rise in temperature compared to present climate (Rana et al*.,* 2012; Rana et al*.,* 2013; Pareek et al*.,* 2021).

Himachal Pradesh, with only 21.8% of wheat area under irrigation, grows wheat on 319.4 thousand hectares area, producing 609.3 thousand tonnes with an average yield of 1.90 t/ha for wheat (Department of Agriculture, 2022-23; Salaria et al*.,* 2024a) which is well below the national average. Rainfed cultivation, limited water resources, and poor crop management are key constraints for wheat-based production systems. Agriculture consumes 70-80% of available freshwater, making water scarcity the most critical limiting factor in crop production. Apart from substantial water demand for wheat, the water supply for crop production has been advocated to be decreased due to changes in climatic conditions in mountains during past three decades (Rana et al*.,* 2014).

A paradigm shift is needed-from maximizing yield per unit area to maximizing yield per unit of water. Changing rainfall patterns, particularly inadequate precipitation during sowing and reproductive stages, combined with terminal heat stress, demand judicious use of stored or conserved water through water-saving techniques. Agronomic practices and field adaptations has the potential to tackle the malign effects of climate change on crop production systems under mountainous regions (Rana et al*.,* 2021). Apart from optimized capturing of solar radiations, soil fertility and soil moisture management can help improve crop productivity levels (Rana and Rana, 2014). Deficit irrigation, involving the application of less water than full crop evapotranspiration (ET) requirements, has emerged as a viable strategy to enhance water use efficiency without significantly compromising yield. It can involve limiting irrigation during less-sensitive growth stages or strategically stressing the crop to induce adaptive responses. Regulated deficit irrigation (RDI) builds on this concept by imposing controlled water stress to enhance root development and improve water uptake.

In Himachal Pradesh, where most wheat is rainfed, evaporation losses are lower due to the *rabi* season. Mild to moderate water stress may not substantially reduce yield, provided irrigation is managed wisely. While traditional methods include skipping irrigation at specific stages or alternate-row irrigation, limited research exists on stage-specific water application based on ET variation. Adopting deficit irrigation approaches tailored to local conditions can optimize water use and improve productivity in water-scarce environments.

2. MATERIALS AND METHODS

A field experiment was conducted during the *rabi* season of 2021-2022 at the Irrigation and Water Management Farm of the Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya (CSK HPKV), Palampur. The experimental site is situated at 32°06′39.1″ N latitude and 76°32′10.5″ E longitude, at an elevation of 1290 meters above mean sea level in the North-Western Himalayas in Himachal Pradesh. The climatic conditions during the crop growth period, from October 2021 to April 2022, indicated that the mean weekly minimum and maximum temperatures ranged from 2.4°C to 16.8°C and 10.8°C to 31.3°C, respectively. Relative humidity during the season ranged between 33.6% and 85.9%.

The soil at the experimental site was classified as silty clay loam with an acidic pH of 5.4, soil organic carbon content of 0.73%, and a bulk density of 1.27 Mg m^{-3}. The available nutrient status of the soil included 270.5 kg ha^{-1} of nitrogen (N), 29.3 kg ha^{-1} of phosphorus (P), and 175.4 kg ha^{-1} of potassium (K).

The experiment was laid out in a Randomized Block Design (RBD) with eight irrigation treatments replicated three times, resulting in a total of 24 plots. The wheat variety HPW 236 was sown on 26th October 2021 with all recommended agronomic practices, except for the irrigation treatments, which were modified as per the experimental design to study regulated deficit irrigation. The eight treatments involved different combinations of water deficit levels applied at three critical growth phases: Phase I (Crown Root Initiation and Jointing), Phase II (Flowering) and Phase III (Dough stage). Water deficit levels included high (50% of crop evapotranspiration, ETc), medium (70% ETc), low (90% ETc) and no deficit (100% ETc). The treatment combinations were as follows: T1 - FFF (no deficit in all phases), T2 - LLL (low deficit throughout), T3 - MMM (medium deficit throughout), T4 - FMM (no deficit at Phase I, medium deficit at Phases II and III), T5 - HFM (high deficit at Phase I, no deficit at Phase II, medium deficit at Phase III), T6 - MFH (medium at Phase I, no deficit at Phase II, high at Phase III), T7 - MFM (medium deficit at Phases I and III, no deficit at Phase II), and T8 - HFH (high deficit at Phases I and III, no deficit at Phase II). These treatments were designed to assess the effects of deficit irrigation on water use efficiency and yield under water-limited conditions typical of rainfed hill agriculture.

