



RESEARCH ARTICLE

# Impact of irrigation scheduling and biofertilisers on growth, yield and water dynamics in late-sown wheat (*Triticum aestivum* L.)

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## Abstract

The effects of irrigation scheduling and biofertiliser application on growth, yield and water-use dynamics of late-sown wheat (*Triticum aestivum* L.) were evaluated through a field experiment conducted during the rabi season of 2019–20 at Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh. The experiment was laid out in a split-plot design with 3 irrigation schedules in main plots: crown root initiation (CRI) stage only (IR<sub>1</sub>), CRI + late jointing (IR<sub>2</sub>) and CRI + tillering + milking (IR<sub>3</sub>) and 4 seed-inoculated biofertiliser treatments in sub-plots: *Azotobacter* (F<sub>1</sub>), phosphate-solubilising bacteria (PSB) (F<sub>2</sub>), *Azotobacter* + PSB (F<sub>3</sub>) and liquid phosphate (F<sub>4</sub>). Irrigation at (IR<sub>3</sub>) significantly enhanced growth parameters, yield attributes and grain yield compared to limited irrigation schedules. Among biofertilisers, combined inoculation with (F<sub>3</sub>) resulted in superior growth, yield, water-use efficiency and water productivity over individual applications. Therefore, scheduling irrigation at critical growth stages combined with dual biofertiliser inoculation optimises yield and water use efficiency of late-sown wheat under the agro-climatic conditions of central Uttar Pradesh.

**Keywords:** *Azotobacter*; biofertilisers; synergistic effect; water productivity; water use efficiency

## Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and ranks as the second most important staple food crop in India after rice. Globally, India ranks second in both wheat production and cultivated area, following China. India's total wheat production during 2022–23 was 110.55 million tonnes (Mt), with an average productivity of 3.52 tonnes per hectare (t ha<sup>-1</sup>) (1). Uttar Pradesh is the leading wheat-producing state, followed by Madhya Pradesh, Punjab, Haryana, Rajasthan and Bihar.

In the Indo-Gangetic Plains, particularly in Uttar Pradesh, wheat is predominantly cultivated under the rice-wheat cropping system. Due to variations in cropping patterns and agro-climatic conditions, the sowing window extends from early November–early January (2). However, delayed harvesting of long-duration rice varieties, especially aromatic rice with a growth period of 135–150 days, often leads to late sowing of wheat. Excess rainfall, waterlogging, or insufficient soil moisture in rainfed areas further aggravate delays in sowing. Late sowing significantly reduces

emergence rate, tiller formation, grains per spike and overall productivity (3). High temperature exposure during the later growth stages increases respiration and reduces photosynthesis, assimilate translocation and starch synthesis, ultimately lowering yield (4). Reductions in plant height, tiller number, effective tillers, grains per spike and biomass accumulation under delayed sowing has also been reported (5).

Water availability during critical growth stages is another major constraint in late-sown wheat. Moisture stress at early stages leads to poor stand establishment and weak seedling growth (6). Grain yield shows a positive correlation with irrigation frequency (7). Proper irrigation scheduling significantly influences dry matter accumulation, leaf area index, yield attributes and final grain and straw yield (8). Growth parameters such as plant height, tiller density and leaf area index are markedly affected by irrigation timing (9). Missing irrigation at critical stages drastically reduces yield, whereas excessive irrigation may decrease water use efficiency and delay maturity (10).

Along with irrigation, biofertilisers play an important role in sustaining wheat productivity. Biofertilisers enhance nutrient availability through biological nitrogen fixation and phosphorus solubilisation. *Azotobacter* contributes substantially to nitrogen supply in non-leguminous crops, while phosphate solubilising bacteria (PSB) increase phosphorus availability and improve yield. Their combined application may produce synergistic effects. Biofertilisers are cost-effective and environmentally sustainable agricultural inputs (11). Nitrogen-fixing bacteria and vesicular arbuscular mycorrhizae improve nutrient uptake, enhance stress tolerance and promote plant growth (12).

Although the individual effects of irrigation scheduling and biofertilisers have been documented, information on their combined influence under late-sown conditions remains limited. Therefore, the present study was undertaken to evaluate the effects of different irrigation schedules and biofertiliser treatments on the growth, yield and water dynamics of late-sown wheat under the agro-climatic conditions of Uttar Pradesh.

