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Optimizing irrigation schedules to enhance wheat yield and water productivity in semi-arid regions of India

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Abstract

Water scarcity across the semi-arid tracts of Central India no longer operates merely as a periodic limitation; it increasingly defines the operational boundaries within which wheat-based production systems function. Although the annual rainfall may range between 600 and 800 mm, its temporal distribution remains erratic, often misaligned with crop demand. This, coupled with high evaporative demand during the rabi season, accelerates depletion of soil moisture, particularly in lighter-textured and structurally unstable soils. Under such conditions, wheat (*Triticum aestivum* L.; family Poaceae) exhibits marked sensitivity to the timing of irrigation, with critical stages—crown root initiation, flowering, and grain filling—assuming disproportionate importance in determining final yield outcomes. The present investigation sought to examine how method and timing of irrigation, when considered in conjunction rather than isolation, influence productivity and water-use dynamics under semi-arid field conditions. The experiment was laid out in a Randomized Complete Block Design with three replications, comparing three irrigation methods—conventional flood, sprinkler, and drip systems—while scheduling irrigation in accordance with phenological stages instead of adopting rigid calendrical intervals. Such an approach, though conceptually sound, often encounters practical moderation under field realities where operational flexibility is constrained. The analysis indicated statistically discernible variation among treatments ($p < 0.05$). Drip irrigation, by virtue of localized and regulated water delivery, tended to sustain higher grain yields alongside improved water-use efficiency relative to flood irrigation. Sprinkler irrigation occupied an intermediate position, exhibiting relatively stable performance, particularly under conditions of moderate wind drift and uniform field slope. It is worth noting, however, that the magnitude of response was not entirely uniform across replications, suggesting the influence of micro-level soil variability and distributional inequities in applied water. Indices such as water-use efficiency ($WUE = Y/ET_n$) and water productivity ($WP = Y/I$) reflected measurable improvement under controlled irrigation regimes. Yet, these gains appeared contingent upon the degree to which field conditions approximated experimental assumptions. In several instances, slight deviations in soil texture or infiltration characteristics altered the effective root-zone moisture environment, thereby moderating the expected advantage of precision irrigation systems. A consistent pattern, nonetheless, emerged in relation to irrigation timing. Scheduling aligned with critical growth stages imparted greater stability to yield than uniform interval-based irrigation. This observation, while not entirely novel, acquires renewed relevance under increasing climatic variability. At the same time, its translation into farmer practice remains mediated by constraints—availability of irrigation infrastructure, labour scheduling, and, not least, the interpretive understanding of crop phenology at the field level. The findings thus point toward a direction rather than a prescription. While precision irrigation methods, particularly drip systems, demonstrate potential in enhancing both yield and water productivity, their performance remains embedded within a broader matrix of soil conditions, resource access, and management capability. The interplay of these factors suggests that irrigation scheduling, even when scientifically optimized, cannot be viewed in isolation from the variability inherent in semi-arid agro-ecosystems.

Keywords: Wheat (*Triticum aestivum* L.), irrigation scheduling, water-use efficiency, water productivity, drip irrigation, sprinkler irrigation, flood irrigation, semi-arid regions, sustainable agriculture

1. Introduction

Wheat (*Triticum aestivum* L.) occupies a central position in the cereal economy of India, contributing substantially to national food security and forming a major component of the rabi cropping system. Its cultivation extends across diverse agro-ecological regions; however, in the

