# STANDARDIZATION OF IRRIGATION SCHEDULING BASED ON CANOPY TEMPERATURE AND SOIL MOISTURE REGIMES IN WHEAT (*Triticum aestivum* L.)

Thesis Submitted for the Award of the Degree of

**DOCTOR OF PHILOSOPHY**

**in**

**Agronomy**


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**2025**

# DECLARATION

I, hereby declared that the presented work in the thesis entitled **"Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)"** in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of Dr. Vandna Chhabra (UID – 21027), working as Associate Professor, in the Department of Agronomy, School of Agriculture of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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# CERTIFICATE-I

This is to certify that the work reported in the Ph. D. thesis entitled **"Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the Department of Agronomy, School of Agriculture, is a research work carried out by Gurleen Kaur, 12021169, is bonafide record of his/her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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## CERTIFICATE -II

This is to certify that the work reported in the Ph. D. thesis entitled **"Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)"** submitted by **Gurleen Kaur (Registration No.-12021169)** to the Lovely Professional University, Phagwara submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the discipline of Agriculture (Agronomy) has been approved by the Advisory Committee after oral examination of the student in collaboration with an external examiner.

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# ABSTRACT

The present study "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)" was conducted at Agricultural Research Farm of Lovely Professional University, Phagwara, Punjab, during the *rabi* season of 2022-23 and 2023-24. The field experiment was carried out in a randomized block design comprised of nine treatments *i.e.,* $T_1$ (recommended irrigation), $T_2$ (irrigation at CRI and flowering stage), $T_3$ (irrigation at 0.25 PSI), $T_4$ (irrigation at 0.50 PSI), $T_5$ (irrigation at 0.75 PSI), $T_6$ (irrigation at 25% depletion of FC), $T_7$ (irrigation at 30% depletion of FC), $T_8$ (irrigation at 75% depletion of FC) and $T_9$ (rainfed). The results demonstrated that all chosen irrigation scheduling methodologies significantly impacted plant development, yield characteristics, grain and straw yields, and irrigation water use efficiency (IWUE) within the designated study region. Among all the selected treatments, $T_1$ achieved the highest plant height (104.1 and 107.7 cm), dry matter accumulation (794.7 g $m^{-2}$ and 819.5 g $m^{-2}$), effective tillers (396.4 and 416.5 $m^{-2}$), spike length (11.1 and 11.3 cm), test weight (48.3 and 48.6 g), grain yield (5.9 and 6.1 t $ha^{-1}$), straw yield (7.4 and 7.8 t $ha^{-1}$) and biological yield (13.3 and 13.9 t $ha^{-1}$) in both 2022-23 and 2023-24 respectively. As per the pooled analysis, the maximum IWUE (0.143 t $ha^{-1}$ cm), irrigation water productivity (1.426 kg $m^{-3}$) and amount of water required for producing 1 kg of wheat (871 litres) in treatment $T_2$, but this treatment does not support sustainable wheat yield. Conversely, irrigation based on a 0.50 PSI ($T_4$) proves to be a more effective scheduling strategy as this method achieved the significant grain yield of 5.7 t $ha^{-1}$, water productivity of 0.923 kg $m^{-3}$ along with 11 % irrigation water savings as compared to the conventional method of irrigation scheduling. The enhanced Benefit-Cost (B:C) ratio observed in the PSI-based treatments, particularly in $T_4$ (2.0 and 2.3) across both years based on water saving, indicates that the prudent utilization of water not only increases yields but also enables the irrigation of additional land, thereby enhancing overall income and improving economic returns. Hence, adopting this irrigation strategy could significantly aid in the sustainable production of wheat and the efficient management of water resources in areas characterized by water scarcity.

***Keywords***: Canopy temperature, Field capacity, Irrigation scheduling, Plant stress index, Water use efficiency, Wheat

# ACKNOWLEDGEMENT

*First and foremost, I bow my head in reverence and sincerely express my gratitude to God, who is the most gracious, merciful, and compassionate being. It is through his grace, glory, and blessing that I was able to muster the courage to complete this degree at certain difficult times.*

*I would like to express my sincere gratitude to my advisor,* ***Dr. Vandna Chhabra*** *Professor in the Department of Agronomy at Lovely Professional University in Punjab, for her wise counsel and helpful criticism throughout my research and manuscript preparation. I owe her my undying love, respect, and sincere gratitude for her zeal, support, and kindness.*

*I would like to thank* ***Dr. Vikas Sharma****, Assistant Professor in the Department of Soil Science at Lovely Professional University, Punjab for his impeccable help and valuable suggestions.*

*I humbly and respectfully thank my parents,* ***Ms. Surpreet Kaur*** *and* ***S. Harjit Singh*** *and my sister* ***Harleen Kaur*** *for their unwavering support, encouragement, and inspiration as I pursued my higher education. I convey my wholehearted thanks to my brother* ***Gurvansh Singh****. This research would not have been possible without the kind time, wisdom, and experiences that my friend* ***Sreethu S.*** *so kindly shared with me. I will always be grateful to her for that.*

*I will always be grateful to everyone who supported me, whether directly or indirectly. Lastly, I would like to express my gratitude to Lovely Professional University, Punjab, for providing me with the information I needed for my investigation. Not all have been acknowledged, but none are overlooked.*

***Date:***

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ` | Rupee |
| % | Per cent |
| @ | At the rate of |
| °C | Degree Celsius |
| ANOVA | Analysis of variance |
| AAS | Atomic Absorption Spectrophotometer |
| AGR | Absolute growth rate |
| B:C | Benefit: Cost |
| CD | Critical difference |
| CGR | Crop growth rate |
| cm | Centimetre |
| CRI | Crown root initiation |
| DAP | Di ammonium phosphate |
| DAS | Days after sowing |
| $dSm^{-1}$ | Deci Siemens per meter |
| *et al.* | et alia |
| EC | Electrical conductivity |
| ER | Effective rainfall |
| Fig | Figure |
| FC | Field Capacity |
| g | gram |

| | |
|---|---|
| g/kg | Gram per kilogram |
| ha | Hectare |
| HI | Harvest index |
| $H_2SO_4$ | Sulphuric acid |
| i.e. | That is |
| K | Potassium |
| $K_2O$ | Potassium oxide |
| kg | Kilo gram |
| kg/ha | Kilo gram per hectare |
| km/hr | Kilometre per hour |
| LAI | Leaf area index |
| LSWI | Land surface water index |
| m | metre |
| Max | Maximum |
| Min | Minimum |
| mg | Milligram |
| mg/g | Milligram per gram |
| mm | millimetre |
| MOP | Muriate of potash |
| MSL | Mean sea level |
| N | Nitrogen |
| NAR | Net assimilation rate |
| NaOH | Sodium Hydroxide |
| NDVI | Normalised difference vegetation index |

| | |
|---|---|
| NIR | Near-infrared |
| No. | Number |
| OC | Organic carbon |
| P | Phosphorus |
| $P_2O5$ | Phosphorus Pentoxide |
| pH | Potential of hydrogen |
| ppm | Parts per million |
| PSI | Plant Stress Index |
| RDF | Recommended dose of fertilizer |
| RGR | Relative growth rate |
| RWC | Relative water content |
| SWIR | Shortwave infrared |
| WUE | Water use efficiency |
| WP | Water productivity |
| t | Tonne |
| $t\ ha^{-1}$ | Tonne per hectare |

***CHAPTER 1***

# *INTRODUCTION*

With the increase in the global populace, wheat (*Triticum aestivum* L.) is one of the prominently cultivated crops. It is an essential dietary staple for over two billion individuals, constituting approximately 35% of the worldwide demographic. Regarding acreage and productivity, it is regarded as India's second most significant crop, behind rice. Wheat is cultivated across 31.4 Mha domestically and 220.41 Mha internationally, producing 110.5 MMT and 798.98 MMT, respectively (FAOSTAT, 2023). There are between 3390 and 3371 kg of output per hectare on average. The central state in India that produces wheat, Punjab, is currently having problems, as evidenced by the persistent decrease in the annualised growth rate of wheat production. Punjab grows 35.3 lakh hectares of wheat, producing 149 lakh tonnes of grain annually (MoA & FW, 2021). India is the second-largest wheat-growing country following China in area and production.  Winter wheat is grown from October through November to April. The predominant winter agricultural product in Punjab is wheat, cultivated across an area of 3.52 Mha and yielding a year-long production of 14.86 MT, which corresponds to an average productivity rate of 42.16 quintals per hectare (Package of Practices, *Rabi,* 2023-24). In Punjab, 115 mm of rainfall falls on average throughout the wheat season, while 400 mm of crop water (evapotranspiration) is required. Because of this, farmers rely heavily on groundwater supplies for irrigation to raise crop production.