Plant height was measured from ground level to the tip of the tallest leaf or spike at periodic intervals using a measuring scale. Fresh plant samples were collected from sampling rows at regular intervals and dried in an oven at 60°C to a constant weight to determine dry matter accumulation.

The yield contributing characters of wheat such as number of tillers per square meter, number of ears per square meter, number of grains per ear and 1000 grain weight were recorded using two rows randomly selected from each plot. The straw, grain and biological yield were following standard procedure. The biological yield was calculated by adding the grain and straw yield observed for each treatment (Rana and Kumar, 2014). Harvest index was worked out by using the formula:

$$\text{Harvest Index} = \frac{\text{Grain Yield (kg ha}^{-1}\text{)}}{\text{Total Biological Yield (kg ha}^{-1}\text{)}} \times 100$$

3. RESULTS AND DISCUSSION

3.1 Effect of Regulated Water Levels on Growth of Wheat

The effect of regulated water levels on various growth parameters of wheat was significant across all observed stages (Table 1). Plant height was highest under full irrigation throughout (FFF: 100% ET_C at CRI & jointing, flowering, and dough stages), followed closely by low water deficit treatment (LLL: 90% ET_C at all stages). In contrast, significantly shorter plants were recorded under severe water deficit regimes (HFH and HFM). The early water deficit restricted internode elongation and node development, reducing plant height. This is consistent with Zhou (2020), who reported reduced height with decreasing water volume. Dry matter accumulation followed a similar pattern. The highest accumulation was observed under FFF, followed by LLL and both were statistically at par. Medium deficits at CRI with recovery irrigation in later phases (MFM and MMM) improved biomass compared to HFH and HFM. High moisture levels during early growth enhance phosphorus solubility and nutrient uptake, contributing to robust growth and photosynthetic activity (Pramanik et al*.,* 2009). Water stress lowered photosynthetic rate and translocation, resulting in reduced dry matter production, which aligned with findings by Zhan-Jiang et al. (2010).

3.2 Effect of Regulated Water Levels on Developmental Parameters of Wheat

Developmental parameters such as days to emergence were not significantly influenced by irrigation regimes (Table 2). However, days to 50% flowering were notably reduced under water-stressed conditions, especially under HFH, HFM, and MMM treatments, indicating early flowering due to drought escape mechanisms (Chaves et al*.,* 2003; Kottmann et al*.,* 2016). The plants exposed to water deficit at CRI and jointing and dough accelerated flowering to complete their life cycle. Conversely, full irrigation (FFF) and mild deficit (LLL) treatments delayed flowering due to better vegetative growth. Days to physiological maturity were also influenced by irrigation. Full irrigation and mild deficit extended crop duration, while high or medium deficits at early and late phases (HFH, HFM, MFH) led to significantly earlier maturity. This early maturity may be a result of stress-induced leaf senescence and decreased vegetative growth, forcing plants to complete their life cycle early (Rehman et al*.,* 2010).