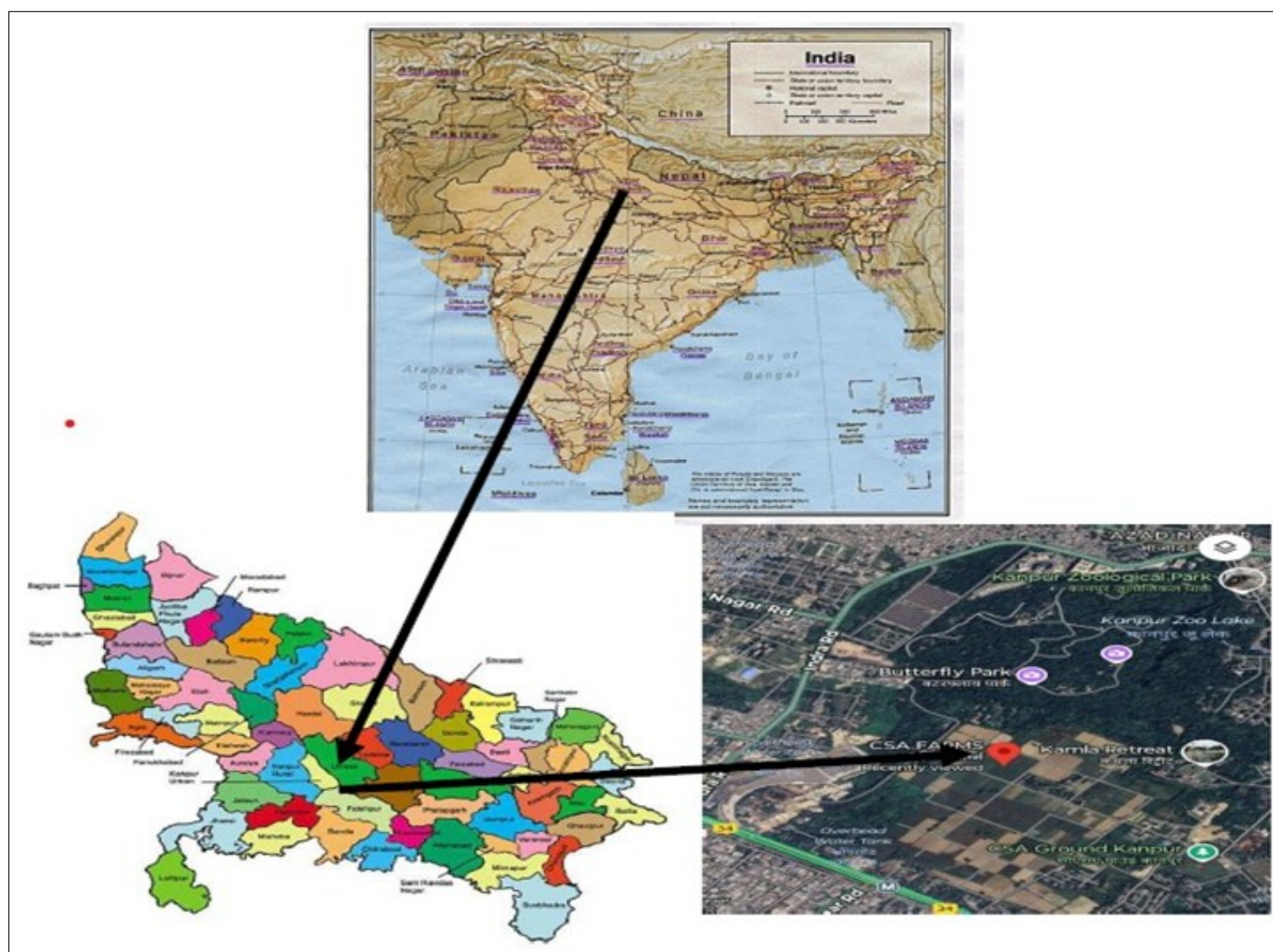
## Materials and Methods

The field experiment was conducted during the rabi season from 17 December 2019–29 April 2020 at the students' instructional farm, Chandra Shekhar Azad University of Agriculture and Technology (CSAUAT), Kanpur, Uttar Pradesh, India (Fig. 1). The experimental site is in the Indo-Gangetic Plains at an elevation of 126.3 m above

mean sea level (25°26'–26°58' N latitude and 79°31'–80°34' E longitude). The soil of the experimental field was sandy loam in texture with a neutral reaction and uniform fertility. Irrigation was provided through a tube well. Initial soil analysis of the experimental site revealed a pH of 8.05, organic carbon of 0.43 %, available nitrogen, phosphorus and potassium of 14534.2 and 235 kg ha<sup>-1</sup> respectively. During the experimental period (December 2019–April 2020), mean maximum temperature ranged from 14.6–36.5 °C, while the mean minimum temperature ranged between 6.3–19.4 °C. Total rainfall was negligible during December and January, with 1.8 mm in February and 36.4 mm in March.

The experiment was laid out in a split-plot design, replicated thrice. Main plot treatments comprised 3 irrigation schedules: IR<sub>1</sub> (irrigation at crown root initiation (CRI)), IR<sub>2</sub> (irrigation at CRI and late jointing stages) and IR<sub>3</sub> (irrigation at CRI, tillering and milking stages). Sub-plot treatments consisted of 4 biofertiliser applications applied through seed inoculation: F<sub>1</sub> (*Azotobacter*), F<sub>2</sub> (PSB), F<sub>3</sub> (*Azotobacter* + PSB) and F<sub>4</sub> (liquid phosphate). Each main plot measured 16 × 4 m and was divided into 4 × 4 m sub-plots. A 1 m buffer space was maintained between sub-plots and 0.5 m borders separated adjacent plots.

Carrier-based *Azotobacter*, PSB and liquid phosphate cultures were obtained from Department of Soil Science, CSAUAT, biofertiliser production unit. *Azotobacter* and PSB were applied as seed treatment at the rate of 25 g kg<sup>-1</sup> seed. The liquid phosphate



**Fig. 1.** Location map and satellite view of the study area.

Source: ArcGIS Pro version 3.6.2 (Esri, Redlands, CA, USA; <https://www.esri.com/arcgis>). The high-resolution satellite imagery was obtained from Google Earth Pro version 7.3 (Google LLC; <https://www.google.com/earth/versions/#earth-pro>).

formulation used in F<sub>4</sub> was applied at 5 mL kg<sup>-1</sup> seed. For seed inoculation, the biofertilisers were first mixed with 10 % jaggery solution as a sticker, uniformly coated on the seeds, shade dried for 30 min and sown immediately.

Wheat was sown on 17 December 2019 using a seed rate of 120 kg ha<sup>-1</sup> with 20 cm row spacing. The recommended fertiliser dose of 150-60-60 kg N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup> was applied through urea, diammonium phosphate (DAP) and muriate of potash (MOP). The full dose of phosphorus and potassium and half of nitrogen were applied as basal at sowing, while the remaining nitrogen was top-dressed in 2 equal splits at CRI and heading stages. Irrigations were applied as per treatment with 6 cm depth of water at each scheduled stage. The crop was harvested on 29 April 2020.