semi-arid tracts of Central India, productivity is increasingly conditioned by the availability and management of water. Although the region receives an annual rainfall of approximately 600–800 mm, its concentration within the monsoon period limits its direct utility for rabi crops. As a consequence, wheat cultivation in these areas depends largely on residual soil moisture supplemented by irrigation, the adequacy of which often remains uncertain. Under semi-arid conditions, the crop exhibits a pronounced sensitivity to moisture availability at specific phenological stages. The stages of crown root initiation (CRI), flowering, and grain filling are widely recognized as critical, where water deficits tend to exert disproportionate effects on growth and yield formation. Moisture stress at CRI can restrict root development and reduce tillering potential, while stress during flowering may impair pollination and spikelet fertility. Similarly, inadequate moisture during grain filling often limits assimilate translocation, resulting in reduced grain weight. These responses, though physiologically understood, are often accentuated under field conditions characterized by high evaporative demand and variable soil moisture retention. Irrigation, therefore, assumes a central role in stabilizing wheat productivity in such environments. Conventional flood irrigation remains the most commonly practiced method due to its operational simplicity and low initial cost. However, its efficiency is frequently compromised by uneven water distribution, deep percolation losses, and surface runoff, particularly in soils with variable infiltration characteristics. In contrast, micro-irrigation systems such as drip and sprinkler offer the possibility of more precise water application, potentially improving water-use efficiency and crop performance. Yet, their adoption in semi-arid regions remains limited, influenced by factors such as capital investment, maintenance requirements, and variability in field conditions. Beyond the method of irrigation, the timing of water application emerges as a critical determinant of crop response. Crop water requirements vary dynamically with growth stage and atmospheric demand; however, irrigation practices are often governed by external constraints such as water availability, irrigation scheduling systems, and labour considerations rather than crop need. This misalignment between water supply and crop demand can reduce the effectiveness of irrigation, even when total water applied appears adequate.

In recent years, increasing emphasis has been placed on improving water productivity—defined as the yield obtained per unit of water used—rather than solely maximizing yield. This shift reflects growing concerns over water scarcity and the need for sustainable resource management in agriculture. Within this context, integrating efficient irrigation methods with stage-specific scheduling offers a potential pathway for enhancing both yield and water-use efficiency in wheat cultivation.

The present study is undertaken with the objective of evaluating the combined influence of irrigation methods—namely flood, sprinkler, and drip—and irrigation scheduling aligned with critical growth stages on the yield and water productivity of wheat under semi-arid conditions. By examining these factors in conjunction, the study seeks to generate insights that are not only agronomically relevant but also adaptable to the practical constraints of farming systems in water-limited environments.

2. Materials and Methods

2.1 Experimental Site

The field investigation was undertaken at an Agricultural Research Farm located in Madhya Pradesh, Central India, representative of a semi-arid agro-climatic zone. The region is

characterized by an annual rainfall of about 600–800 mm, received predominantly during the southwest monsoon, leaving the winter season relatively dry. During the wheat-growing period (November–March), temperature regimes generally ranged between 25°C and 35°C, accompanied by a relatively high evaporative demand, a factor that often accentuates soil moisture depletion under open-field conditions. The experimental soil was classified as loamy sand with a near-neutral reaction (pH 7.2) and moderate fertility status. Such soils, while conducive to timely field operations, are known for relatively lower water-holding capacity, thereby making irrigation management a critical determinant of crop performance. These conditions provided a reasonably representative framework for evaluating irrigation strategies in wheat (*Triticum aestivum* L.) under moisture-constrained environments.

2.2 Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications, primarily to account for inherent spatial variability in soil properties and micro-environmental conditions. Such a design, while statistically robust, also reflects a practical attempt to minimize unexplained variation often encountered under field situations.

Three irrigation treatments were evaluated:

1. Flood irrigation (conventional practice), applied uniformly at fixed intervals.
2. Drip irrigation, wherein water was delivered directly to the root zone with an attempt to align supply with soil moisture status.
3. Sprinkler irrigation, involving overhead application adjusted in accordance with crop demand.

The comparative assessment of these treatments was intended not merely to examine their individual effects, but to understand their relative performance within a semi-arid production context.

2.2.1 Irrigation Scheduling

Irrigation was scheduled with reference to critical phenological stages of wheat (*Triticum aestivum* L.), namely tillering (30–40 DAS), flowering (60–70 DAS), and grain filling (90–100 DAS). These stages, identified through both physiological understanding and field experience, represent periods of heightened sensitivity to moisture stress.

