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Irrigation Scheduling for Improving Yield and Water Productivity of Chickpea (*Cicer arietinum* L.) Variety BARI Chola-9

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Abstract

Chickpea (*Cicer arietinum* L.) is an important pulse crop in Bangladesh, yet its productivity remains low due to inadequate soil moisture during the Rabi season. Although several high-yielding varieties have been recently released by the Bangladesh Agricultural Research Institute (BARI) but information on irrigation scheduling for those varieties are limited. This study aimed to evaluate the effects of irrigation scheduling on the growth and yield of BARI Chola-9 under field conditions. Field experiments were conducted during 2018 – 2019 at BARI, Gazipur, and at farmer's field in Godagari, Rajshahi, using a randomized complete block design with four replications. Four irrigation treatments were evaluated: T1 (no irrigation, residual soil moisture), T2 (one irrigation after sowing), T3 (one irrigation at pod development stage), and T4 (two irrigations at post-sowing and pod development stages). The soils at both locations were silty clay loam, with field capacity of 28.5–29% and bulk density of 1.44–1.48 g cm^{-3}. Irrigation significantly influenced chickpea productivity. Treatment T3 produced the highest seed yield, which was statistically comparable to T4, whereas T4 resulted in the highest biological and straw yields. Based on seed yield, treatment performance followed the order T3 > T4 > T2 > T1. The results

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indicated that moisture availability during the reproductive stage, particularly at pod development, is critical for maximizing grain yield. These findings suggest that a single irrigation at the pod development stage can optimize chickpea yield while reducing water use and labor requirements, offering a practical and efficient irrigation strategy for moisture-limited environments in Bangladesh.

Keywords: Critical Growth Stages, Irrigation Scheduling, Soil Moisture Regimes, Water Stress, Yield Optimization

Introduction

Chickpea (*Cicer arietinum* L.) is an important pulse crop in Bangladesh. It is primarily cultivated during early Rabi season under residual soil moisture conditions. Cropping patterns that involve chickpea play a critical role to ensure food and nutritional security of the country. It is a relatively low-input crop requiring less labor and external inputs as compared to cereals, making it a suitable choice for resource-constrained farming systems. Globally, chickpea ranks the third most important food legume, cultivated on approximately 15 million hectares with an annual production of about 18 million tons (FAO, 2022–2024; Gurjar et al., 2011). In Bangladesh, chickpea is grown on approximately 4.58 thousand hectares, contributing about 12% of total pulse production, with an annual output of 5 thousand tons (Rezia et al., 2024; BBS, 2017, 2024). Despite its nutritional value, with a protein digestibility-corrected amino acid score of 76% higher than most fruits and vegetables (Sujatha et al., 2007), chickpea production has declined over the past decade in Bangladesh. Consequently, domestic supply meets only a small fraction of national demand, leading to increasing reliance on imports. Chickpea is well adapted to a wide range of soil types, from medium to heavy textured soils. It grows optimally under 400–700 mm of rainfall and temperatures of 24–30°C (Swetha, 2014). The crop possesses a deep taproot system, enabling it to tolerate moderate drought by extracting water from deeper soil layers. In addition, chickpea contributes to soil fertility through biological nitrogen fixation, which can reach up to 140 kg N ha^{-1}, thereby improving soil health and benefiting subsequent crops (Neenu et al., 2017).

In Bangladesh, chickpea is commonly grown in rice-based cropping systems as rice–fallow–chickpea or rice–chickpea–fallow. November to April period is considered optimal for chickpea cultivation, with approximately 60–65% of the crop grown under the rice–fallow–chickpea pattern (Rashid et al., 1999). However, during this period, rainfall is minimal and often insufficient to meet crop evapotranspiration demand. Delayed sowing or inadequate soil moisture can significantly reduce yield, with reported losses ranging from 50% to 80% depending on genotype and stress severity (Leport et al., 1999). Water deficit adversely affects biomass accumulation and seed development as well (Ghassemi-Golezani et al., 1998). Moreover, excessive irrigation beyond optimal soil moisture levels reduces water-use efficiency and grain yield (Hassan & Sarkar, 1999). Chickpea yields in Bangladesh remain low, averaging about 745 kg ha^{-1}, compared to neighboring countries (ICRISAT, 2017).