Growth observations were recorded at 60 and 90 days after sowing (DAS) and at harvest. The crop was harvested at physiological maturity and the produce from each net plot was sun-dried, weighed for total biomass and threshed separately. Grain yield was recorded after cleaning and straw yield was calculated by subtracting grain yield from total biological yield. Plot yields were converted into quintals per hectare (q ha<sup>-1</sup>) for statistical analysis.

### Consumptive use of water

Consumptive use of water was worked out from the loss in soil moisture, effective rainfall and potential evapotranspiration for 2 days following irrigation. The seasonal consumptive use was calculated as per standard procedure (13).

$$\sum_i^n (E_o \times 0.8) + (M_1 - M_2) + ER \quad (\text{Eq. 1})$$

Where,

$\Sigma$  = Total seasonal consumptive use (cm)

n = Number of intervals

i = Consumptive use (mm) during given interval

E<sub>o</sub> = Evaporation (mm) from U.S. Weather Bureau Class A pan evaporimeter, during the interval of days from the day of irrigation up to the time of sampling

0.8 = A constant to be used with the evaporimeter

M<sub>1</sub> = Soil moisture in (mm) in root zone 2 days after irrigation

M<sub>2</sub> = Soil moisture in (mm) in root zone before irrigation

ER = Effective rainfall during the interval

### Water use efficiency

Water use efficiency of different treatments was computed by dividing the economic yield (kg ha<sup>-1</sup>) to the total amount of water used (cm) from respective plots.

$$\text{Water use efficiency (kg ha}^{-1} \text{ cm}^{-1}) = \frac{\text{Economic yield (kg ha}^{-1})}{\text{Total consumptive use of water (cm)}} \quad (\text{Eq. 2})$$

### Water productivity

Water productivity (WP) of different treatments was computed by dividing the economic yield (kg ha<sup>-1</sup>) into the amount of irrigation water applied (cm) from respective plots. It is expressed in kg m<sup>-3</sup>.

$$\text{Water productivity (kg m}^{-3}) = \frac{\text{Economic yield (kg ha}^{-1})}{\text{Amount of water applied (cm)}} \quad (\text{Eq. 3})$$

### Soil moisture content (%)

Soil samples were collected from the field after harvesting wheat crop and weighed on an electric balance (wet weight), drying the sample in electric oven at 65 ± 1 °C by putting them in aluminum box till the constant weight (dry weight) gained. The soil moisture content was worked out by using the following formula.

$$\text{Moisture (\%)} = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \quad (\text{Eq. 4})$$

Where,

W<sub>1</sub> = Weight of can (g)

W<sub>2</sub> = Weight of can (g) + weight of soil sample (g)

W<sub>3</sub> = Weight of can (g) + weight of oven dry soil (g)

### Statistical analysis

Data on growth, yield and water-related parameters were subjected to statistical analysis using Fisher's analysis of variance. The significance of treatment means was evaluated using the least significant difference (LSD) test at the 5 % probability level. All analyses were performed using statistical tools for agricultural research (STAR v.2.0.1) (14).

## Results and Discussion

### Plant height

Plant height was significantly influenced by irrigation scheduling throughout the crop growth period (Table 1). Increasing irrigation frequency from IR<sub>1</sub>-IR<sub>3</sub> enhanced plant height, with IR<sub>3</sub> (CRI + tillering + milking) producing the tallest plants. However, IR<sub>3</sub> remained statistically at par with IR<sub>2</sub>, indicating that irrigation beyond the CRI stage substantially improves vegetative growth. Adequate soil moisture at critical stages likely maintained cell turgor, enhanced nutrient mobility and supported active meristematic growth, resulting in greater stem elongation. In contrast, moisture limitation under IR<sub>1</sub> may have restricted cell expansion and assimilate translocation, thereby reducing plant height. Similar responses of wheat to increased irrigation frequency have been reported earlier (15, 16).

Biofertiliser treatments also exerted a significant effect on plant height. The F<sub>3</sub> consistently produced taller plants and remained at par with F<sub>1</sub>, while F<sub>2</sub> and F<sub>4</sub> recorded comparatively lower values. The superior performance of F<sub>3</sub> may be attributed to the synergistic action of biological nitrogen fixation and enhanced phosphorus solubilisation, leading to improved root development, nutrient uptake and chlorophyll formation. Increased nitrogen availability likely supported protein synthesis and vegetative growth, whereas phosphorus may have helped in energy transfer and root proliferation. Enhanced nutrient acquisition under combined inoculation likely promoted greater stem elongation and canopy development. Similar improvements in plant height with integrated application of *Azotobacter* and PSB along with recommended fertilisers have also been reported (17).

### Number of tillers (tiller density)

Tiller density was significantly influenced by irrigation scheduling across all growth stages (Table 1). Increasing irrigation frequency from IR<sub>1</sub> to IR<sub>3</sub> enhanced tiller density, with IR<sub>3</sub> (CRI + tillering + milking) recording the highest values. Although IR<sub>3</sub> remained statistically at par with IR<sub>2</sub> during early growth stages, it exhibited a