Soil moisture status was monitored using sensors placed at multiple depths within the root zone. Irrigation decisions were accordingly adjusted in response to observed moisture depletion and prevailing weather conditions. While such monitoring introduces a degree of precision, its effectiveness under field conditions remains contingent upon sensor reliability and interpretation of readings.

2.2.2 Experimental Layout

The experimental area was divided into four blocks, each comprising three plots of 50 m². Treatments were randomly allocated within each block to reduce bias arising from positional effects. A buffer strip of approximately 2 m was maintained between plots to minimize lateral movement of water, particularly important in treatments involving surface irrigation.

Even with such precautions, minor interactions between adjacent plots cannot be entirely ruled out, especially under conditions of variable infiltration and micro-relief.

2.2.3 Data Collection

Observations were recorded at periodic intervals to capture both growth dynamics and final productivity. Soil moisture content was measured at depths of 15, 30, and 45 cm to assess root-zone moisture distribution. Growth parameters included plant height at 30, 60, 90, and 120 days after sowing (DAS), leaf area index at 45, 75, and 105 DAS, and tiller count at corresponding stages. Yield attributes such as number of spikes per m², grains per spike (based on representative sampling), and grain yield at harvest were recorded. Water-use efficiency (WUE) was computed as the ratio of grain yield to the total irrigation water applied, serving as an indicator of treatment-wise water productivity. While such indices provide a useful comparative measure, they do not fully capture losses occurring beyond the measured root zone.

2.3 Crop Management and Field Practices

A widely cultivated high-yielding wheat variety, HD 2967, was selected for the study, given its adaptability to semi-arid conditions. Seeds were treated with Carbendazim 50 WP at 2 g kg⁻¹ to reduce the incidence of seed-borne pathogens. A recommended basal dose of fertilizers was applied, consisting of Urea (100 kg ha⁻¹), Single Super Phosphate (50 kg ha⁻¹), and Muriate of Potash (40 kg ha⁻¹). Nitrogen was applied in split doses at 30 and 60 DAS to synchronize nutrient availability with crop demand. Integrated Pest Management (IPM) practices were followed, including the use of biological control agents such as *Trichogramma* spp., supplemented with need-based application of Imidacloprid and Tebuconazole. Weed management involved pre-emergence application of Pendimethalin (1 kg ha⁻¹), followed by manual weeding at 30 and 60 DAS. In certain instances, post-emergence application of MCPA was undertaken where weed pressure persisted.

2.4 Statistical Analysis

The experimental data were subjected to Analysis of Variance (ANOVA) to evaluate the effect of irrigation treatments on growth parameters, yield attributes, and water-use efficiency. The analytical framework allowed partitioning of total variation into treatment and error components, thereby facilitating interpretation of treatment effects.

$$Y_{ij} = \mu + T_i + B_j + \epsilon_{ij}$$

Where, Y_{ij} represents the observation from the i^{th} treatment in the j^{th} block, μ is the overall mean, T_i is the treatment effect, B_j is the block effect, and ϵ_{ij} is the random error component. Treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$. In addition, regression analysis—both linear and multiple—was employed to examine relationships between water application, yield, and water-use efficiency. Statistical analyses were performed using R (v4.1.2) and IBM SPSS (v26), ensuring computational reliability.

2.5 Limitations and Assumptions

The study was conducted under field conditions where a certain degree of variability is inherent. Despite the use of RCBD, spatial heterogeneity in soil properties and microclimate may have influenced crop response. Operational inefficiencies in

irrigation systems, such as emitter clogging in drip or distribution non-uniformity in sprinkler systems, could not be entirely eliminated. Climatic variability during the cropping season, including unexpected rainfall events or temperature fluctuations, may have interacted with irrigation treatments, particularly during sensitive growth stages. It was assumed that soil moisture sensors provided reasonably accurate readings across depths and that crop management practices remained uniform across treatments. However, minor deviations in field operations are difficult to avoid and may have contributed to experimental variability.