3.3 Effect of Regulated Water Levels on Yield and Yield Attributes of Wheat

Yield components were significantly influenced by irrigation (Table 3). The number of tillers per m², number of ears per m², number of grains per ear were highest under FFF and LLL and lowest were observed under HFH and HFM. HFH and HFM recorded the fewest tillers, attributed to limited root development and nutrient uptake due to early water deficit. Jiang et al. (2020) also reported lower tiller density under water stress. Constant water supply enhanced photosynthetic activity, thus improving ear formation (Moghaddam et al*.,* 2012). The HFH and HFM resulted in significantly fewer grains due to impaired assimilate translocation. The increased grain number in well-irrigated plots can be attributed to higher leaf area, enhanced photosynthetic capacity, and improved nutrient availability (Khanzada et al*.,* 2001).

The highest values of 1000-grain weight were observed in FFF and LLL and lowest were recorded in HFH and MFH, indicating that water scarcity during CRI and jointing and dough stages impedes grain filling. These conditions limit photosynthesis and nutrient translocation, resulting in shrivelled grains (Abhineet et al*.,* 2019). This supports the findings of Moghaddam et al. (2012), who observed a significant reduction in grain weight under deficit irrigation.

Grain yield, straw yield, biological yield and harvest index were found to be highest in FFF and LLL and lowest in HFH and HFM. The FFF regime recorded the highest grain yield (3320 kg/ha), followed closely by LLL (3129 kg/ha), which was statistically similar but slightly lower. HFH and HFM regimes had the lowest yields (1853 kg/ha), suffering upto 44% loss compared to FFF. This confirms CRI as a critical stage for irrigation, as noted by Bauder (2001). Yield losses under HFH and HFM were caused by poor root establishment, limited biomass and insufficient photosynthate for grain filling, leading to early senescence and incomplete development. Medium water deficit in two phases with full irrigation at least once improved straw yield by 39-52% compared to severe stress regimes. Straw production is linked to plant height and dry matter; early water deficit restricts node elongation and limits biomass production. Shivani et al. (2001) reported similar observations. HFH and HFM recorded the lowest biomass yields due to reduced plant height, tillering, and dry matter accumulation. Field studies have advocated that optimized field conditions to help wheat efficiently convert the heat units into the economic yield and

Table 1. Effect of regulated water levels on plant height and dry matter accumulation for wheat

Regulated water levels	Plant height (cm)					Dry matter accumulation (g m^{-2})				
	60 DAS	90 DAS	120 DAS	150 DAS	At harvest	60 DAS	90 DAS	120 DAS	150 DAS	At harvest
T_1 (FFF)	24.7	39.1	71.2	104.7	107.0	99.1	248.3	523.3	748.3	780.3
T_2 (LLL)	23.9	37.6	69.4	102.7	105.4	97.6	243.2	514.6	732.2	763.1
T_3 (MMM)	22.3	34.4	66.6	99.8	100.3	92.3	231.6	491.2	632.2	664.9
T_4 (FMM)	24.5	38.9	71.0	100.4	103.4	99.4	248.0	523.1	686.0	702.6
T_5 (HFM)	20.4	31.9	62.8	96.0	96.7	85.5	213.6	372.4	468.7	489.6
T_6 (MFH)	22.2	34.6	66.2	100.0	101.2	92.0	231.8	490.9	529.6	548.2
T_7 (MFM)	22.1	34.8	66.4	100.3	103.2	92.1	231.1	491.7	712.7	732.0
T_8 (HFH)	20.5	31.8	62.6	95.8	96.5	84.9	212.5	372.6	453.2	472.3
SEm±	0.5	0.7	0.9	1.2	1.1	1.1	2.6	4.4	5.5	6.0
CD (P=0.05)	1.4	2.2	2.7	3.6	3.2	3.3	8.0	13.4	16.8	18.1

Regulated water levels: High (50%), medium (70%), low (90%), free from deficit *(100%) ET_C Stages of deficit irrigation: Phase I (CRI and jointing), Phase II (Flowering), Phase III (Dough)*