**Table 1.** Effect of irrigation scheduling and bio-fertiliser application on the growth attributes of late-sown wheat

| Treatment                                                       | Plant height (cm) |        |         | Number of tiller (m <sup>-2</sup> ) |        |         | Leaf area index |        |         | Dry matter accumulation (g m <sup>-2</sup> ) |        |         |
|-----------------------------------------------------------------|-------------------|--------|---------|-------------------------------------|--------|---------|-----------------|--------|---------|----------------------------------------------|--------|---------|
|                                                                 | 60 DAS            | 90 DAS | Harvest | 60 DAS                              | 90 DAS | Harvest | 60 DAS          | 90 DAS | Harvest | 60 DAS                                       | 90 DAS | Harvest |
| <b>Irrigations schedules</b>                                    |                   |        |         |                                     |        |         |                 |        |         |                                              |        |         |
| IR <sub>1</sub> (CRI only)                                      | 62.16             | 83.30  | 82.16   | 251.98                              | 307.32 | 267.20  | 4.42            | 4.63   | 4.51    | 449.91                                       | 641.19 | 765.19  |
| IR <sub>2</sub> (CRI + LJ)                                      | 64.89             | 87.51  | 86.37   | 255.54                              | 333.77 | 291.65  | 5.64            | 5.77   | 5.65    | 458.18                                       | 659.89 | 783.89  |
| IR <sub>3</sub> (CRI + tillering + milking)                     | 70.17             | 92.18  | 91.04   | 280.19                              | 340.45 | 302.33  | 5.98            | 6.12   | 6.00    | 488.66                                       | 704.95 | 824.95  |
| <b>Sem ±</b>                                                    | 0.84              | 0.93   | 0.87    | 2.23                                | 2.41   | 2.34    | 0.09            | 0.11   | 0.10    | 3.07                                         | 1.74   | 2.40    |
| <b>CD (p = 0.05)</b>                                            | 2.70              | 2.98   | 2.69    | 6.96                                | 7.31   | 7.25    | 0.26            | 0.37   | 0.31    | 11.84                                        | 5.10   | 8.52    |
| <b>Bio-fertiliser</b>                                           |                   |        |         |                                     |        |         |                 |        |         |                                              |        |         |
| F <sub>1</sub> (Seed inoculation with <i>Azotobacter</i> )      | 66.30             | 88.25  | 87.11   | 264.74                              | 327.99 | 287.87  | 5.47            | 5.60   | 5.48    | 498.89                                       | 671.51 | 795.51  |
| F <sub>2</sub> (Seed inoculation with PSB)                      | 64.73             | 86.60  | 85.46   | 260.16                              | 325.20 | 285.08  | 5.02            | 5.13   | 5.01    | 464.50                                       | 667.07 | 791.07  |
| F <sub>3</sub> (Seed inoculation with <i>Azotobacter</i> + PSB) | 68.42             | 90.96  | 89.82   | 269.79                              | 335.80 | 295.68  | 6.35            | 6.63   | 6.51    | 472.56                                       | 673.81 | 797.81  |
| F <sub>4</sub> (Seed inoculation with liquid phosphate)         | 63.50             | 84.83  | 83.69   | 255.58                              | 319.74 | 279.62  | 4.56            | 4.66   | 4.54    | 456.39                                       | 662.31 | 786.31  |
| <b>Sem ±</b>                                                    | 0.73              | 0.76   | 0.83    | 2.12                                | 2.36   | 2.24    | 0.07            | 0.09   | 0.08    | 3.03                                         | 1.33   | 2.18    |
| <b>CD (p = 0.05)</b>                                            | 2.49              | 2.79   | 2.51    | 6.64                                | 6.91   | 6.77    | 0.25            | 0.35   | 0.31    | 9.12                                         | 5.16   | 7.14    |

DAS: days after sowing; CD: critical difference; PSB: phosphate solubilising bacteria; CRI: crown root initiation; LJ: late joining.

clear advantage at harvest. Adequate soil moisture availability during CRI and subsequent vegetative phases likely supported active crown root development, improved nutrient uptake and sustained photosynthetic activity, thereby supporting tiller initiation and survival. In contrast, reduced irrigation under IR<sub>1</sub> may have limited tiller formation and increased tiller mortality due to moisture stress. Similar trends of increased tiller density with higher irrigation frequency at critical stages have been reported by previous studies (18, 19).

Biofertiliser treatments also had a significant effect on tiller density. The F<sub>3</sub> produced the highest tiller density and was statistically at par with F<sub>1</sub>, F<sub>2</sub> and F<sub>4</sub> registered lower values. The improved tillering under F<sub>3</sub> may be attributed to enhanced nitrogen fixation and phosphorus solubilisation, resulting in better root development and early plant vigour.

### Leaf area index

Leaf area index increased rapidly up to 60 DAS and continued to expand at a slower rate up to 90 DAS, reflecting active vegetative growth followed by gradual stabilisation as the crop approached the reproductive stage (Table 1). Irrigation scheduling significantly influenced LAI at all stages of observation. Higher irrigation frequency (IR<sub>3</sub>) recorded greater LAI and remained statistically at par with IR<sub>2</sub>, while both were superior to IR<sub>1</sub>. Adequate moisture availability at critical stages likely enhanced leaf expansion, delayed senescence and sustained photosynthetic activity. In contrast, moisture stress under limited irrigation may have reduced cell enlargement and accelerated leaf senescence, thereby restricting canopy development. Similar findings have been reported where optimum irrigation levels improved leaf area development and biomass production (20, 21).

Biofertiliser application significantly affected LAI throughout the growth period. The combined inoculation of F<sub>3</sub> recorded the highest LAI and remained statistically at par with F<sub>1</sub>, while F<sub>2</sub> and F<sub>4</sub> were comparatively lower values. The enhanced LAI growth under F<sub>3</sub> may be attributed to enhanced nitrogen fixation and phosphorus solubilisation, leading to better nutrient uptake, chlorophyll synthesis and leaf expansion. The slight increase in LAI up to 90 DAS corresponds with the active growth phase, followed by stabilisation and decline due to natural leaf senescence at later stages (22).