3. Results

The behaviour of wheat (*Triticum aestivum* L.) under varying irrigation regimes revealed a pattern that, while broadly consistent, did not appear entirely insulated from the inherent variability of field conditions. The differences among treatments were statistically significant ($p < 0.05$), yet their expression suggests an interplay between method of water application, soil characteristics, and stage-specific crop demand rather than a single overriding factor.

3.1 Impact of Irrigation Treatments on Grain Yield

Grain yield varied significantly across irrigation treatments, with drip irrigation recording the highest mean yield (5,350 ± 250 kg ha⁻¹), followed by sprinkler irrigation (4,950 ± 230 kg ha⁻¹), while flood irrigation remained comparatively lower (4,200 ± 200 kg ha⁻¹). The magnitude of difference, though clearly distinguishable, does not appear disproportionate; rather, it reflects a steady advantage maintained across replications.

Table 3.1: Grain Yield of Wheat under Different Irrigation Treatments

Replication	Flood (kg ha ⁻¹)	Drip (kg ha ⁻¹)	Sprinkler (kg ha ⁻¹)
1	4180	5400	4890
2	4190	5380	4940
3	4230	5320	4960
4	4250	5330	4950
5	4180	5370	4930
6	4210	5350	4960
7	4250	5390	4950
8	4180	5310	4940
9	4220	5340	4920
10	4240	5360	4970
11	4190	5380	4940
12	4220	5340	4950
Mean ± SE	4200 ± 200	5350 ± 250	4950 ± 230

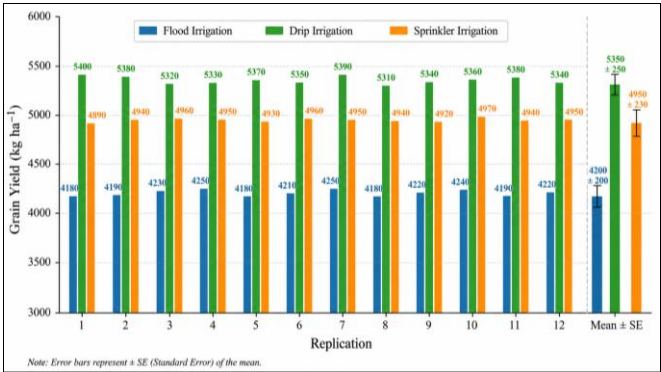


Fig 3.1: Comparative grain yield under different irrigation methods.

The relatively higher yield under drip irrigation may be attributed to more consistent moisture availability within the

root zone, thereby reducing intermittent stress during critical stages. Flood irrigation, on the other hand, appears to have suffered from uneven distribution and non-productive losses, while sprinkler irrigation maintained an intermediate but relatively stable response.

3.2 Water-Use Efficiency (WUE)

Water-use efficiency followed a pattern similar to yield, with significant differences among treatments ($p < 0.05$). Drip irrigation recorded the highest WUE ($3.52 \pm 0.28 \text{ kg m}^{-3}$), followed by sprinkler irrigation ($2.85 \pm 0.26 \text{ kg m}^{-3}$), whereas flood irrigation showed the lowest efficiency ($2.18 \pm 0.18 \text{ kg m}^{-3}$).

Table 3.2: Water-Use Efficiency under Different Irrigation Treatments

Replication	Flood (kg m ⁻³)	Drip (kg m ⁻³)	Sprinkler (kg m ⁻³)
1	2.15	3.55	2.90
2	2.20	3.50	2.85
3	2.18	3.48	2.88
4	2.25	3.53	2.83
5	2.10	3.54	2.80
6	2.22	3.50	2.87
7	2.20	3.55	2.86
8	2.18	3.51	2.85
9	2.23	3.56	2.89
10	2.15	3.50	2.82
11	2.17	3.52	2.84
12	2.20	3.51	2.81
Mean ± SE	2.18 ± 0.18	3.52 ± 0.28	2.85 ± 0.26