Aquifers in Punjab were rapidly depleted because of the careless extraction of groundwater resources. Anonymous (2017), provided estimated numbers demonstrating the drop in groundwater levels throughout an 85% state area between 1984 and 2016. Thus, the uncontrolled utilization of groundwater reserves results in brisk exhaustion of the water table at a concerning rate of approximately 0.4 meters annually (Brar *et al.,* 2012). Consequently, it becomes imperative to effectively manage the excessive exploitation of groundwater for irrigation purposes while ensuring that it does not negatively impact crop productivity. However, the degree of soil moisture depletion crops can tolerate without losing yield must be quantified. It is imperative to restore the moisture of soil at a specified depth of root zone when it attains a specific depletion level by supplying a commensurate volume of irrigation water to realize optimal water productivity. Optimizing irrigation scheduling can enhance water use efficiency and prevent excessive water application while ensuring crop productivity. This optimization involves determining the appropriate amount and timing of irrigation on the basis of allowable soil moisture depletion (Meena *et al.,* 2015). According to certain research studies conducted at the international, regional, and national levels, climate fluctuations are crucial in influencing water availability and consumption (Mainuddin *et al.,* 2015; Acharjee *et al.,* 2019). Further, with each degree of temperature increase, wheat productivity is predicted to decrease globally by 6% due to heat stress brought on by climate change (Shi *et al.,* 2022). The region's heightened climate variability and associated extremes have adversely affected crop productivity, which is expected to rise even more (Ali & Erenstein, 2017; Shah *et al.,* 2021). Throughout the growing season of the crop, they exhibit heightened susceptibility to fluctuations in meteorological conditions. Extreme weather patterns are also anticipated to cause variations in the span of the growing season and in the timing of all agricultural growth phases, which differ depending on the place and season (Acharjee *et al.,* 2017). Thus, anticipating weather-related uncertainties can lead to erratic rainfall and unequal distribution; however, this can be mitigated by promoting programs for the wise utilization of irrigation water (Dastorani *et al.,* 2022; Madane *et al.,* 2023).

Irrigation scheduling is a designated procedure wherein the quantity and timing of irrigation are influenced by limitations imposed by labour and agricultural practices. The goal is to maximize returns on inputs by efficiently utilizing available irrigation water resources. It is accomplished by utilizing diverse methodologies predicated on assessing soil-water equilibrium, plant development phases, and meteorological circumstances. Calculating crop evapotranspiration based on climatic factors provides an objective standard for planning irrigation schedules. Soil moisture tension is also used, and application of irrigation is done according to the soil moisture available in the root zone of the crop. Negative water potential in plant tissues or crop canopy heating because of water stress are two ways to quantify water stress in plants. Therefore, measuring soil moisture tension or soil water content is necessary for scheduling irrigation. When the soil moisture tension is combined with the capacity of soil moisture retention, a deliberate increase in water is administered at the appropriate moment, thereby mitigating the adverse impacts of water displacement.

Furthermore, a plant indicator strategy exists that considers the water state of the plants when scheduling irrigation. It has been demonstrated that plant canopy temperature is a good index of plant water status (Idso *et al.,* 1981; Jackson, 1982). A proposed index for measuring water stress in crops, known as the crop water stress index (CSWI), was developed by utilizing an infrared thermometer to measure the difference between the temperatures of the crop canopy and the surrounding air. This index is based on a comparison to a baseline temperature, representing the typical temperature of a well-watered crop not experiencing water stress (Idso *et al.,* 1981).

Global water scarcity has prompted researchers to explore various water management strategies. According to research by the International Water Management Institute (IWMI), increased irrigation efficiency can account for around half of the anticipated rise in water demand by 2025. In the current scenario, a significant portion of the wheat cultivation area in India relies on border irrigation, which has a water utilization efficiency of only about 60% due to substantial losses during conveyance. Therefore, considering the water scarcity issue, the prudent and efficient allocation of water necessitates the implementation of a well-structured irrigation schedule.

The current investigation aims to develop and propose a strategy for standardizing irrigation scheduling using wheat canopy temperature and soil moisture regimes. Given the potential benefits of scheduling irrigation to enhance crop performance and optimize water usage efficiency, the present experiment, "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum*)," was conducted with the enumerated objectives:

1. To determine the effect of canopy temperature-based irrigation scheduling on the growth and yield of wheat,
2. To assess the effect of soil moisture depletion on water use efficiency
3. To evaluate the soil moisture stress relationship with plant water status based on remote sensing techniques and
4. To evaluate the economic feasibility of various irrigation scheduling methods for wheat.

*CHAPTER 2*

## *REVIEW OF LITERATURE*

The disquisition about the study on "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)" has been reviewed to abstract the available knowledge and to identify the knowledge gaps under the following headings:

- Canopy temperature-based irrigation scheduling
- Soil moisture regimes-based irrigation scheduling
- Phenological stages-based irrigation scheduling

***Canopy temperature-based irrigation scheduling***

Canopy temperature has been employed as a critical parameter in the scheduling of irrigation practices. It acts as a valuable tool for assessing the water status of plants, as transpiration in non-stressed plants helps create a cooling effect in their environment. Conversely, water-stressed plants exhibit reduced transpiration due to stomatal closure, resulting in elevated temperatures (Idso *et al.,* 1981). An infrared thermometer is utilized for the measurement of canopy temperature (Kirkham, 2005), as this parameter serves to characterize the crop water status (Kirkham *et al.,* 1983) and thus can be used to schedule irrigation. Different indices such as crop water stress index (CWSI), temperature-time threshold (TTT) and temperature stress days (TSD) are used to schedule irrigation based on the canopy of the crop. The variation between the atmospheric and canopy temperatures is the base for the empirical CWSI methodology, which is determined at different points of vapour pressure deficit (VPD). A linear relationship of canopy air temperature was observed with VPD when CWSI was measured in the absence of stress (Idso *et al.,* 1981). The theoretical method used by Jackson *et al.,* (1982) to calculate CWSI relies on the energy available as well as the aerodynamics of the crops. However, the performance of the lower baseline is subjected to aerodynamic resistance, net radiation and resistance of the canopy. Thus, baselines can be used to determine the CWSI of the crop which helps to detect the water stress in the crop. CWSI was determined by using an empirical method where baselines were defined during the experiment involving non-stressed and fully stressed treatments in wheat crops. An upper limit of 0.3 was identified as the threshold for CWSI, suggesting that irrigation is necessary whenever this limit is exceeded (Gonita & Tiwari, 2008). The utilization of CWSI has been demonstrated in the literature to enable the monitoring of water status and facilitate irrigation scheduling by developing the baseline equation which can be used as the integration of collected data with a reference point representing non-water-stress conditions (Alderfasi & Neilsen, 2000). Yuan *et al.,* (2003) assessed three different models for CWSI - the Jackson model, the Idso empirical model and the new Alves model to monitor water stress in winter wheat crops in NCP. The findings indicated that crop water stress in winter wheat can be identified with the use of CWSI computed using infrared canopy temperature.