**FFF: Free from deficit at all three phases; LLL: Low deficit at all three phases; MMM: Medium deficit at all three phases; FMM: Free from deficit at phase I, Medium at phase II, Medium at phase III; HFM: High at Phase I, Free from deficit at Phase II, Medium at Phase III; MFH: Medium at Phase I, Free from deficit at Phase II, High at Phase III; MFM: Medium at Phase I, Free from deficit at Phase II, Medium at Phase III; HFH: High at Phase I, Free from deficit at Phase II and High at Phase III*

Table 2. Effect of regulated water levels on different phenological phases of wheat

Regulated water levels	Days to emergence	Days to 50% flowering	Days to physiological maturity
T_1 (FFF)	10.2	140.8	167.3
T_2 (LLL)	9.7	139.5	165.5
T_3 (MMM)	10.3	136.2	160.5
T_4 (FMM)	10.4	137.1	162.1
T_5 (HFM)	10.2	133.6	156.3
T_6 (MFH)	10.1	135.2	158.0
T_7 (MFM)	10.0	137.6	163.4
T_8 (HFH)	9.9	131.6	155.3
SEm±	0.3	1.0	1.0
CD (P=0.05)	NS	2.9	2.9

Table 3. Effect of regulated water levels on yield attributes and yield of wheat

Regulated water levels	Number of tillers per meter square	Number of ears per meter square	Number of grains per ear	1000-grain weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)
T_1 (FFF)	242.7	231.0	39.5	43.3	3320	4785	8105	41.0
T_2 (LLL)	236.4	224.0	38.3	42.6	3129	4558	7687	40.8
T_3 (MMM)	214.7	202.7	36.2	40.3	2682	4028	6710	40.0
T_4 (FMM)	219.7	207.7	37.1	41.4	2830	4223	7054	40.2
T_5 (HFM)	204.2	193.3	34.5	40.1	2046	3126	5172	39.6
T_6 (MFH)	210.7	198.3	36.1	39.4	2250	3415	5665	39.8
T_7 (MFM)	226.3	212.4	38.2	41.6	2973	4374	7347	40.5
T_8 (HFH)	199.0	187.9	33.0	38.2	1853	2876	4729	39.3
SEm±	3.0	2.7	0.6	0.4	66	85	148	0.1
CD (P=0.05)	9.0	8.1	1.7	1.4	201	258	448	0.4

biomass (Pathania et al*.,* 2019). A strong linear relationship was observed between irrigation volume and biomass production, aligning with reports by Eissa et al. (2018). The findings under sub temperate agro-climatic conditions in Himachal on rabi season crop, the modified Penman Monteith method using real-time weather data proved to reduce crop water requirement and irrigation schedules without affecting the potato yield. Higher HI under FFF was supported by its superior grain yield performance. These results align with those of Asif et al. (2012), confirming suppressive effects of early and late-stage water deficit on crop partitioning efficiency. The lower HI in severe deficit conditions was due to a higher proportion of straw biomass compared to grain yield.

The full irrigation (FFF) and mild regulated deficit (LLL at 90% ET_C) across all three critical growth stages provided optimal growth, dry matter accumulation, and yield in wheat. Severe water deficit, especially at the CRI stage, caused substantial reductions in all key parameters, emphasizing the importance of adequate irrigation during early growth. Medium regulated deficit strategies showed some recovery in yield but were clearly less effective than FFF and LLL.

4. CONCLUSION

Regulated water application significantly influences wheat growth and yield. Full irrigation (FFF) and mild deficit (LLL) throughout all three phases resulted in optimal plant height, biomass accumulation and yield attributes. Severe deficits, particularly at the early CRI stage, led to reduced vegetative growth, early maturity and lower grain and straw yields. Medium deficit treatments showed partial compensation but could not match the performance either of FFF or LLL. Therefore, ensuring adequate moisture, especially during the CRI and flowering stages, is crucial for maximizing wheat productivity. Strategic irrigation planning, especially targeting CRI and flowering stages, can substantially mitigate yield losses and improve water productivity in wheat production systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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