Maintaining optimal soil moisture at critical growth stages is, therefore, essential for maximizing productivity. Previous studies have shown that irrigated chickpea crops can produce significantly higher biomass and grain yield compared to rainfed conditions (Verghis et al., 1999). Seed yield has been reported to increases with soil moisture availability within a range of 50-90% (Gan et al., 2004), while maximum biological yield is often achieved when irrigation is scheduled at approximately 80% depletion of available soil moisture (Aslam et al., 2010). Although chickpea can utilize residual soil moisture efficiently, reliance on rainfall alone during the Rabi season is insufficient to sustain optimal growth. Consequently, irrigation scheduling becomes a critical management practice for improving yield and water productivity under Bangladesh conditions. However, information on stage-specific irrigation requirements for recently released high-yielding varieties, such as BARI Chola-9, remains limited. The present study aims to investigate the effects of different soil moisture regimes on the growth and yield of chickpea and identify the critical growth stages at which chickpea is the most sensitive to water stress.

Study Area

The field experiment was conducted during Rabi season at two representative agro-ecological locations in Bangladesh: the experimental farm of the Irrigation and Water Management (IWM) Division of the Bangladesh Agricultural Research Institute (BARI), Gazipur, and a farmer's field in Godagari, Barind region, Rajshahi. The Barind region is characterized by low rainfall, high evapotranspiration demand, and limited groundwater availability, making it highly sensitive to water stress. These sites were selected to represent contrasting yet important chickpea-growing environments under moisture-limited conditions. The Gazipur site is located in the central region of Bangladesh, characterized by a subtropical monsoon climate with relatively moderate temperatures and soil moisture retention capacity. In contrast, the Godagari site in the Barind tract of Rajshahi represents a drought-prone environment with comparatively lower soil moisture availability during the Rabi season. The inclusion of these two locations allowed evaluation of irrigation performance under varying soil–water conditions. The soils at both experimental sites were classified as silty clay loam, with field capacity ranging from 28.5 to 29.0% and bulk density between 1.44 and 1.48 g cm^{-3}. These soil characteristics are typical of major chickpea-growing areas in Bangladesh and are suitable for assessing soil moisture dynamics and irrigation response.

The chickpea variety used in this study, BARI Chola-9, was obtained from BARI, Gazipur. A location map of the study sites is presented in Figure 1.

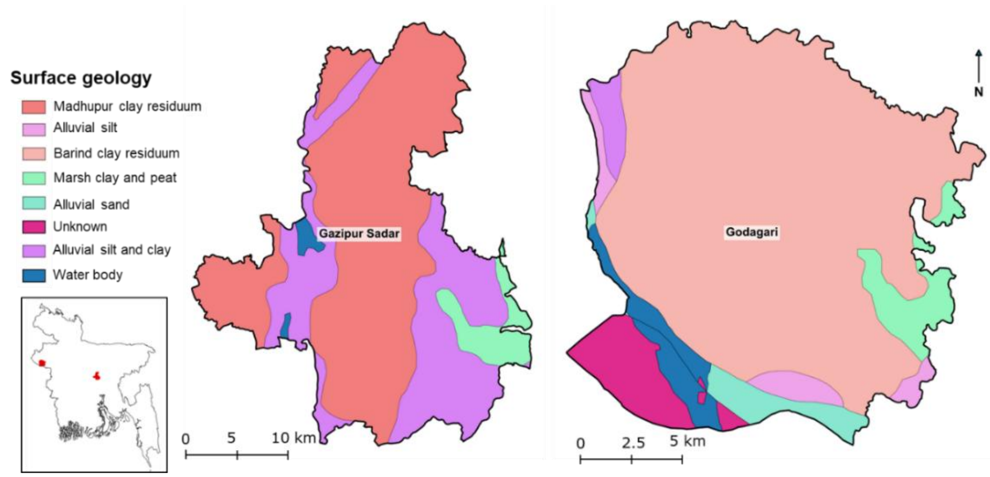

Fig. 1. Surface geology of Gazipur Sadar and Godagari Upazila showing (modified from Uddin et. al., 2026)