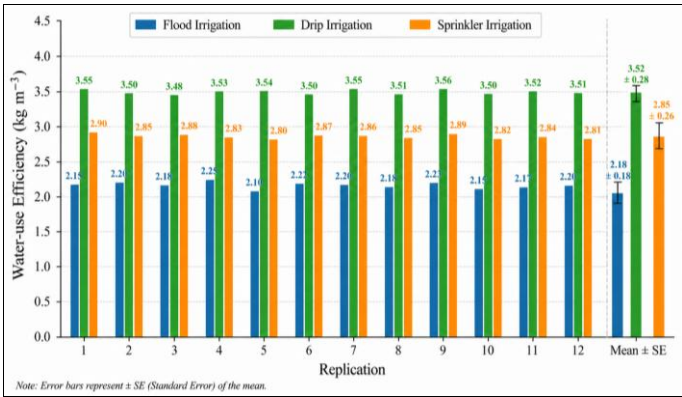


Fig 3.2: Water-use efficiency across irrigation treatments.

The higher WUE under drip irrigation reflects a closer synchronization between water application and crop demand. Yet, the extent of this advantage would likely remain sensitive to system efficiency under actual farm conditions.

3.3 Soil Moisture Content at Critical Growth Stages

Soil moisture content differed significantly across irrigation treatments ($p < 0.05$) at all critical stages—tillering, flowering, and grain filling. Drip irrigation consistently maintained higher and more stable moisture levels, followed by sprinkler irrigation, while flood irrigation showed comparatively lower values.

Table 3.3: Soil Moisture Content (%) at Critical Growth Stages (Condensed mean values)

Stage	Flood (%)	Drip (%)	Sprinkler (%)
Tillering	34 ± 1	52 ± 3	47 ± 2
Flowering	39 ± 1	58 ± 3	53 ± 2
Grain Filling	42 ± 1	60 ± 3	55 ± 2

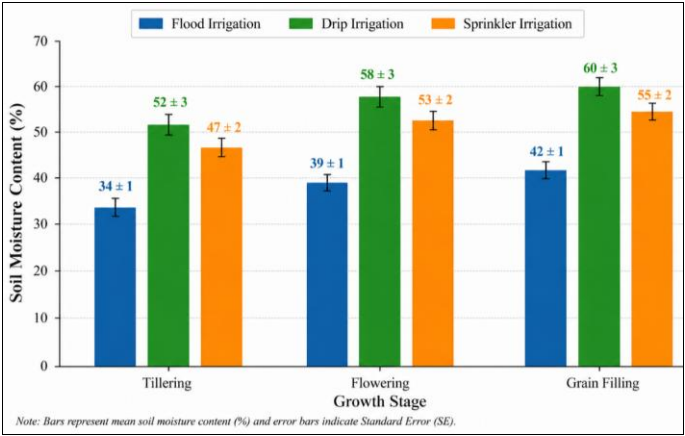


Fig 3.3: Soil moisture trends under different irrigation methods.

The relatively stable moisture regime under drip irrigation appears to have reduced fluctuations during sensitive stages, though the role of soil texture in moderating these effects cannot be overlooked.

3.4 Growth Parameters

Growth parameters exhibited significant differences ($p < 0.05$) across treatments. Drip irrigation produced higher plant height ($110 \pm 5 \text{ cm}$), LAI (4.5 ± 0.5), and tiller density ($\sim 320 \pm 15 \text{ m}^{-2}$), followed by sprinkler and flood irrigation.

Table 3.4: Growth Parameters of Wheat

Parameter	Flood	Drip	Sprinkler
Plant Height (cm)	90 ± 7	110 ± 5	100 ± 6
LAI (m ² m ⁻²)	3.5 ± 0.4	4.5 ± 0.5	4.0 ± 0.4
Tillers (m ⁻²)	250 ± 12	320 ± 15	280 ± 13