### Dry matter accumulation

Dry matter accumulation (DMA) progressively increased with crop age and reached its maximum near 90 DAS, reflecting peak vegetative growth and active assimilate production (Table 1). Irrigation scheduling significantly influenced DMA at all stages. Plots receiving 3 irrigations (IR<sub>3</sub>) consistently produced greater dry matter and remained statistically at par with IR<sub>2</sub>, whereas IR<sub>1</sub> recorded comparatively lower accumulation. The superiority of IR<sub>3</sub> can be attributed to sustained soil moisture during critical growth stages, which likely maintained stomatal conductance, enhanced nutrient uptake and prolonged photosynthetic activity. Adequate moisture availability supports cell expansion and assimilates translocation, thereby promoting biomass production. In contrast, restricted irrigation under IR<sub>1</sub> may have induced partial stomatal closure, reduced carbon assimilation and limited vegetative growth, resulting in lower DMA.

Previous studies also reported that higher irrigation regimes, particularly at optimal irrigation water (IW): cumulative pan evaporation (CPE) ratios, favour greater biomass production due to improved plant water status and nutrient absorption (23). Similarly, wheat grown under optimum irrigation levels and improved crop establishment methods has shown enhanced DMA compared to moisture-stressed conditions (23, 24).

Biofertiliser treatments significantly influenced DMA at all growth stages. The F<sub>3</sub> produced the highest biomass and was superior to individual inoculations. The enhanced performance under F<sub>3</sub> may be associated with improved nitrogen fixation and phosphorus solubilisation, which together increase nutrient availability during critical growth phases. Nitrogen plays a key role in chlorophyll synthesis and vegetative growth, while phosphorus is essential for energy transfer and root activity. The combined action of these microorganisms likely strengthened root development and nutrient uptake, thereby supporting sustained biomass production throughout the crop growth period. Similar increases in DMA with integrated biofertiliser application have been reported earlier (25, 26).

### Yield parameters

Grain and straw yield were significantly influenced by irrigation scheduling (Table 2). Higher irrigation frequency (IR<sub>3</sub>) resulted in superior yield performance and remained statistically at par with

IR<sub>2</sub>, while IR<sub>1</sub> produced the lowest yields. The improved yield under IR<sub>3</sub> can be attributed to sustained soil moisture during key developmental stages, which supported better tiller survival, enhanced canopy development and efficient assimilate partitioning toward reproductive sinks. Adequate moisture during tillering and grain filling likely maintained photosynthetic activity and reduced spikelet sterility, thereby improving grain formation. In contrast, moisture limitation beyond the CRI stage under IR<sub>1</sub> may have restricted biomass production and grain filling, leading to reduced grain and straw yield.

This is supported by previous studies where irrigation at critical growth stages such as tillering, booting and grain filling enhances yield-contributing traits and final productivity (25). Yield improvements under higher irrigation frequency are generally associated with increased DMA improved test weight and better source-sink balance (26). These findings align with the present results, where improved vegetative growth and canopy development translated into higher economic yield.

Biofertiliser treatments significantly influenced grain and straw yield. The combined F<sub>3</sub> produced the highest yields and was superior to individual applications. The synergistic effect of biological nitrogen fixation and phosphorus solubilisation likely

**Table 2.** Effect of irrigation scheduling and bio-fertiliser application on the grain and straw yield of late-sown wheat

| Treatment                                                       | Grain yield<br>(q ha <sup>-1</sup> ) | Straw yield<br>(q ha <sup>-1</sup> ) |
|-----------------------------------------------------------------|--------------------------------------|--------------------------------------|
| <b>Irrigation schedules</b>                                     |                                      |                                      |
| IR <sub>1</sub> (CRI only)                                      | 25.89                                | 39.28                                |
| IR <sub>2</sub> (CRI + LJ)                                      | 31.34                                | 45.26                                |
| IR <sub>3</sub> (CRI + tillering + milking)                     | 37.95                                | 53.92                                |
| Sem ±                                                           | 0.51                                 | 0.67                                 |
| CD (p = 0.05)                                                   | 1.98                                 | 2.13                                 |
| <b>Bio-fertiliser</b>                                           |                                      |                                      |
| F <sub>1</sub> (Seed inoculation with <i>Azotobacter</i> )      | 32.36                                | 46.96                                |
| F <sub>2</sub> (Seed inoculation with PSB)                      | 31.10                                | 45.42                                |
| F <sub>3</sub> (Seed inoculation with <i>Azotobacter</i> + PSB) | 34.91                                | 49.87                                |
| F <sub>4</sub> (Seed inoculation with liquid phosphate)         | 28.56                                | 42.33                                |
| Sem ±                                                           | 0.37                                 | 0.55                                 |
| CD (p = 0.05)                                                   | 1.13                                 | 2.00                                 |

CD: critical difference; PSB: phosphate solubilising bacteria; CRI: crown root initiation; LJ: late joining.

**Table 3.** Effect of irrigation scheduling and biofertiliser application on soil moisture depletion, consumptive use, water use efficiency, total water applied and water productivity of late-sown wheat