CWSI values were computed for various crops, extending beyond wheat, and are utilized for the precise management of irrigation, as evidenced by the application in sunflower cultivation, where irrigation was triggered once the CWSI value reached the critical level of 0.6 (Erdem *et al.,* 2006). Both the lower and upper CWSI baselines were designed for corn and wheat crops. Thus, facilitating the CWSI method as a practical tool which can be utilized to schedule irrigation in both crops (Payero & Irmak, 2006). In a semi-arid climate, Usman *et al.,* (2010) established lower and upper baselines for utilizing CWSI to schedule irrigation for cotton. Primarily, a linear relationship between yield and season CWSI values was observed. The maximum CWSI value of 0.76 was noted in the treatment where only rainfall was used for irrigation, while the minimum value of 0.24 occurred when irrigation was provided during the vegetative, flowering, boll formation, and late growth stages. Similarly, the utilization of phenology-based irrigation scheduling with the CWSI was investigated in winter maize cultivation. During this study, baseline equations were created at divergent critical stages of growth. At silking stage, CWSI ranged from 0.42 to 0.48, which was significantly less than the suggested value of 0.6 for scheduled irrigation (Kar & Kumar, 2010). Bockhold *et al.,* (2011) determined the canopy temperature with the infrared thermometer in corn, soybean and cotton crops. A threshold temperature of up to 1ºC for corn and soybean whereas up to 0.5 ºC was determined for cotton. Ünlü *et al.,* (2011) further investigated the efficiency of CWSI in cotton crops by establishing a baseline for non-water stresses using canopy temperature data obtained from fully irrigated plots, as well as a baseline for non-transpiring conditions based on canopy temperature readings from stressed plots. It was noted that when CWSI approached near 0.36, irrigation should be applied. In semi-arid regions of Colorado, Western USA, infrared thermometry was juxtaposed with weather parameters to design baselines (i.e., non-transpiring and non-water-stressed) for maize crops. From the results, it was revealed that with the application of an independent remotely sensed energy balance model, $ET_a$ of maize was observed to be 159 mm, which was 30% more than CSWI - $T_a$ (122 mm) and 9% less than standard-condition maize ET (174 mm). Thus, concluding that a reliable CWSI threshold can be determined to schedule irrigation (Taghvaeian *et al.,* 2012). Also, CWSI was used for scheduling irrigation under the sub-humid climate of Bursa, which was used to schedule irrigation in soybean by Candogan *et al.,* (2013). CWSI was computed with the help of baselines for stressed and non-stressed conditions. A threshold value of 0.22 was determined for CWSI to apply irrigation to the crop. However, the maximal water use efficiency (WUE) at the observed CWSI value was approximately 0.6, reinforcing the suitability of using the CWSI value for irrigation scheduling in these conditions. The canopy temperature, CWSI, and grain yield of five distinct Iranian wheat varieties were assessed under conditions of late-season drought stress, by Bijanzadeh & Emam, (2012). The highest average CWSI values of 0.73 and 0.71 were noted for Shiraz and Yavroz varieties. However, under severe drought conditions the CWSI ranged between 0.61 to 0.64 in Bahar, Pishtaz, and Sistan varieties. The relationship between CWSI and the net photosynthetic rate of the flag leaf, as well as the water supplied under different irrigation levels, was found to exhibit a negative correlation. Maximum grain yield was observed in Shiraz and Yavroz cultivars under excess watering conditions and the range of CWSI lies between 0.31 to 0.36.

To manage deficit irrigation for sprinkler-irrigated wheat, CWSI and water potential of leaves were evaluated by Alghory & Yazar (2018). Both grain yield and available soil moisture were observed to be linearly correlated with CWSI, and this can be used to predict the yield response towards water stress. CWSI value of less than 0.26 can be used as an indicator to apply irrigation and thus, resulted in higher grain yield.

The correlation between leaf water potential, grain yield and CWSI was also found to be significant. Tekelioğlu *et al.,* (2017) asserted that the utilization of an infrared thermometer for measuring canopy temperature serves as a crucial factor to assess water stress in soybean. The methodology employed an empirical approach for quantifying the CWSI values. It was observed that irrigation and evaporation quantities may equate upon the attainment of a CWSI value of 0.40. To procure the maximum yield and water productivity in soybean, CWSI was used for irrigation management by Ahmadi *et al.,* (2018). The maximal yield of 1765.4 kg/ha was achieved with a 100% level of irrigation whereas, however, when irrigation was applied at 80% of full water requirement water productivity was found to be maximum (of 0.26 kg/m$^3$). Therefore, the observed values for CWSI to attain optimum water productivity for crop maturity, reproduction, and vegetative growth were 0.29, 0.37 and 0.42.

Similar to prior studies, Saeidinia *et al.,* (2019) calculated CWSI to schedule irrigation and estimate the forage yield of maize. The influence of water stress on CWSI was found to be considerable. At a CWSI value of 0.17, optimum yield was obtained whereas 0.21 was associated with minimum yield. CWSI was also used as an index to schedule irrigation in legume crops like black gram by Khorsand *et al.,* (2019) under drip irrigation. When water stress intensifies throughout the plant's growth cycle, there is a corresponding increase in the CWSI, leading to a subsequent decline in grain yield. Based on the results, irrigation scheduling can be done using a CWSI value of 0.15 that was achieved under the no-stress regime. Erdem *et al.,* (2005) evaluated different CWSI threshold levels to optimize drip irrigation scheduling in watermelon cultivation. The highest levels of WUE were attained when the CWSI reached a value of 0.6, indicating an optimal balance between water conservation and crop productivity. A CWSI value of 0.4 has the potential to be employed to recognise water stress and the strategic management of irrigation in Indian mustard (*Brassica juncea*) through the application of canopy temperature, as highlighted in the study by Kumar *et al.,* (2021).

CWSI is a helpful technique for assessing irrigation schedules by optimising crop production and saving water. Leaf canopy temperature was used to examine CWSI values under different water stress conditions by Khan *et al.,* (2022). The lower baseline, representing a fully irrigated crop, and the upper baseline, indicative of maximum stress conditions, were established during both the pre- and post-heading phases of wheat to ascertain the CWSI. The computation of the baseline was done using the difference between air temperature canopy temperature and VPD. To obtain a better yield the optimum CWSI value was noted as 0.08. Results suggest that the lowest mean CWSI of 0.079 for irrigation at 0% deficit from field capacity treatment with a wheat yield of 3800 kg/ha, while the maximum CWSI was 0.65 for irrigation at 100% deficit from field capacity with a yield of 983 kg/ha. According to Jeyasingh, (2023), irrigation at 0.2 CWSI is an effective method for optimizing WUE and irrigation use efficiency (IUE) with minimal water input, leading to significantly higher maize kernel and stover yields in both the *kharif* and *rabi* seasons. Growing interest in irrigation management using canopy temperature-based methods including CWSI was observed by Katimbo *et al.,* (2022). In the experiment, both the theoretical as well as empirical CWSI methods were evaluated under various levels of stress. A notable sensitivity of CWSI to the depletion of soil moisture was identified, and this sensitivity was assessed across multiple soil depths. In conditions of extreme stress (Dr, i > 80%), the coefficient of determination ($R^2$) values exhibited a range from 0.61 to 0.80 at deeper soil levels of 1.8 and 2.1 meters.

CWSI has been documented to exhibit a strong correlation with various other indicators of stress, such as soil moisture content or its depletion. Thus, CWSI under different levels of soil moisture depletion (SMD) in sunflower by using pot-based drip irrigation was evaluated by Madane *et al.,* (2024). The mean CWSI of 0.085 for sunflower cultivation aligns with the range established by the lower and upper baselines. As a result, the closeness of the CWSI value to the lower baselines implies the existence of considerable water stress in the crop.