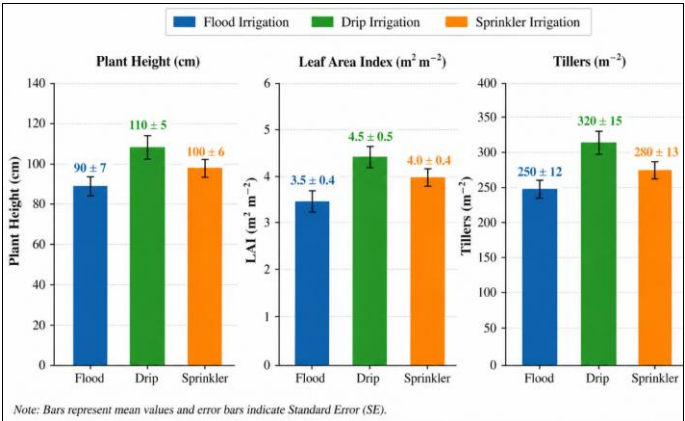


Fig 3.4: Growth parameters under different irrigation treatments.

The enhanced vegetative growth under drip irrigation suggests improved moisture availability, though nutrient interactions and micro-environmental factors likely contributed as well.

3.5 Crop Stress Indicators and Canopy Temperature

Crop stress index (CSI) and canopy temperature differed significantly ($p < 0.05$). Drip irrigation recorded the lowest CSI (0.4 ± 0.1) and canopy temperature ($30 \pm 1.5^\circ\text{C}$), while flood irrigation showed higher values (1.3 ± 0.1 and $35 \pm 1.5^\circ\text{C}$, respectively).

Table 3.5: Crop Stress Indicators

Parameter	Flood	Drip	Sprinkler
CSI	1.3 ± 0.1	0.4 ± 0.1	0.7 ± 0.1
Canopy Temperature (°C)	35 ± 1.5	30 ± 1.5	32 ± 2

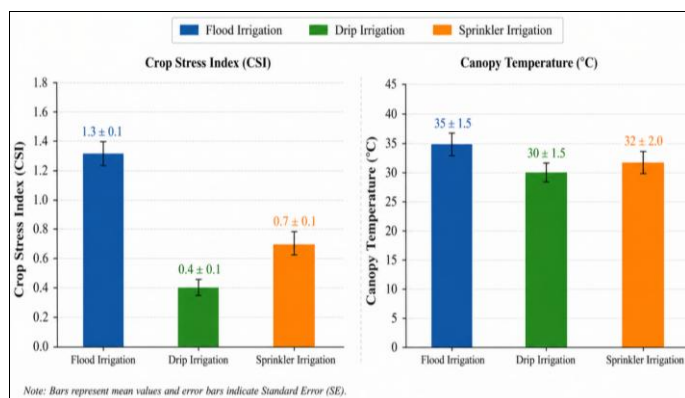


Fig 3.5: Crop stress and canopy temperature under different irrigation methods.

Lower canopy temperature and CSI under drip irrigation indicate improved plant water status. However, such indicators remain sensitive to short-term weather variations, suggesting cautious interpretation under broader field conditions.

The results, taken together, indicate a consistent advantage of drip irrigation across parameters, though the extent of response appears moderated by field variability and operational conditions rather than determined solely by irrigation method.

4. Discussion

The response of wheat (*Triticum aestivum* L.) to irrigation treatments, when viewed across yield, water-use efficiency, and physiological indicators, suggests a pattern that is at once coherent and yet conditioned by the inherent variability of semi-arid production environments. The superiority of drip irrigation, as observed in the present study, aligns with earlier reports emphasizing the role of controlled water application in enhancing crop performance (Feres & Soriano, 2007). Yet, it would be reductive to attribute the observed responses solely to the method of irrigation. The alignment of irrigation with critical phenological stages—particularly crown root initiation, flowering, and grain filling—appears to have exerted an equally important influence, shaping the manner in which water availability translated into growth and yield.

What emerges, therefore, is less a hierarchy of irrigation methods in isolation and more a functional relationship between method and timing. The advantage of drip irrigation, while evident, appears to operate through its ability to maintain a relatively stable root-zone moisture regime, especially during stages where the crop exhibits heightened sensitivity. At the same time, the degree to which this advantage is expressed may depend on field conditions that are not always amenable to precise control.