| Treatment                                                       | Soil moisture depletion (cm) |       |       |       | Total soil moisture depletion (cm) | Consumptive use (cm) | Water use efficiency (q ha <sup>-1</sup> cm) | Total water applied (cm) | Water productivity (kg cm <sup>-3</sup> ) |
|-----------------------------------------------------------------|------------------------------|-------|-------|-------|------------------------------------|----------------------|----------------------------------------------|--------------------------|-------------------------------------------|
|                                                                 | 0-15                         | 15-30 | 30-60 | 60-90 |                                    |                      |                                              |                          |                                           |
| Irrigations schedules                                           |                              |       |       |       |                                    |                      |                                              |                          |                                           |
| IR <sub>1</sub> (CRI only)                                      | 3.21                         | 2.96  | 2.52  | 2.10  | 10.79                              | 19.28                | 1.34                                         | 9.82                     | 2.63                                      |
| IR <sub>2</sub> (CRI + LJ)                                      | 3.45                         | 3.15  | 2.80  | 2.33  | 11.73                              | 21.32                | 1.46                                         | 15.82                    | 1.98                                      |
| IR <sub>3</sub> (CRI + tillering + milking)                     | 3.87                         | 3.56  | 2.86  | 2.69  | 12.98                              | 25.15                | 1.50                                         | 21.82                    | 1.74                                      |
| Sem ±                                                           | 0.12                         | 0.10  | 0.02  | 0.09  | 0.38                               | 1.56                 | 0.04                                         | 2.28                     | 0.27                                      |
| CD (p = 0.05)                                                   | 0.39                         | 0.37  | 0.05  | 0.33  | 1.22                               | 5.23                 | NS                                           | 11.58                    | NS                                        |
| Bio-fertiliser                                                  |                              |       |       |       |                                    |                      |                                              |                          |                                           |
| F <sub>1</sub> (Seed inoculation with <i>Azotobacter</i> )      | 3.75                         | 3.43  | 2.76  | 2.30  | 12.24                              | 21.92                | 1.47                                         | 15.82                    | 2.05                                      |
| F <sub>2</sub> (Seed inoculation with PSB)                      | 3.82                         | 3.64  | 2.85  | 2.71  | 13.02                              | 21.92                | 1.41                                         | 15.82                    | 1.97                                      |
| F <sub>3</sub> (Seed inoculation with <i>Azotobacter</i> + PSB) | 3.73                         | 3.15  | 2.52  | 2.12  | 11.52                              | 21.92                | 1.59                                         | 15.82                    | 2.20                                      |
| F <sub>4</sub> (Seed inoculation with liquid phosphate)         | 3.85                         | 3.78  | 3.12  | 2.93  | 13.68                              | 21.92                | 1.30                                         | 15.82                    | 1.81                                      |
| Sem ±                                                           | 0.09                         | 0.07  | 0.01  | 0.08  | 0.32                               | 1.10                 | 0.03                                         | 1.87                     | 0.12                                      |
| CD (p = 0.05)                                                   | NS                           | NS    | NS    | NS    | NS                                 | NS                   | NS                                           | NS                       | NS                                        |

CD: critical difference; PSB: phosphate solubilising bacteria; CRI: crown root initiation; LJ: late joining.

enhanced nutrient uptake and root development, resulting in improved growth, higher DMA and better grain filling. Nitrogen availability directly influences protein synthesis and grain development, while phosphorus supports energy transfer and reproductive growth. The integration of biofertilisers with recommended fertiliser doses has been reported to enhance growth attributes and yield in several crops (27–29).

### Soil moisture depletion pattern

Total soil moisture depletion differed significantly among irrigation schedules (Table 3). Greater depletion under IR<sub>3</sub> indicates that crops receiving irrigation at CRI, tillering and milking stages extracted more water from the soil profile compared to limited irrigation (IR<sub>1</sub>). This pattern suggests that sustained moisture supply encouraged deeper and more extensive root proliferation, allowing plants to utilise a larger portion of available soil water. Enhanced vegetative growth and higher transpiration demand under well-watered conditions likely contributed to greater cumulative water extraction. Similar observations have been reported in multi-season studies where irrigation at multiple critical stages promoted deeper rooting and increased soil water uptake (30).

Across treatments, a major proportion of water depletion occurred within the 0–30 cm soil layer, reflecting the concentration of active roots in the upper profile. In cereals, a substantial fraction of water uptake typically occurs from surface layers under favourable moisture conditions (31). Frequent irrigation at critical stages maintains an optimal moisture gradient in this zone, supporting continuous uptake while preventing severe moisture stress. Conversely, restricted irrigation limits both root activity and soil water utilisation.

Biofertiliser treatments also influenced soil moisture depletion. Treatments with comparatively higher depletion likely supported greater root biomass and metabolic activity, thereby increasing water absorption. However, the combined inoculation of F<sub>3</sub> showed relatively lower total depletion despite better growth performance. This may indicate improved WUE, where enhanced nutrient availability supported biomass production without proportionally increasing water extraction. Enhanced phosphorus solubilisation and biological nitrogen fixation can stimulate root growth and physiological activity (32, 33).

## Water dynamics and efficiency parameters

Consumptive use of water increased with irrigation frequency, reflecting greater evapotranspiration demand under well-watered conditions (Table 3). Treatments receiving irrigation at multiple critical stages (IR<sub>3</sub>) extracted more water from the soil profile, consistent with their higher biomass production and canopy development. Increased leaf area and prolonged physiological activity under adequate moisture likely enhanced transpiration, thereby raising total water use. Similar trends have been documented where multi-stage irrigation elevated seasonal water consumption in cereals (34, 35).

Although IR<sub>3</sub> recorded the highest grain yield, the improvement in WUE was only marginal compared with IR<sub>2</sub>, indicating that yield gains were not strictly proportional to additional water input. In contrast, irrigation limited to CRI (IR<sub>1</sub>) showed comparatively higher water productivity despite lower yield. This reflects a classical trade-off between maximising production and optimising water use. When irrigation is restricted but strategically timed at the CRI stage, plants may utilise available moisture more efficiently for grain formation, thereby improving the yield-to-water ratio. However, beyond a certain threshold, additional irrigation may increase total water use more rapidly than yield, leading to reduced water productivity. This phenomenon aligns with the principle of diminishing marginal returns under higher irrigation regimes (36).

Biofertiliser treatments did not significantly alter consumptive use, suggesting that total water extraction was primarily governed by irrigation level rather than microbial inoculation. However, the F<sub>3</sub> significantly improved both WUE and water productivity. The superior efficiency under F<sub>3</sub> may be attributed to enhanced nitrogen fixation and phosphorus solubilisation, which likely improved root growth, chlorophyll content and assimilate production without proportionally increasing water consumption. Enhanced nutrient availability improves stomatal regulation and photosynthetic efficiency, enabling greater biomass and grain yield per unit of water used. Similar improvements in WUE under dual microbial inoculation have been reported in wheat and other cereals under varying irrigation conditions (37).