Methodology

Experimental design and crop management

The experiment was conducted during the Rabi season of 2018 – 2019. Seed of chickpea (*Cicer arietinum* L.) variety BARI Chola-9, developed by the Bangladesh Agricultural Research Institute (BARI), Gazipur was used. This variety is a high-yielding genotype with a maturity duration of approximately 125–130 days and a reported yield potential of 1.5–2.3 t ha^{-1} (Mia, 2017). Field experiment were established at Godagari in the Barind region of Rajshahi under typical rainfed conditions. The experiment was laid out in a randomized complete block design (RCBD) with four replications. Each experimental plot size was 6 m × 6 m. Seeds were sown at a spacing of 40 cm between rows and 25 cm between plants, ensuring a uniform plant population across treatments. Standard agronomic practices, including land preparation, fertilizer application and weed management, were applied uniformly to all plots in accordance with recommended guidelines for chickpea cultivation in Bangladesh, in order to isolate the effects of irrigation treatments.

Four irrigation treatments were imposed based on crop growth stages:

T1: No irrigation (residual soil moisture only; control)

T2: One irrigation at post-sowing (crop establishment stage)

T3: One irrigation at pod development stage

T4: Two irrigations each at post-sowing and pod development stages

Irrigation treatments were designed to evaluate the effect of timing and frequency of water application on crop performance, particularly under moisture-limited conditions typical of the Rabi season.

Estimation of irrigation water

Irrigation water was applied to restore soil moisture within the effective root zone to field capacity, considering the soil moisture deficit at the time of irrigation. The required depth of irrigation water was calculated following standard soil–water balance principles (Michael, 1985):

$$d = \frac{F_c - M_{ci}}{100} \times A_s \times D \quad \text{......} \quad (1)$$

Where,

d = depth of water applied (cm),

F_c= field capacity moisture content (% by weight);

M_{ci} = soil moisture content at the time of irrigation (% by weight);

A_s = apparent specific gravity of the soil, and

D = effective root zone depth (cm).

The effective root zone depth was assumed based on the typical rooting depth of chickpea during the respective growth stages. This approach ensures that the applied irrigation water replenishes the soil moisture deficit to field capacity within the root zone, thereby minimizing water stress during critical growth stages.

Soil moisture

Soil moisture content was measured at 10-day intervals throughout the crop growth period to assess soil water dynamics under different irrigation treatments. The measured soil moisture data were used to estimate the soil moisture deficit and to determine the amount of irrigation water required to restore soil moisture in the effective root zone to field capacity, as described in Equation (1). Soil samples were collected from three depths intervals (0–10 cm, 10–20 cm, and 20–30 cm) using a hand auger. Sampling was carried out at multiple locations within each treatment plot to obtain representative measurements of soil moisture conditions. Composite samples were used to minimize spatial variability within each plot. Fresh soil samples were immediately weighed and then oven-dried at 105°C for 72 hours to obtain constant dry weight. Soil moisture content on a dry weight basis (%) was calculated using the following equation:

$$W = \frac{M_{WS} - M_{DS}}{M_{DS}} \times 100 \quad \text{......} \quad (2)$$

Where,

W= Soil moisture content, (% by weight),

M_{WS}= mass of moist soil sample (g), and

M_{DS}= mass of oven dry soil sample (g).

This method provides a reliable estimate of soil moisture content and enables accurate determination of irrigation requirements based on soil water deficit within the root zone.

Water use

Total water use (mm) for each treatment was estimated using a simplified soil–water balance approach, accounting for all major sources of water contributing to crop evapotranspiration during the growing period. Water use was calculated as:

Water use (mm) = irrigation water applied (mm) + effective rainfall (mm) + change in soil moisture storage within the effective root zone (mm).

The change in soil moisture storage was determined from periodic soil moisture measurements at different depths (Section 3.4) and represents the soil moisture depletion or contribution over the crop growth period. This approach provides an estimate of the total water available to the crop and is widely used to evaluate water use under different irrigation regimes. Runoff and deep percolation losses were assumed negligible due to controlled field conditions and low rainfall during the Rabi season.