4.1 Impact of Irrigation Treatments on Wheat Yield

The higher grain yield recorded under drip irrigation (5,350 kg ha⁻¹) relative to sprinkler (4,950 kg ha⁻¹) and flood irrigation (4,200 kg ha⁻¹) suggests a more favourable moisture environment during key growth phases. This response is consistent with the understanding that yield formation in wheat is closely tied to uninterrupted physiological activity during reproductive stages. The localized and regulated water supply under drip irrigation likely minimized intermittent stress, thereby supporting more effective tiller survival and grain development.

However, it may be noted that the yield advantage, while consistent, does not indicate an abrupt divergence among treatments. Sprinkler irrigation, for instance, maintained a

relatively stable performance, possibly due to its ability to distribute water more uniformly than flood irrigation. The comparatively lower yield under flood irrigation appears linked not only to water losses but also to uneven soil moisture distribution, which may have introduced localized stress conditions within the field.

4.2 Water-Use Efficiency (WUE)

The observed differences in water-use efficiency further reinforce the role of irrigation method in determining resource productivity. Drip irrigation recorded the highest WUE (3.52 kg m⁻³), followed by sprinkler (2.85 kg m⁻³) and flood irrigation (2.18 kg m⁻³). These values suggest that the efficiency gains under drip irrigation are not merely a function of reduced water application but also of improved synchronization between water supply and plant uptake.

Under semi-arid conditions, where evaporative demand remains high, the losses associated with surface application methods become more pronounced. Flood irrigation, in particular, appears to incur substantial non-productive losses through evaporation and deep percolation. Sprinkler irrigation mitigates some of these losses through improved distribution, though it remains susceptible to atmospheric influences such as wind drift. Even so, it may be worth considering that WUE, as an index, does not fully capture all dimensions of water dynamics, particularly those related to soil storage and redistribution. The apparent efficiency of drip irrigation, therefore, should be interpreted within the limits of the measurement framework employed.

4.3 Soil Moisture Content at Critical Growth Stages

The maintenance of higher and relatively stable soil moisture under drip irrigation across critical stages—tillering, flowering, and grain filling—appears to have been a central factor influencing crop response. Moisture levels averaging around 52% at tillering and rising to approximately 60% during grain filling under drip irrigation indicate a more sustained availability of water within the root zone.

In contrast, the lower and more variable moisture levels observed under flood irrigation suggest a less predictable soil-water environment. Such variability, particularly during sensitive growth stages, may have contributed to fluctuations in physiological processes, including nutrient uptake and assimilate partitioning.

The results point toward an important distinction: it is not merely the quantity of water applied but its temporal and spatial distribution within the soil profile that determines crop response. This distinction assumes greater significance in soils with lower water-holding capacity, where rapid depletion can occur between irrigation events.

4.4 Growth Parameters

The improvement in growth attributes under drip irrigation—reflected in higher plant height (~110 cm), leaf area index (~4.5 m² m⁻²), and tiller density (~320 m⁻²)—suggests a more favourable vegetative environment. These parameters, while often treated as intermediate indicators, provide insight into the cumulative effect of moisture availability on canopy development and biomass accumulation.

The relatively higher LAI under drip irrigation indicates enhanced photosynthetic surface area, which likely contributed to improved assimilate production. At the same time, increased tiller density suggests better establishment and survival of productive tillers, a factor closely linked with final yield.

Nevertheless, it would be premature to attribute these responses exclusively to irrigation. Nutrient dynamics, soil structure, and microclimatic conditions within the canopy may have interacted with moisture availability to shape growth outcomes. The observed differences, therefore, should be viewed as the result of a combined effect rather than a single controlling factor.

4.5 Crop Stress Indicators and Canopy Temperature

The lower crop stress index (CSI) and canopy temperature recorded under drip irrigation provide a physiological dimension to the observed agronomic responses. A CSI value of approximately 0.4, coupled with canopy temperatures around 30°C, suggests that plants under drip irrigation experienced relatively favourable water status, enabling sustained transpiration and cooling.