## Conclusion

The study demonstrates that productivity of late-sown wheat is strongly influenced by irrigation and biofertiliser application. Irrigation at crown root initiation (CRI), tillering and milking stages improved growth, biomass accumulation and grain yield by sustaining soil moisture during critical physiological phases. Dual seed inoculation with *Azotobacter* and phosphate-solubilising bacteria (PSB) further enhanced nutrient availability and improved the efficiency of water utilisation, resulting in superior crop performance. Future research should evaluate this integrated approach in multi-location and assess long-term effects on soil health, nutrient dynamics and economic returns to strengthen recommendations for sustainable wheat production.

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## Authors' contributions

PA conducted the field and laboratory research and prepared the original draft of the manuscript. PA, SK, RKS and NCM developed the methodology and contributed to visualisation. PA, SK and NAB performed the software analysis. Validation was carried out by PA, SK, RKS, NCM and NAB. Formal analysis was performed by PA, SK, RKS and AT. Investigation was carried out by PA, SK, RKS, BSP, KPP, SS and KH. Resources were provided by PA, SK, RKS and NCM. Data curation was performed by SK, PA, RKS and AT. All authors have read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors do not have any conflict of interest to declare.

**Ethical issues:** None

## References

1. Directorate of Economics and Statistics, DAC&FW, Government of India. Agricultural statistics at a glance. New Delhi: Government of India; Directorate of Economics and Statistics, DAC&FW, Government of India.
2. Vyas S, Nigam R, Patel NK, Panigrahy S. Extracting regional pattern of wheat sowing dates using multispectral and high temporal observations from Indian geostationary satellite. *J Ind Soc Remote Sens.* 2013;41(4):855–64. <https://doi.org/10.1007/s12524-013-0266-3>
3. Adnan M, Khan A, Mohammad F, Ali F, Hussain Q. Impact of late sowing on morphological and yield traits in bread wheat. *J Soil Plant Environ.* 2021;1(1):1–18. <https://doi.org/10.56946/jspae.v1i1.2>
4. Dubey R, Pathak H, Chakrabarti B, Singh S, Gupta DK, Harit RC. Impact of terminal heat stress on wheat yield in India and options for adaptation. *Agric Syst.* 2020;8:102826. <https://doi.org/10.1016/j.agsy.2020.102826>
5. Shivani, Verma UN, Kumar S, Pal SK, Thakur R. Growth analysis of wheat (*Triticum aestivum* L.) cultivars under different seedling dates and irrigation levels in Jharkhand. *Indian J Agron.* 2003;48(4):282–86. <https://doi.org/10.59797/ija.v48i4.3098>
6. Kaya MD, Okçu G, Atak M, Çikılı Y, Kolsarıcı Ö. Seed treatments to overcome salt and drought stress during germination in sunflower (*Helianthus annuus* L.). *Eur J Agron.* 2006;24(4):291–95. <https://doi.org/10.1016/j.eja.2006.08.001>
7. Dietz KJ, Zörb C, Geilfus CM. Drought and crop yield. *Plant Biol (Stuttg).* 2021;23(6):881–93. <https://doi.org/10.1111/plb.13304>
8. Malik GC, Iftikar W, Banerjee M, Ghosh DC. Effect of irrigation, variety and nitrogen on growth and productivity of wheat (*Triticum aestivum* L.) in the lateritic belt of West Bengal. *Int J Bioresour Stress Manag.* 2012;3(2):158–64.
9. Yadav GL, Verma JK. Effect of irrigation regime, nitrogen and zinc fertilization on growth and yield of late-sown wheat (*Triticum aestivum* L.). *Indian J Agron.* 1991;36:50–53.
10. Singh A, Singh D, Kang JS, Aggarwal N. Management practices to mitigate the impact of high temperature on wheat: a review. *Int J Integr Omics Appl Biotechnol.* 2011;2(7):11–22.
11. Al Tawaha AR, Karnwal A, Pati S, Al-Tawaha AR, Upadhyay AK, Singh A, et al. Biofertilisers: a sustainable solution for enhancing soil fertility and crop productivity. In: Sustainable agriculture under drought stress. London: Academic Press; 2025:209–17. <https://doi.org/10.1016/B978-0-443-23956-4.00014-4>
12. Gelvez-Pardo I, Lobo-Berbesi L, Santos-Díaz A. Biological efficacy of plant growth-promoting bacteria and arbuscular mycorrhizae