Water productivity

Water productivity (WP) was calculated for each treatment as the ratio of economic yield to total water use during the growing period. It represents the efficiency of water utilization in producing grain yield. Water productivity is widely used as an indicator of resource-use efficiency in irrigated agriculture, particularly under water-limited conditions. It was determined using the following relationship:

$$\text{Water productivity, WP (Kg.m}^{-3}\text{)} = \frac{\text{Economic yield } (t.ha^{-1})}{\text{Water used (mm)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

For consistency of units, total water use measured in millimeters (mm) was converted to cubic meters per hectare (m³ ha⁻¹), where 1 mm of water over 1 hectare is equivalent to 10 m³.

Calculation of reference evapotranspiration (ETo)

Meteorological data, including maximum and minimum air temperature (°C), relative humidity (%), rainfall (mm), wind speed (km h⁻¹), and evaporation (mm day⁻¹), were collected from the Bangladesh Meteorological Department (BMD) and the Gazipur Agricultural University (GAU) meteorological station during the study period. These data were used to estimate atmospheric water demand and to support the calculation of crop water use under different irrigation treatments. Reference evapotranspiration (ETo) was estimated using the Modified Penman equation as described in FAO Irrigation and Drainage Paper No. 24 (FAO, 1977):

$$ET_{\circ} = c\,[W\times R_n + (1-W)\times f(u)\times(e_a - e_d)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where,

$ET_{\circ}$ = reference crop evapotranspiration (mm day^{-1})

e_a = saturation vapor pressure (mbar) at the mean air temperature in °C

e_d = mean actual vapor pressure of the air in (mbar) = $e_a \times \frac{RH_{mean}}{100}$ in which

RH = relative humidity

f(u) = wind related function

(1-W) = temperature and elevation related weighing factor for wind and humidity,

W = temperature and elevation related weighing factor for the effect of radiation,

R_n = Net radiation = $R_{ns} - R_{nl}$

R_{ns} = net incoming shortwave solar radiation = $R_A(1-\propto)(0.25+0.50\times n/N)$

$R_A = Q_A$ or extra-terrestrial radiation, expressed in equivalent evaporation in mm day^{-1}.

n/N= ratio between actual and possible hours of bright sunshine

$\propto$= reflection coefficient

R_{nl}= net long wave radiation= f(t)×f(ed)×f(n/N)

C= adjustment factor to compensate for the effect of day and night weather conditions

Although the FAO-56 Penman–Monteith method is widely recommended, the Modified Penman approach was adopted due to data availability and consistency with local agro-meteorological practices.

Actual evapotranspiration (ETa)

Actual crop evapotranspiration (ETa) was estimated using the crop coefficient (Kc) approach, which relates crop water use to reference evapotranspiration. ETa was calculated as:

$ET_a = K_c \times ET_0$

Where ET_a = actual crop evapotranspiration (mm day^{-1}), Kc = crop coefficient, and ET_0 = reference evapotranspiration (mm day^{-1}) estimated using the Modified Penman equation (Section 3.7).

The K_c values were selected based on standard FAO guidelines for chickpea and adjusted to reflect local climatic conditions. The crop coefficient (K_c) values were assigned according to the phenological growth stages of chickpea, namely: initial stage (20 days), crop development stage (25 days), mid-season stage (35 days), and late-season stage (25 days). These stages represent variations in canopy development and water demand throughout the crop growth cycle.

Economic analysis

Gross return

Gross return was calculated by multiplying the economic yield (t ha^{-1}) by the prevailing market price of chickpea grain during the study period (Perin et al., 1979).

Net return

Net return was estimated as the difference between gross return and the total cost of cultivation:

Net return = Gross return - Cost of cultivation……………………………………. (5)

Benefit-cost ratio (BCR)

The benefit–cost ratio (BCR) was calculated to assess the economic feasibility of different irrigation treatments:

$$\text{BCR} = \frac{\text{Gross returns}}{\text{Cost of cultivation}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design (RBD) to evaluate the effects of irrigation treatments on different parameters. Treatment means were compared using the least significant difference (LSD) test at the 5% level of significance, following the procedure described by Panse and Sukhatme (1978). All analyses were performed using standard statistical software.