To overcome the limitations of soil water monitoring and facilitate the utilisation of stored soil water, a thermal-based CWSI was used in sugar beet for scheduling irrigation by King *et al.,* (2021). It was found that, in deficit irrigation treatments, the daily CWSI was a more sensitive indicator of water stress than soil water monitoring. Growth of tomatoes was observed in sandy and silty loam and crop water stress index ($CWSI_W$) was determined and was used to map water stress, yield mapping and scheduling irrigation. The findings showed that, for both soil types, there was a good connection between CWSI by Idso ($CWSI_{Idso}$) and $CWSI_W$ in assessing the crop water status with $R^2$ values exceeding 0.60 at various stages of growth (Alordzinu *et* *al.,* 2021). The CWSI determined by temperature demonstrates a precise indication of the level of water deficiency in crops. A research study conducted in the plains of North China investigated threshold values for CWSI in relation to grain yield and WUE for winter wheat and summer maize. A robust positive linear relationship was noted between WUE ($r^2$ = 0.873) and increasing CWSI, whereas a significant negative correlation was found between CWSI and the grain yield of winter wheat ($r^2$ = 0.915). The grain yield ($r^2$ = 0.856) and WUE ($r^2$ = 0.629) of summer maize were represented by quadratic functions (Qin *et al.,* 2021). In two varieties of safflower (Goldasht and Local Isfanah cultivars), CWSI was evaluated in four distinct irrigation treatments determined by field capacity (FC). The correlation between vapour pressure deficit and the difference between canopy air temperature and ambient air temperature (Tc – Ta) was illustrated using both upper (fully stressed) and lower (non-stressed) baselines. CWSI ranged between 0.28 to 0.33 when irrigation was applied at 75% FC, which can be considered an effective strategy for irrigating safflower during the period of water scarcity (Bijanzadeh *et al.,* 2022). The reaction of mung bean towards water stress was examined by implementing various levels of irrigation, utilizing CWSI as a tool to manage irrigation schedules. Observations of CWSI revealed a spectrum of values spanning from 0.13 to 0.93. The maximal yield of 163 kg/day was achieved with full irrigation, whereas the minimal yield of 39.7 kg/day was recorded in rainfed plots that did not receive any additional irrigation. A significant correlation between yield and CWSI was established. The threshold CWSI values for initiating drip irrigation in mung bean cultivation ranged from 0.33 to 0.22 (Gölgül *et al.,* 2023).

Gu *et al.,* (2021) performed a study to examine how effectively CWSI detects water stress levels in crops and forecasts their physiological attributes and growth under both water and salt stress conditions. The researchers continuously monitored canopy temperature (Tc) to calculate the CWSI for two varieties of maize (ZD958 and XY335) alongside stage-specific baselines for non-water-stressed conditions (NWSB). Under varying levels of salt and water stress, CWSI showed strong correlations with leaf water potential, stomatal conductance, and net photosynthesis rate, aiding in the explanation of deviation in leaf area index, crop yield biomass and water use. Overall, the findings suggest that CWSI can serve as a reliable proxy for high-throughput phenotyping of maize performance under combined water and salt stress conditions, which could prove instrumental in yield prediction and enhancing water use efficiency. In Bursa, Turkey's subhumid climate, the CWSI response was measured in conjunction with chlorophyll readings in drip-irrigated sugar beetroot, both under full and deficit irrigation. Seasonal CWSI values varied significantly across the four irrigation treatments, with the highest values recorded at 0% soil water depletion, measuring 0.85 in 2019 and 0.89 in 2021. Conversely, the lowest CWSI values were noted under 100% soil water depletion, at 0.12 for 2019 and 0.19 for 2021. It was concluded that the greatest root and sugar yield can be achieved by endorsing a CWSI of 0.12 as a threshold value for irrigation scheduling (Yetik *et al.,* 2023). Seçme, (2021) noted a negative correlation between CWSI and the yield of sunflower seeds, indicating a decrease in yield with an increase in CWSI. The CWSI reached a critical value of 0.33, beyond which a decline in yield was evident upon the application of irrigation. In potato, CWSI was evaluated when grown under surface and sub-surface drip methods. CWSI for surface and sub-surface drip irrigation lies from 0.16 to 0.56 and 0.15-0.49. It was concluded that to optimize the yield irrigation should be implemented when CWSI lies between the range of 0.16 to 0.20 in the subsurface drip irrigation method (Shalamzari *et al.,* 2019).

The evaluation of CWSI has been conducted to quantify plant water stress and determine an irrigation threshold for hybrid grain sorghum, comparing automated and manual irrigation systems. Significant improvements in irrigation water use efficiency (IWUE) were noted with 80% automatically controlled irrigation treatments, suggesting that CWSI and time threshold index could serve as effective tools for scheduling deficit irrigation in grain sorghum (O'Shaughnessy *et al.,* 2010). To ascertain the ideal irrigation schedule for a furrow irrigation system, Suleiman *et al.,* (2021) conducted field research on maize. The researchers obtained a CWSI value of 0.175, revealing that treatments exhibiting a stress index of 0.175 or less did not experience significant stress, whereas those exceeding this threshold were under stress. Using canopy temperature as a scheduling tool for irrigation, Pramanik *et al.,* (2017) created the plant water stress index (PSI). Irrigation was scheduled when the PSI levels reached 0.25. 0.50 and 0.75 respectively. The results revealed that a PSI of 0.5 should be maintained to achieve the optimum yield in wheat. The proportionate reduction of accessible moisture in soil was determined roughly to be 32%, which is associated with a pressure of 0.5 PSI.

The results that have been obtained from the studies indicate that canopy temperature and CWSI have the potential to serve as valuable tools for scheduling irrigation. This is due to their capability to offer real-time information regarding the status of water in the plant, thereby enabling the implementation of flexible adjustments in the irrigation timetable. Such flexibility proves to be particularly advantageous when dealing with diverse climatic circumstances. Moreover, the utilization of these tools can assist in achieving optimal water utilization, elevating crop productivity, and promoting sustainable agricultural practices.

***Soil moisture status-based irrigation scheduling***

The application of soil moisture as a premise to schedule irrigation involves the optimization of irrigation practices through the application of water following the specific moisture levels present in the soil, rather than according to the preset schedule. This methodology assumes a crucial function in ensuring that agricultural plants receive the optimal volume of irrigation at the exact timing, thereby resulting in a reduction of water loss while concurrently improving both the productivity and quality of the crops. Several field studies suggested an available soil moisture depletion approach as the basis for scheduling irrigation. Muktar & Yigezi (2016) assessed various irrigation strategies, considering different degrees of soil moisture reduction and their impact on the yield and WUE of hybrid maize (BH-140). A notable enhancement in both grain yield and WUE was evident with the application of irrigation at 140% depletion compared to the recommended threshold of 0.55 soil moisture depletion. Consequently, the study also indicated the importance of determining suitable irrigation levels for each phenological stage of the crop. Kashyap & Panda (2003) examined the effects of water stress on irrigation scheduling in potato crops, basing treatment decisions on available soil water (ASW) and maximum allowed depletion (MAD). As the frequency of irrigation increases a significant surge in potato tuber yield was also noticed when compared to low-frequency irrigation. MAD decreased from 45 to 75% the reduction in yield of fresh tuber was recorded due to the depletion of the availability of water. Similarly, potato crop production was also observed by scheduling irrigation by using various soil moisture potentials. Evapotranspiration, yield and WUE of the crop were affected by drip irrigation frequency and soil matric potential. The highest WUE and yield were obtained with a daily irrigation scheduling and a soil matric potential threshold of -25kPa (Kang *et al.,* 2004). The potential soil moisture deficit (PSMD) method has been utilized in early and late sowing varieties of wheat to optimize the yield. Results suggested that deficit irrigation at 45 mm PSMD can be used to save water when compared to conventional farmer practices of full irrigation (Bashir *et al.,* 2016). An investigation into the impact of soil moisture variability under various irrigation schedules was conducted across varied levels of available soil water depletion, in conjunction with different soil depths. The inferences indicated that the significant portion of soil moisture uptake by plants occurred within the 0-45 cm soil layer. The optimal water use efficiency for wheat cultivation was achieved when irrigation was timed at a 45% depletion threshold of available soil water, as reported by Panda *et al.,* (2003). Further in wheat and cotton different MAD levels were assessed, and results suggest that MAD at 65% for cotton and 55% for wheat, the highest WUE was recorded (Laghari *et al.,* 2010).