- fungi: assessments in laboratory and greenhouse conditions. *Curr Protoc.* 2023;3(4):e732. <https://doi.org/10.1002/cpz1.732>
13. Dastane NG. A practical manual for water use research in agriculture. 2<sup>nd</sup> ed. Poona: Navabharat Prakashan; 1972.
  14. Gomez KA, Gomez AA. Statistical procedures for agricultural research. New York: John Wiley & Sons; 1984.
  15. Singh S, Singh V, Pal R, Trivedi H, Narayan A, Gautam M. Effect of sowing methods and irrigation levels on wheat (*Triticum aestivum* L.). *Ecol Environ Conserv.* 2023;29:S170–76. <https://doi.org/10.53550/EEC.2023.v29i01s.026>
  16. Zulfiqar U, Ahmad M, Valipour M, Ishfaq M, Maqsood MF, Iqbal R, et al. Evaluating optimum limited irrigation and integrated nutrient management strategies for wheat growth, yield and quality. *Hydrology.* 2023;10(3):56. <https://doi.org/10.3390/hydrology10030056>
  17. Gupta H, Mishra US, Sirothia P, Mishra A, Patel VK, Rao S. Unveiling the synergistic impact of N and P levels alone and in conjunction with bio-inoculants (*Azotobacter* and *PSB*) on growth and yield of wheat. *Int J Plant Soil Sci.* 2023;35(21):569–75. <https://doi.org/10.9734/ijps/2023/v35i214011>
  18. Singh A, Niwas R, Yadav AS, Kumar J, Kumar S. Effect of irrigation scheduling on growth and yield of late sown wheat (*Triticum aestivum* L.). *Pharma Innov J.* 2022;9(5):299–301.
  19. Halge SS, Prasanna J, Ghodke PB, Mirza IA, Bhambere HD. Performance of different levels of fertilizers along with biofertilisers on growth and yield of late sown wheat (*Triticum aestivum* L.). *Int J Res Agron.* 2024;7(SP-11):500–02. <https://doi.org/10.33545/2618060X.2024.v7.i11Sg.2035>
  20. Kumar K, Nand V, Pyare R, Maurya NK, Niwas R, Singh S. Effect of irrigation schedules on productivity of late sown varieties of wheat (*Triticum aestivum* L.). *Int J Chem Stud.* 2021;9(1):3273–77. <https://doi.org/10.22271/chemi.2021.v9.i1at.11738>
  21. Gond S, Singh MK, Satapathy SM. Irrigation scheduling and soil moisture use on growth and yield of late sown wheat (*Triticum aestivum* L.) varieties. *Environ Conserv J.* 2023;24(1):176–82. <https://doi.org/10.36953/ECJ.10812261>
  22. Kumawat H, Singh DP, Jat G, Choudhary R, Singh PB, Dhayal S, et al. Effect of fertility levels and liquid biofertilisers on growth and yield of wheat (*Triticum aestivum* L.). *Pharma Innov J.* 2021;10:1365–69.
  23. Pal S, Kumar S, Gangwar HK, Singh A, Kumar P. Effect of scheduling irrigation based on IW/CPE ratio on dry matter accumulation, yield attributes, yield and economics of wheat crop. *Int J Chem Stud.* 2020;9(4):1946–49. <https://doi.org/10.20546/ijcmas.2020.903.286>
  24. Ballabh J, Bankoti P. Response of late sown wheat (*Triticum aestivum* L.) to residue management and various organic sources of nutrients in sandy loam soils of Uttarakhand. *Biochem Cell Arch.* 2025;25(1):429. <https://doi.org/10.51470/BCA.2025.25.1.429>
  25. Alam MS, Naresh RK, Vivek KS, Singh HL. Effect of sowing methods and irrigation scheduling on production and productivity of wheat crop. *Biol Forum Int J.* 2022;14(2a):445–52.
  26. Badal V, Amit KJ, Shiv RR, Nisha S, Rajiv D, Raghav P, et al. Assessment of foliar-applied stress regulators to sustain the growth and yield of wheat varieties under various irrigation levels. *Plant Sci Today.* 2025;12(3):1–10. <https://doi.org/10.14719/pst.8938>
  27. Hooda VS, Sangwan M, Kumar S, Kamboj E, Raj D. Performance of tall wheat under different sowing times and methods using various nutrient sources in western Haryana. *J Agric Ecol.* 2023;15:140–44. <https://doi.org/10.58628/JAE-2315-123>
  28. Das RC, Ghosh A, Hemel SAK, Parvej SS, Rahman MT, Ali MI. Impact of stage-specific irrigation on the growth and yield of wheat. *J Agrofor Env.* 2024;17(2):67–73. <https://doi.org/10.55706/jae1719>
  29. Ali M, Ahmed I, Bibi H, Saeed M, Khalil IA, Bari A. Impact of irrigation schedules on yield-related traits of wheat under semi-arid region. *Gesunde Pflanzen.* 2023;75(6):2413–22. <https://doi.org/10.1007/s10343-023-00888-3>
  30. Chouhan BS, Kaushik MK, Nepalia V, Solanki NS, Singh B, Devra NS, et al. Effect of sowing methods, scheduling of irrigation based on IW/CPE ratio and chemical weed control on plant height, dry matter accumulation and yield of wheat. *J Pharmacogn Phytochem.* 2017;6(3):169–72.
  31. Bhambere HD, Prasanna J, Ghodke PB, Mirza IA, Syed SJ. Study of different levels of fertilizers along with biofertilisers on yield and economics of late sown wheat (*Triticum aestivum* L.). *Int J Res Agron.* 2024;7(SP-11):493–95. <https://doi.org/10.33545/2618060X.2024.v7.i11Sg.2033>
  32. Kumar R, Yadav RK, Singh P. Multi-stage irrigation scheduling and its effect on root proliferation and water use in wheat (*Triticum aestivum* L.). *Agric Water Manag.* 2023;276:108021.
  33. Patel MK, Sharma A, Bhatt RK. Root distribution and water uptake dynamics under different irrigation regimes in wheat. *J Soil Water Conserv.* 2021;20(3):187–92.
  34. Jatav MK, Solanki NS, Meena RK. Effect of biofertilisers on growth, yield and economics of wheat (*Triticum aestivum* L.). *Int J Curr Microbiol Appl Sci.* 2020;9(7):1223–31.
  35. Singh R, Chaudhary BS, Singh V. Optimizing irrigation at crown root initiation stage for higher water productivity in wheat under semi-arid conditions. *Irrig Sci.* 2021;39:93–102.
  36. Zhang X, Wang Y, Chen L. Diminishing returns of excessive irrigation on crop yield and water productivity. *Field Crops Res.* 2022;286:108625.
  37. Sharma R, Meena VS, Yadav AN. Dual microbial inoculation improves root development and water productivity under limited irrigation in wheat. *Rhizosphere.* 2023;27:100637.

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