Result and Discussion

Straw yield (t ha^{-1})

Irrigation had a significant effect on straw yield at both experimental locations (Table 1). In Gazipur, the highest straw yield was obtained under T4 (2.88 t ha^{-1}), followed by T3 (2.81 t ha^{-1}), both of which were significantly higher than the non-irrigated treatment (T1: 2.38 t ha^{-1}). A similar trend was observed in Rajshahi, where T4 and T3 produced the highest straw yields (2.01 and 1.93 t ha^{-1}, respectively), while T1 resulted in the lowest yield (1.50 t ha^{-1}). The comparatively higher straw yield under T4 suggests that additional irrigation during both establishment and reproductive stages promotes sustained plant growth, leading to greater biomass production. However, the difference between T3 and T4 was statistically non-significant, indicating that a single irrigation at the pod development stage may be sufficient to achieve near-maximum straw yield. Straw yield was consistently lower in Rajshahi than in Gazipur across all treatments, which may be attributed to the relatively drier conditions and lower soil moisture retention capacity in the Barind region. These findings highlight the importance of site-specific moisture conditions in determining crop response to irrigation.

Table 1. Effect of irrigation treatments on seed, straw, and biological yield of chickpea at Gazipur and Rajshahi locations.

Treatment	Seed yield (t ha^{-1})		Straw yield (t ha^{-1})		Biological yield (t ha^{-1})	
	Gazipur	Rajshahi	Gazipur	Rajshahi	Gazipur	Rajshahi
T2 + T3 (T4)	2.33 ab	1.45 a	2.88 a	2.01 a	5.22 a	3.46 a
One irrigation at pod development stage (T3)	2.36 a	1.46 a	2.81 ab	1.93 a	5.17 ab	3.40 a
One irrigation at crop establishment stage (T2)	2.22 ab	1.35 b	2.55 bc	1.67 b	4.76 bc	3.02 b
No irrigation (T1)	2.17 b	1.29 c	2.38 c	1.50 c	4.55 c	2.78 c
CV (%)	4.84	1.97	6.47	5.49	5.51	3.32
LSD (0.05)	0.18	0.04	0.27	0.16	0.43	0.16

**significant difference at α=0.05 (Values followed by different letters within a column differ significantly at the 5% level of probability.)

Similar responses of chickpea biomass to irrigation have been reported under moisture-limited environments, where improved soil water availability enhances vegetative growth (Sharma et al., 2025; Naveed et al., 2024).

Seed yield (t ha^{-1})

Seed yield responded significantly to irrigation treatments at both experimental locations (Table 1). In Gazipur, the highest seed yield was recorded under T3 (2.36 t ha^{-1}), which was statistically comparable to T4 (2.33 t ha^{-1}) and T2 (2.22 t ha^{-1}), but significantly higher than the non-irrigated treatment (T1: 2.17 t ha^{-1}). A similar trend was observed in Rajshahi, where T3 produced the highest seed yield (1.46 t ha^{-1}), followed closely by T4 (1.45 t ha^{-1}), while T1 resulted in the lowest seed yield (1.29 t ha^{-1}). The superior performance of T3 indicates that irrigation at the pod development stage plays a critical role in enhancing grain formation and final yield. Adequate soil moisture during this reproductive phase likely improved assimilate partitioning towards seed development, resulting in higher economic yield. Although T4 provided slightly higher total biomass (Section 4.1), its seed yield was not significantly greater than T3, suggesting that additional irrigation beyond the critical stage may favor vegetative growth rather than grain yield. The consistently lower seed yield in Rajshahi as compared to Gazipur reflects the influence of site-specific environmental conditions, particularly the lower soil moisture availability and higher evapotranspiration demand in the Barind region. These findings highlight that strategic irrigation at critical growth stages is more effective than increasing irrigation frequency for improving chickpea productivity under moisture-limited conditions. Similar responses of chickpea yield to irrigation at reproductive stages have been reported in water-limited environments (Gan et al., 2004; Aslam et al., 2010).