It was reported by Mohamed, (1994) that irrigation scheduling in wheat at 60% available soil moisture depletion (ASMD) led to the highest grain yield and harvest index. In contrast, Ahmed *et al.,* (1996) noted a significant reduction in wheat grain yield when irrigation was scheduled at 50% to 75% ASMD. The maximum grain yield of 4.71 t/ha was noted with irrigation at 35% ASMD and 120 kg N/ha. In contrast, a yield of 4.13 t/ha and the maximal WUE of 196.5 kg/ha-cm were achieved with irrigation at 65% ASMD and 80 kg N/ha (Karim *et al.,* 1997). Research executed by Narang *et al.,* (2000) revealed a favourable correlation between distinct genotypes of wheat and diverse moisture conditions. The highest utilization of water and efficiency in water usage was observed when irrigation was implemented at 40 and 60% ASMD. A decline in wheat grain yield as soil moisture depletion levels increased was observed. However, the maximal WUE was achieved at the maximum tested level of soil moisture depletion, specifically at 60% ASMD. Similarly, optimum wheat yield was observed by Aydin *et al.,* (2000) when scheduled irrigation was applied at 66% ASMD. In a different study, water utilisation efficiency was recorded as 1.13, 1.05, 0.82, and 0.86

kg/m$^3$, and grain yield was 3384, 3050, 3094, and 2273 kg/ha when irrigation scheduling was done at 10, 25, 50, and 75% ASMD (Tahmasabi & Fardad, 2000). A significantly higher grain yield of 2967 kg/ha and harvest index of 0.23 in wheat was observed with irrigation applied at 50% ASMD juxtaposed to irrigation at 70% ASMD (Mahmood & Ahmad, 2005).

To develop more efficient and sustainable agriculture practices a study was conducted by Metwally, (2014) by managing the different irrigation regimes in wheat. It was observed that applying irrigation at 45% soil moisture depletion using the bed planting method enhanced grain yield, water productivity (WP), and irrigation water productivity (IWP) by 15.3%, 10.4%, and 8.8%, respectively, compared to irrigation applied at 75% depletion of available water. According to Balwinder-Singh *et al.,* (2016) irrigation at 50% soil water deficit (SWD) allows water saving of 50 mm and 60 mm in sandy and clay loam soils. The influence of various irrigation regimes, determined by maximum allowable depletion (MAD) of available soil moisture (ASM), on growth parameters, yield attributes, total yield, and WUE. Irrigation scheduling at 25% MAD of ASM yielded the highest grain output (4.93 t/ha), trailed by irrigation at 50% MAD of ASM during critical stages, and then at 75% MAD of ASM. The highest WUE of 15 kg ha$^{-1}$ mm was achieved with both 25% MAD of ASM and 50% MAD of ASM (Meena *et al.,* 2015). Moursi *et al.,* (2019) conducted a study to examine the impact of varying levels of allowable soil moisture depletion (ASMD) on wheat yield and water efficiencies through the utilization of the pan evaporation method (PEM). Their findings indicated that employing PEM for irrigation scheduling at 40% ASMD represents the optimal approach for achieving increased wheat production and enhanced profitability. A comparison was conducted by Ansari *et al.,* (2019) between irrigation scheduling utilizing soil moisture data and climatological data (cumulative pan evaporation). The results showed that applying irrigation at a threshold of 30% MAD led to a 7.94% increase in agricultural output compared to slate irrigation based on cumulative pan evaporation (CPE) of 20 mm. This suggests that the soil moisture-based method is more dependable than the climatological approach.

Apart from the application scheduling irrigation based on the reduction of the existing soil moisture, irrigation can also be administered in cases of reduction in field capacity. Dar *et al.,* (2017b) executed a study in which irrigation was employed on wheat under various degrees of reduction in levels of soil moisture from field capacity (FC). The results showed a combined decrease of 30% in grain yield and 21% in crop evapotranspiration, along with a 29% increase in water productivity, when irrigation was applied at a 45% reduction in soil moisture from field capacity (FC), compared to irrigation at a 15% reduction from FC. Hence, the proposition was made that the irrigation of wheat at a 15% reduction of FC in drip irrigation can be seen as an innovative approach that conserves irrigation water while ensuring a high grain yield. In the realm of cotton cultivation, various irrigation levels were implemented utilizing two distinct irrigation scheduling methodologies, namely gravimetric and pan evaporimeter. The findings indicated that employing the pan evaporimeter approach for irrigation scheduling proves to be more optimal for enhancing cotton production in regions characterized by semi-arid climatic conditions. Specifically, the seed cotton yield exhibited superior performance when irrigation was administered at 67% of the deficit irrigation level within the gravimetric approach (Tunali *et al.,* 2021).

***Phenological stages-based irrigation scheduling***

In the region of Punjab, the initial application of irrigation for wheat cultivation occurs three weeks after the sowing of crops in October, whereas, for crops planted in November, irrigation is administered four weeks post-planting. Subsequent irrigations are given at four to six weeks intervals, contingent on the kind of soil and meteorological conditions. The reaction to crop growth stage-based irrigation varied.

The highest grain output was obtained by irrigation during the wheat's crown root initiation (CRI), booting, tillering, milking, and dough stages (Dar *et al.,* 2017a). Comparable results proclaimed that the maximum yield of grain in wheat was noticed when irrigation was implemented during crop phenological stages (Ram *et al.,* 2013). In wheat, statistically similar grain and straw yield was observed amidst the partial deficit (single or two-stage deficit) and no-deficit irrigation. Single irrigation applied at the CRI resulted in a straw yield of 6.3 t/ha, which was statistically at par with the yield from irrigation at 50% soil moisture depletion (7.5 t/ha) but significantly maximum than the yield from no irrigation (3.9 t/ha). However, the implementation of alternate deficit irrigation during the stages of maximal tillering (from jointing to shooting) and from flowering to the soft dough stage of crop growth. The results showed that this approach achieved the highest levels of irrigation water productivity and crop water productivity, compared to a single irrigation administered at the CRI stage (Ali *et al.,* 2007). Irrigation of 60 mm applied both at heading and jointing stage resulted in a higher spike count (580 g/$m^2$) and grain yield (678 g/$m^2$) compared to irrigation at 120 mm during jointing (556 per $m^2$ and 558 g/$m^2$), and irrigation provided at each of the jointing, heading, and milking stages of 40 mm (528 g/$m^2$ and 409 g/$m^2$) respectively (Li *et al.,* 2010). This outcome was linked to the increased water demand during the jointing and heading stages in contrast to the stage of milking, where an excessive water supply can lead to the lodging of wheat crops.

Dar *et al.,* (2017c) discovered that providing four irrigations at the CRI, tillering, booting, and milking stages led to a significantly higher grain yield than applying three irrigations at CRI, booting, and milking. Using a drip system to apply 100 mm of irrigation water in four splits achieved a significantly higher grain yield than applying the same amount of water in two or three splits. Irrigation in 2 splits of 50 mm each produced grain yield similar to that of conventional irrigation. Thus, it was deduced that the application of irrigation water at 50 mm through drip irrigation can be advocated as a yield-sustaining and water-saving energy. Mamatha *et al.,* (2022) evaluated various combinations of irrigation (ranging from two to five) in mustard at different phenological phases. It was discerned that the intervention involving five irrigations administered during the vegetative stage, pre-flowering phase, flowering period, siliqua initiation, and siliqua development led to the most significant enhancement in growth, yield characteristics, and overall yield. A controlled experiment was undertaken involving winter wheat, wherein irrigation was administered once, twice, and thrice during the critical growth stages of jointing, heading, or milking, with a cumulative volume of irrigation water limited to 120 mm. When 2- and 3-time irrigation was compared with 1-time irrigation jointing irrigation increased the density of root length in >30 cm depth of soil profile. However, when 1 and 3 times of irrigation were compared to 2 times of irrigation, a remarkable escalation in grain yield was observed: also 2 times irrigation at jointing and heading leads to higher production of WUE (Li *et al.,* 2010). Irrigation was administered to multiple wheat varieties by Mubeen *et al.,* (2013) at different crucial phases of growth. The results showed that a high grain yield of 4.23 t $ha^{-1}$ was achieved with irrigation applied during the tillering, stem elongation, booting, and grain filling stages, which was greater than the yield from irrigation applied only during booting and stem elongation stages. Consequently, the recommendation is that irrigation should be practised during stem elongation and booting stages to attain optimal economic yield in situations where there is a limited number of irrigation opportunities. Similarly, Bashir *et al.,* (2016) also suggested that full availability of water for irrigation at stem elongation, tillering, booting and grain formation is recommended to achieve optimum yield. But under water-scarce conditions, to diminish the loss in grain yield and biomass irrigation should be applied at the tillering stage. A significant reduction in yield and yield attributes was reported by Akram, (2011) when subjected to stressful conditions at the tillering and anthesis stages of wheat growth. Results of Sarwar *et al.,* (2010) found similar results, where the maximal yield of grain was achieved with irrigations applied at the five phases i.e., CRI, tillering, booting, earing, and milking wheat crops. An experiment performed by Gill *et al.,* (2013) showed that the maximal grain yield (3.92 at Ludhiana and 3.35 t/ha in Bathinda) was discerned for wheat when irrigation was supplied at CRI, tillering, jointing, booting and milking in two different locations of Punjab region and was observed to be at par with irrigation given based on the weather forecast.