In contrast, higher canopy temperatures under flood irrigation (~35°C) indicate periods of relative stress, even where surface moisture may have been present. This apparent paradox reflects the importance of root-zone moisture rather than surface wetting in determining plant water status.

These observations, while indicative, remain sensitive to short-term climatic variations. Temperature fluctuations, wind conditions, and radiation intensity can all influence canopy temperature measurements, necessitating cautious interpretation.

4.6 Implications for Sustainable Agriculture

The findings underscore the importance of refining irrigation practices in semi-arid regions, where water availability increasingly constrains agricultural productivity. Drip irrigation, by enabling precise water delivery, demonstrates clear advantages in terms of yield and water-use efficiency. However, its wider adoption cannot be considered independent of practical considerations.

Economic factors—initial investment, maintenance requirements, and access to technical support—continue to influence farmer decisions. In this context, sprinkler irrigation may offer a compromise between efficiency and feasibility, particularly where resource constraints limit the adoption of drip systems.

More broadly, the results suggest that improvements in irrigation management are unlikely to arise from technology alone. The alignment of irrigation timing with crop phenology, combined with an understanding of local soil and climatic conditions, remains central to achieving sustainable outcomes.

4.7 Limitations and Future Research

The present study, being confined to a single season, captures only a limited range of climatic variability. Inter-annual fluctuations in rainfall, temperature, and evaporative demand may alter the relative performance of irrigation treatments. Long-term studies, spanning multiple seasons, would be necessary to assess the stability of the observed responses.

In addition, the economic viability of drip irrigation, particularly for smallholder farmers, warrants further examination through detailed cost-benefit analyses. The long-term effects of different irrigation methods on soil properties, nutrient dynamics, and pest-disease interactions also remain areas requiring closer investigation.

Future research may benefit from integrating agronomic evaluation with socio-economic considerations, thereby situating irrigation practices within the broader context of farming systems rather than treating them as isolated interventions.

5. Conclusion

The present enquiry, conducted under semi-arid conditions, indicates that the response of wheat (*Triticum aestivum* L.) to irrigation is governed not by method alone, but by the manner in which water application is synchronized with crop demand. Among the treatments evaluated, drip irrigation maintained a consistent advantage, reflected in higher grain yield (5,350 kg ha⁻¹), improved water-use efficiency (3.52 kg m⁻³), and more favourable growth attributes. These responses appear closely associated with the maintenance of a relatively stable moisture regime within the effective root zone, particularly during stages such as crown root initiation, flowering, and grain filling.

Sprinkler irrigation, while not matching the performance of drip, exhibited a degree of uniformity that distinguishes it from conventional flood irrigation. Its intermediate position suggests that improvements in water distribution, even without precise localization, can contribute to better crop response. Flood irrigation, by contrast, remained constrained by uneven application and higher non-productive losses, which, under conditions of limited water availability, assume greater significance.

It would, however, be an overstatement to regard these findings as universally prescriptive. The observed advantages of drip irrigation are contingent upon factors that extend beyond the experimental framework—system maintenance, soil variability, and the capacity to manage irrigation with a certain degree of precision. Under field conditions, where such control is often partial, the magnitude of response may not always align with experimental expectations.

What the results suggest, more cautiously, is that effective irrigation in semi-arid environments depends on two converging considerations: the method of water delivery and its temporal alignment with crop phenology. Where these are brought into reasonable agreement, gains in both productivity and water-use efficiency become attainable. Where they are not, even technically efficient systems may yield only partial benefits.

The question of wider adoption, particularly in the case of drip irrigation, remains tied to economic feasibility and operational practicality. Initial investment, maintenance requirements, and access to technical support continue to influence its uptake among farmers. In such contexts, the choice of irrigation method may be shaped as much by resource constraints as by agronomic considerations.

Thus, the implications of the study lie less in identifying a single superior method and more in underscoring the need for context-sensitive water management strategies—approaches that acknowledge both the biological requirements of the crop and the practical realities within which cultivation is undertaken.

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