Total biological yield (t ha^{-1})

Irrigation had a significant effect on total biological yield of chickpea at both experimental locations (Table 1). In Gazipur, the highest biological yield was recorded under T4 (5.22 t ha^{-1}), which was significantly higher than the non-irrigated treatment (T1: 4.55 t ha^{-1}). Treatment T3 (5.17 t ha^{-1}) produced a statistically similar yield to T4, while T2 resulted in intermediate biomass production (4.76 t ha^{-1}). A comparable trend was observed in Rajshahi, where the highest biological yields were obtained under T4 (3.46 t ha^{-1}) and T3 (3.40 t ha^{-1}), which were statistically similar. In contrast, the lowest biological yield was recorded under T1 (2.78 t ha^{-1}), indicating a significant reduction in biomass under moisture-limited conditions. The increase in biological yield under irrigated treatments could be attributed to improved soil moisture availability, which enhanced vegetative growth and overall biomass accumulation. The slightly higher biomass under T4 suggests that irrigation at both establishment and reproductive stages supports sustained plant growth throughout the cropping period. However, the absence of a significant difference between T3 and T4 indicates that a single irrigation at the pod development stage is sufficient to achieve near-maximum biological yield. Biological yield was consistently lower in Rajshahi than in Gazipur across all treatments, likely due to comparatively drier climatic conditions and reduced soil moisture availability in the Barind region. This highlights the strong influence of site-specific environmental factors on crop response to irrigation.

From a practical perspective, although T4 produced the highest biological yield, its advantage over T3 was marginal and statistically non-significant. Therefore, T3 may be considered a more efficient irrigation strategy, as it achieves comparable biomass production while reducing water use and labor requirements. These results indicate that while increased irrigation enhances biomass production, the marginal gains decline beyond optimal moisture levels, highlighting the importance of efficient irrigation scheduling.

Soil moisture dynamics and irrigation requirement

Soil moisture dynamics under different irrigation treatments are presented in Figure 2. At Gazipur, soil moisture content ranged from 10.6% to 23.8% during the growing season, reflecting temporal variation in water availability across treatments.

During the early growth stages (up to approximately 40–50 days after sowing, DAS), soil moisture content remained relatively similar across all treatments due to adequate initial soil moisture and low crop water demand. However, as the crop progressed towards the reproductive stage, distinct differences in soil moisture were observed among treatments. The non-irrigated treatment (T1) consistently exhibited the lowest soil moisture levels throughout the season, indicating progressive depletion of soil water under rainfed conditions. In contrast, irrigated treatments (T2, T3, and T4) maintained comparatively higher soil moisture levels, particularly following irrigation events. The effect of irrigation was more pronounced during the pod development stage, where treatments receiving irrigation (T3 and T4) showed improved moisture availability relative to T1. This highlights the importance of timely irrigation in sustaining soil moisture during critical growth stages.

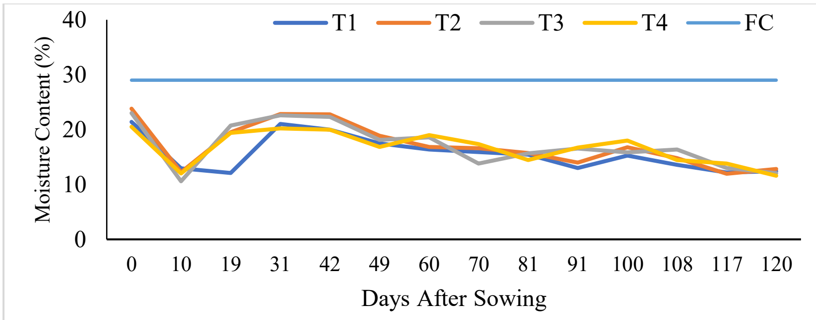

Fig. 2. Temporal variation of soil moisture under different irrigation treatments at Gazipur.

The relationship between soil moisture and crop evapotranspiration is illustrated in Figure 3. At sowing, soil moisture was maintained close to field capacity, ensuring favorable conditions for crop establishment. As the crop developed, evapotranspiration demand increased, leading to gradual depletion of soil moisture, particularly in non-irrigated plots. In irrigated treatments, periodic water application helped to replenish soil moisture and partially meet the evaporative demand.