The decrease in spike length was noted during the tillering (vegetative) phase in the presence of water stress, in contrast to the blooming and grain-filling phases (Sokoto & Singh, 2013). Moreover, in conjunction with the decrease in ear length, the quantity of grains per ear was similarly reduced under water stress conditions throughout both the vegetative and reproductive phases, as documented by Khanzada *et al.,* (2001). An agricultural system model was established by Fang *et al.,* (2014) which was aimed at optimising the utilization of scarce water resources to increase the grain yield and WUE under diverse climatic conditions. The results revealed that satisfying the water demand of crops mainly during the reproductive stage is highly significant when compared to the vegetative stages to achieve higher grain yield and WUE in conditions of water scarcity. According to Cui *et al.,* (2015), moderate or severe water deficit during the tillering stage had no significant impact on the flag leaf of wheat, but such deficits significantly reduced the flag leaf during the jointing stage.

Meena *et al.,* (2019) assessed water usage, WUE, and yield of wheat over three years under thirteen distinct irrigation schemes. The findings demonstrated that the maximal yield, reaching 5372.4 kg/ha, was discerned when the crop received full irrigation during all five crucial phenological phases (60 mm), a result comparable to the yield obtained under 25% deficit irrigation (45 mm) throughout. Nevertheless, a noteworthy water conservation of 50% was recorded with 50% irrigation (30 mm) at all phenological stages, albeit accompanied by a considerable yield reduction of 10.9%. Notably, a WUE value of 2.23 kg $m^{-3}$ was observed with 45 mm of irrigation throughout all growth stages, indicating efficient water usage without compromising yield. A study was carried out by Memon *et al.,* (2021) to assess the impact of deficit irrigation during phenological of winter wheat. The treatment with full irrigation at all six phenological stages highest grain yield (4558.8 kg $ha^{-1}$). However, various aspects of growth, yield characters, and overall crop yield were significantly afflicted by deficit irrigation across different treatments. Notably, a decrease of 17% was observed in yield when deficit irrigation was implemented at the tillering stage. Interestingly, applying 50% deficit irrigation during grain maturity stages led to increased WUE and a grain yield that was nearly equivalent to that achieved with 100% irrigation at all six stages of growth. Niwas *et al.,* (2023) proclaimed that irrigation applied at CRI, booting, tillering and milking stage (4 irrigations) resulted in higher crop growth rates and consumptive use of water. However, irrigation given only at CRI and jointing stage (2 irrigations) higher WUE was noticed thus indicating the significance of specific irrigation timings at different growth stages. Therefore, it is conspicuous that the application of irrigation leads to a consistent increment in wheat productivity as demonstrated by Rahim *et al.,* (2007). This phenomenon is particularly pronounced when irrigation is administered at each discernible phase of growth, as noted by Wajid *et al.,* (2002).

However, Singh and Vashisht, (2019) noted that crop productivity declined with high-frequency irrigation, as the yield increase from a large quantity of irrigation water was less than the corresponding increase in water usage. Moreover, a high frequency of irrigation water resulted in an increased crop evaporation rate (Huang *et al.,* 2005).

Hence, there is a necessity for proficient water administration to enhance irrigation water efficiency in conjunction with optimizing yield, necessitating growers to exercise caution regarding water stress during crucial growth stages, which has the potential to result in significant yield reduction.

# *CHAPTER 3*

# *MATERIALS AND METHODS*

The present study, entitled "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)," was conducted at the Research Farm of Lovely Professional University, Phagwara, during the *rabi* seasons of 2022–2023 and 2023–2024. This chapter outlines the materials employed and the methodologies adopted for the execution of the experiment.

## 3.1 Location and Climate

Phagwara is located at 31.22° N and 75.77° E, with an elevation of 234 meters above mean sea level. The region experiences a subtropical, semi-arid climate, characterized by hot and dry summers (March to June), a humid monsoon period (late June to end September), and cool, dry winters (October to February).

## 3.2 Weather during cropping season

Meteorological parameters showed substantial fluctuations during 2022-23 and 2023-24. Weekly averages of weather variables like maximum and minimum temperatures and relative humidity, rainfall, wind speed and evaporation were recorded from the agrometeorological observatory, Lovely Professional University and are graphically illustrated in Fig. 3.1 and 3.2.

The weather data for the 2022-23 and 2023-24 *rabi* seasons revealed considerable variation in different meteorological parameters throughout the cropping season. In the 2022-23 season, the minimum temperature ranged from 7.3 °C to the maximum temperature of 36.5 °C. Relative humidity varied between 54% and 95%, with an average of 80.87%. A total amount of rainfall of 118.5 mm was observed. During 2023-24, the minimum and maximum temperature ranged from 4.64 °C and 34.66 °C respectively, and the relative humidity varied from 31 % to the maximum of 85 % representing a significant change throughout the growing season during both years. A total amount of rainfall of 104.5 mm was observed respectively. Average windspeed in the year 2022-23 was recorded to be 3 km $hr^{-1}$, whereas it averaged to be 5.45 km $hr^{-1}$ in 2023-24. The total amount of pan evaporation was observed to be 308.3 mm in 2022-23 and 310.3 mm in 2023-24.