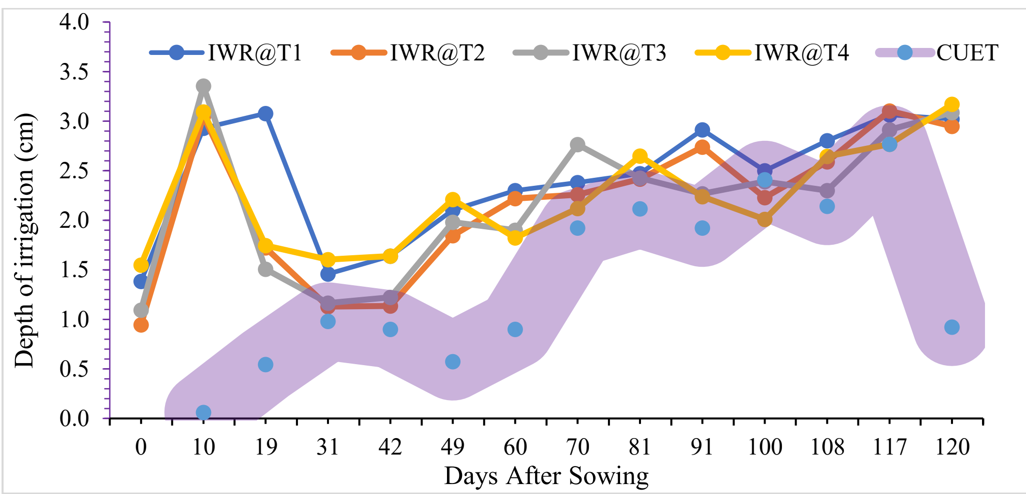

Fig. 3. Relationship between soil moisture and evapotranspiration under different irrigation treatments of chickpea at Gazipur.

Although irrigation improved soil moisture availability, fluctuations in moisture content indicate that the crop likely experienced varying degrees of water stress, particularly under T1 (non-irrigated treatment) and partially under T2 (One irrigation at crop establishment stage). The convergence of soil moisture and evapotranspiration demand during the later growth stages suggests that water availability becomes increasingly limiting toward maturity, which may influence yield formation. These results demonstrate that maintaining adequate soil moisture during the reproductive phase, particularly at pod development, is essential for minimizing water stress and optimizing crop performance. These finding are consistent with the observed yield trends (Sections 4.1–4.3), where treatments receiving irrigation at the reproductive stage (T3 and T4) achieved higher productivity.

Water use and water productivity

Water use and water productivity (WP) varied significantly among irrigation treatments (Table 2). Total water use increased with irrigation frequency, ranging from 57.97 mm in T1 (non-irrigated treatment) to 76.74 mm in T4 (Two irrigations each at post-sowing and pod development stages). Despite the lowest water use, T1 (non-irrigated treatment) recorded the highest WP (3.74 kg m^{-3}), which was statistically comparable to T2 (One irrigation at crop establishment stage) (3.71 kg m^{-3}). This indicated that a single irrigation at post-sowing increased yield (Table 1) without a proportional increase in total water use, thereby maintaining water use efficiency. In contrast, treatments T3 (One irrigation at pod development stage) and T4 (Two irrigations each at post-sowing and pod development stages), although producing higher seed yields, exhibited significantly lower WP values (3.38 and 3.03 kg m^{-3}, respectively). This suggests diminishing returns in water productivity with increasing irrigation, as additional water inputs contributed more to total water use than to proportional yield gains.

Table 2. Water use and water productivity under different irrigation treatments

Treatment	Irrigation (mm)	Effective rainfall (mm)	Soil moisture contribution (mm)	Total water use (mm)	Seed yield (t ha^{-1})	Water productivity (kg m^{-3})
No irrigation (T1)	0	32	9.97	57.97^{d}	2.17^{b}	3.74^{a}
One irrigation at crop establishment stage) T2	9.4	32	2.38	59.78^{c}	2.22^{ab}	3.71^{a}
One irrigation at pod development stage (T3)	15	32	6.75	69.75^{b}	2.36^{a}	3.38^{b}
T2+T3 (T4)	35.5	32	9.24	76.74^{a}	2.33^{ab}	3.03^{c}
CV (%)				0.38	4.84	5.11
LSD				0.39	0.17	0.28
SE				0.17	0.07	0.12
Level of significant				**	**	**

**significant difference at α=0.05

These results highlight a key trade-off between maximizing yield and optimizing water productivity. While T3 (One irrigation at pod development stage) and T4 (Two irrigations each at post-sowing and pod development stages) improved yield through enhanced soil moisture availability during critical growth stages (Sections 4.2–4.4), the associated increase in water use reduced overall efficiency. The findings indicate that increased irrigation does not necessarily lead to higher water productivity, particularly under conditions where water becomes a limiting resource. The observed WP values under irrigated treatments remain higher than those reported in earlier studies for chickpea and similar crops under comparable agro-ecological conditions (Arya et al., 2005; Pal et al., 2007; Pramanik et al., 2009). This suggests that strategic irrigation, rather than increased irrigation frequency, is more effective in balancing yield improvement and water use efficiency. These findings emphasize the importance of optimizing irrigation scheduling rather than maximizing water application to achieve sustainable crop production under water-limited conditions.

Economic analysis

An economic analysis was conducted to evaluate the profitability of different irrigation treatments (Table 3). The results showed that irrigation had a positive impact on economic returns as compared to the non-irrigated treatment (T1) at both locations. The highest benefit–cost ratio (BCR) was obtained under T3 (1.90 in Gazipur and 1.18 in Rajshahi), indicating that a single irrigation at the pod development stage provided the greatest economic return per unit investment. In contrast, the lowest BCR was recorded under T1 (1.79 in Gazipur and 1.05 in Rajshahi), reflecting reduced profitability under rainfed conditions. Although T4 produced slightly higher total biomass and comparable seed yield (Sections 4.2–4.3), its BCR (1.85 in Gazipur and 1.15 in Rajshahi) was lower than that of T3 due to the additional cost of irrigation. Similarly, T2 showed moderate economic performance, with BCR values of 1.81 and 1.10 at Gazipur and Rajshahi, respectively. These results indicate that maximizing yield does not necessarily correspond to maximizing economic return. While treatments with higher irrigation levels (T3 and T4) improved crop productivity, the additional cost associated with irrigation reduced overall profitability. The superior performance of T3 demonstrates that irrigation at the critical pod development stage is sufficient to achieve optimal economic returns without incurring unnecessary input costs. From a practical perspective, T3 can be considered the most efficient and economically viable irrigation strategy, as it balances yield improvement, water use, and production costs. This finding is consistent with the water productivity results (Section 4.5), where moderate irrigation levels provided an optimal trade-off between resource use efficiency and crop yield.

Table 3. Economic analysis of chickpea (BARI Chola-9) under different irrigation treatments

Treatments	Location	Total cost (Tk ha^{-1})	Gross return (Tk ha^{-1})	Gross margin (Tk ha^{-1})	BCR
No irrigation (T1)	Gazipur	60573	108500	47927	1.79
	Rajshahi	60573	64000	3427	1.05
One irrigation at crop establishment stage) T2	Gazipur	61243	111000	49757	1.81
	Rajshahi	61243	67500	6257	1.10
One irrigation at pod development stage (T3)	Gazipur	62039	118000	55961	1.90
	Rajshahi	62039	73500	11461	1.18
T2+T3 (T4)	Gazipur	62967	116500	53533	1.85
	Rajshahi	62967	72500	9533	1.15

These findings emphasize that irrigation scheduling should be optimized not only for yield maximization but also for economic efficiency under water-limited conditions.

Conclusion

The findings of this study demonstrate that irrigation scheduling significantly influences the productivity of chickpea (*Cicer arietinum* L.) variety BARI Chola-9 under moisture-limited conditions. Among the treatments, a single irrigation applied at the pod development stage (T3) resulted in the highest seed yield, which was statistically comparable to two irrigations applied each at post-sowing and pod development stages (T4), while requiring less water and labor input. Although two irrigations applied each at post-sowing and pod development stages (T4) produced the highest biological and straw yields, its advantage in seed yield and economic return was marginal. Based on seed yield performance, the treatments followed the order: T3 > T4 > T2 > T1. The results further indicate that the vegetative and pod development stages are critical for water management, and moisture stress during these stages can significantly reduce yield. Overall, irrigation at the pod development stage is recommended as an efficient and economically viable strategy for optimizing chickpea production in Bangladesh.

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