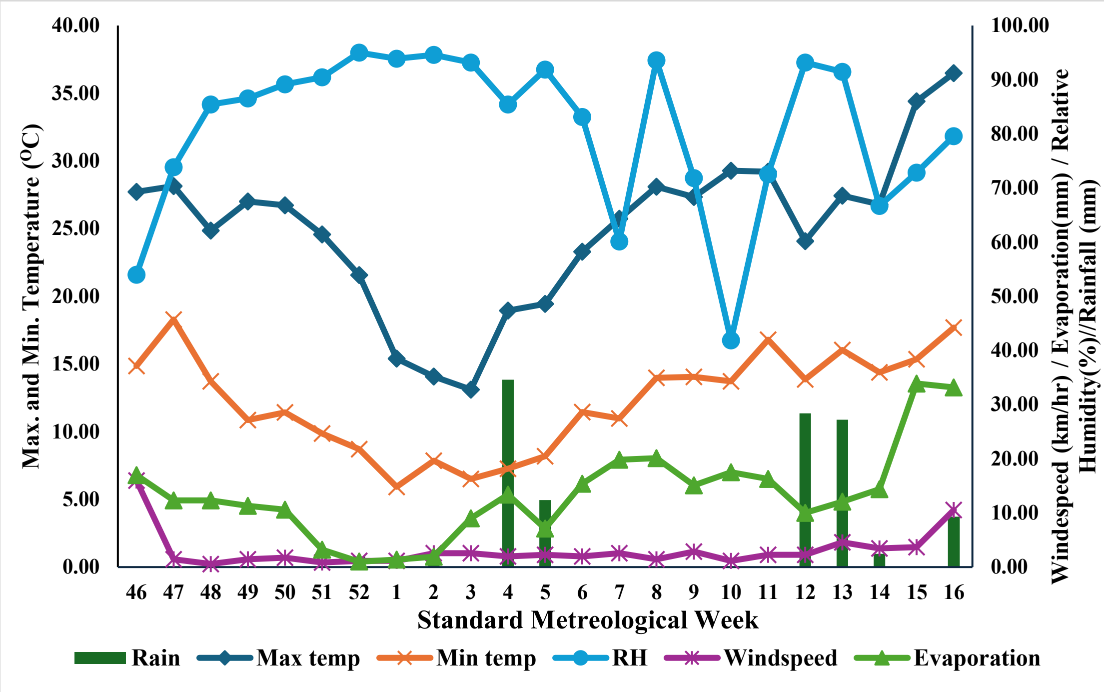



**Fig 3.1: Weekly mean meteorological data for *rabi* season 2022-23**

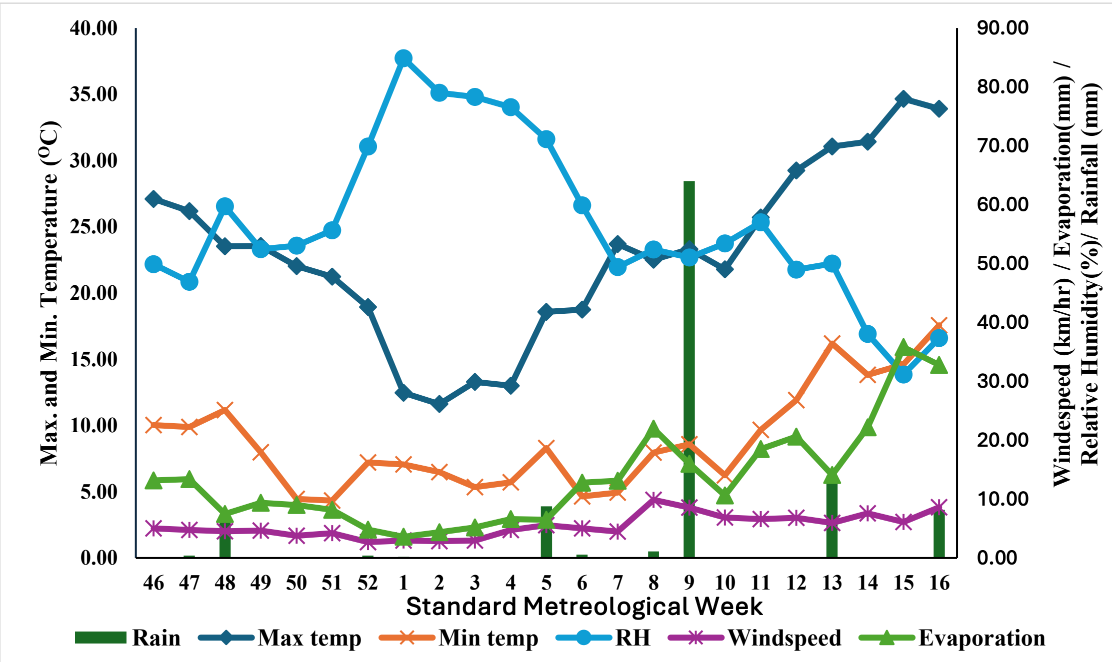



**Fig 3.2: Weekly mean meteorological data for *rabi* season 2023-24**

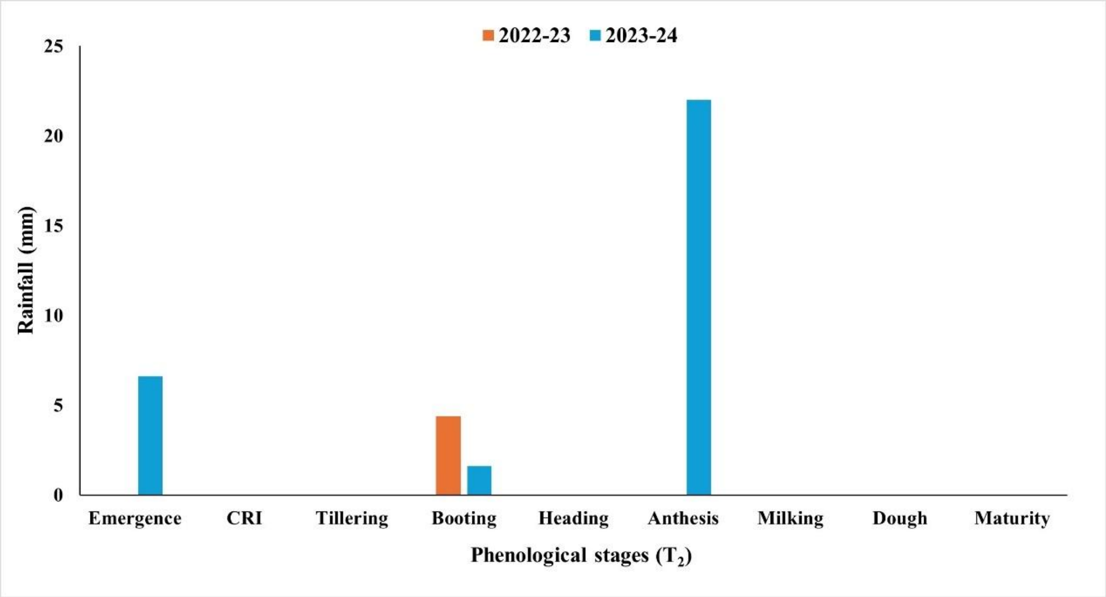



**Fig 3.3: Rainfall (mm) during various phenological stages during 2022-23 and 2023-24**

### 3.3 Cropping history

Analysis of the previous season's cropping scheme can reveal the general fertility and crop production trends of the field. The cropping history can be used to evaluate the site's production potential for the experiment given in Table 3.1.

**Table 3.1: Crop record of the experimental field**

| Year | *Kharif* | *Rabi* |
|---|---|---|
| 2019-20 | Green gram | Wheat |
| 2020-21 | Maize | Mustard |
| 2021-22 | Maize | Wheat |
| 2022-23 | Soybean | Experimental crop |
| 2023-24 | Maize | Experimental crop |

### 3.4 Soil characteristics

Soil samples were gathered from various depths of the soil profile, namely 0-15 cm and 15-30 cm, from randomly selected sites in the experimental field before the crop was sown. The samples were analyzed for chemical properties, and the results are presented in Table 3.2. The sand, silt, and clay fractions were determined using the International Pipette Method (Piper, 1966), while bulk density was measured using the core sampler method. The chemical properties of the soil were examined using composite samples taken from two depths: 0-15 cm and 15-30 cm. The samples were collected from random locations using an auger before the commencement of the experiment. They were analyzed for available N, $P_2O_5$, and $K_2O$, along with soil pH, organic carbon (OC), and electrical conductivity, as detailed in Table 3.2.

**Table 3.2: Chemical properties of soil prior to sowing**

| **Characteristics** | **Values obtained** | | **Methods used** |
|---|---|---|---|
| | **2022** | **2023** | |
| Organic Carbon (%) | 0.43 | 0.42 | Walkley and Black's rapid titration method (Piper, 1966) |
| pH (1:2.5 soil: water) | 7.7 | 7.6 | Glass electrode pH meter (Jackson, 1973) |
| EC (1:2.5 soil: water) ($dSm^{-1}$ at 25°C) | 0.56 | 0.55 | Conductivity bridge (Jackson, 1973) |
| Available N (kg $ha^{-1}$) | 243 | 240 | Modified alkaline potassium permanganate method (Subbiah and Asija, 1956) |
| Available $P_2O_5$ (kg $ha^{-1}$) | 16.4 | 15.6 | Olsen's methods (Olsen *et al.,* 1954) |
| Available $K_2O$ (kg $ha^{-1}$) | 160 | 155 | Flame photometer methods (Jackson, 1973) |

### 3.5 Experimental details

***Treatments and experimental design:***

The investigation was conducted in a randomized complete block design and was replicated four times in both years. Treatments were randomly assigned to plots, which remained consistent across both years. Gross size of each plot was 4 × 5 meters. The details of the treatments are provided below:

| | |
|---|---|
| Design | Randomized block design |
| Year of the experiment | *Rabi* 2022-23 and 2023-24 |
| Crop | Wheat |
| Variety | Unnat PBW-343 |
| Treatments | 9 |
| Replication | 4 |
| Total number of plots | 9 × 4 = 36 |
| Size of gross plot | 4 × 5 $m^2$ |
| Size of net plot | 3 × 4 $m^2$ |
| Buffer between plots | 1.0 m |
| Irrigation channel | 1.5 m |
| Spacing (row × row) | 20 cm |

The details regarding the treatment combined and abbreviations are given in table 3.3. A one-meter buffer zone was ensured between the plots to prevent the interflow of water. The field was prepared through the conventional practice of ploughing with a tractor-driven rotavator. Pre-sowing irrigation was given as per recommendations. Soil moisture was measured using the gravimetric method (soil moisture boxes) for the whole cropping season to monitor soil moisture at the depth effective root zone i.e., 40 cm.

**Table 3.3: Treatment details**

| Treatments | Symbols |
|---|---|
| Recommended irrigation | $T_1$ |
| Irrigation at CRI and flowering stage | $T_2$ |
| Irrigation at 0.25 PSI* | $T_3$ |
| Irrigation at 0.50 PSI | $T_4$ |
| Irrigation at 0.75 PSI | $T_5$ |
| Irrigation at 25% depletion of FC** | $T_6$ |
| Irrigation at 30% depletion of FC | $T_7$ |
| Irrigation at 75% depletion of FC | $T_8$ |
| Rainfed | $T_9$ |

*In treatment $T_1$, irrigation was applied at critical growth stages, and soil moisture depletion was monitored gravimetrically, showing a consistent 50% depletion of field capacity. Thus, $T_1$ represents an irrigation scheduling based on 50% depletion of soil capacity.

** PSI = Plant Stress Index

*** FC = Field capacity

## 3.6 Agronomic practices

The niceties of the agricultural practices employed in the cultivation of wheat are outlined below:

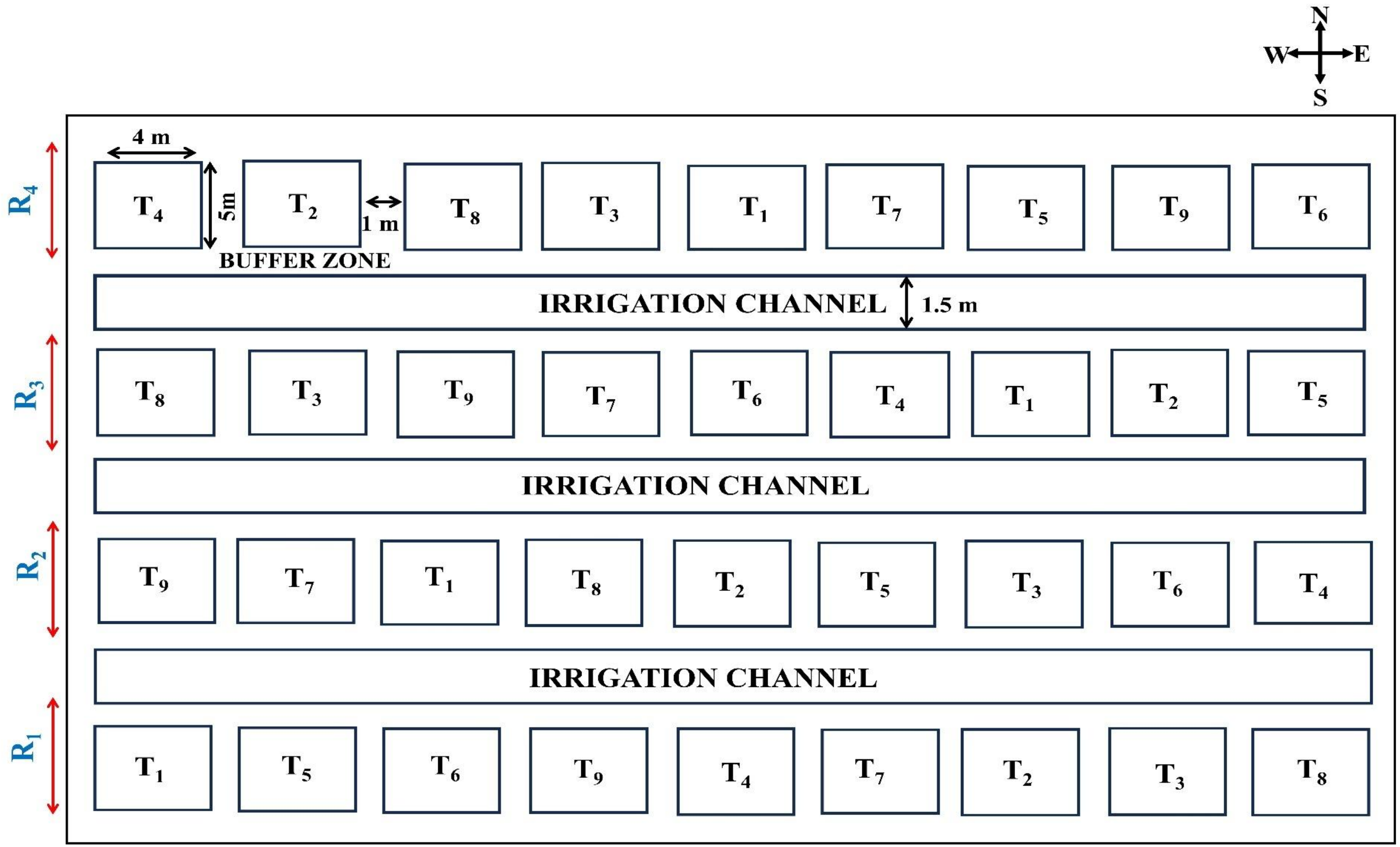
### 3.6.1 *Field Preparation and Sowing*

After harvesting the preceding crop, the stubble was manually removed from the experimental field without disturbing the soil surface. Pre-sowing irrigation was subsequently applied to all plots cultivated. The field was prepared through the conventional practice of ploughing with a tractor-driven rotavator.

Sowing was done on 23$^{rd}$ November and 17$^{th}$ November during 2022-23 and 2023-24, respectively. During both years, the variety Unnat PBW 343 was which is appropriate for timely sowing under irrigation was used. The row spacing between rows was maintained at 20 cm.

**Plate 3.1: Land preparation before sowing**

**Plate 3.2: Sowing of seed**




**Field layout during the experiment**

### 3.6.2 *Fertilizer application*

Nitrogen, phosphorus, and potassium were administered in accordance with the treatments. Nitrogen was supplied in the form of Urea (46% N), phosphorus as DAP (18% N; 46% P), and potassium as MOP (60% K). Nitrogen was administered in three phases: one-third as a basal treatment and the remaining two-thirds in two equal doses during the tillering and booting stages.

### 3.6.3: *Irrigation management*

In the experiment, the measurement of soil moisture was done by using the gravimetric methods with the help of soil moisture boxes. The irrigation was applied at 25%, 30% and 75% depletion of field capacity in treatments $T_6$, $T_7$ and $T_8$. To measure the soil's moisture content, soil samples were collected from each treatment using an auger and placed into aluminium boxes. The soil samples' fresh weight was subsequently documented. The samples were then dried to a constant weight in a hot air oven regulated at 105°C. Sample of dried soil's weight was measured.

$$Moisture\ content\ (\%) = \frac{Fresh\ weight - Dry\ weight}{Oven\ dry\ weight} \times 100$$

For the plant stress index (PSI) based treatments, irrigation was initiated in $T_3$, $T_4$, and $T_5$ when the PSI values reached 0.25, 0.50, and 0.75, respectively. The experimental treatments $T_1$ and $T_9$ were implemented to ascertain the minimum (Tcmin) and maximum canopy temperature (Tcmax), respectively. Comprehensive and regular irrigation practices were implemented for treatment $T_1$ to ensure the absence of water stress conditions, while treatment $T_9$ was subjected to rainfed conditions to induce the most severe water stress conditions on the crops. The PSI values were determined using the equation:

$$PSI = \frac{(Tc - Tcmin)}{Tcmax - Tcmin}$$

Where, Tcmin, Tcmax, and Tc represent the minimum, maximum and observed canopy temperature respectively. The temperature was recorded in the noon period from 12.00 to 2.00 PM.


**Plate 3.3: Measuring the soil moisture with the soil moisture boxes**

**Table 3.4: Number of irrigations applied to different treatments**

| Treatments | Number of irrigations | |
|---|---|---|
| | 2022-23 | 2023-24 |
| Recommended irrigation ($T_1$) | 5 | 5 |
| Irrigation at CRI and flowering stage ($T_2$) | 2 | 1 |
| Irrigation at 0.25 PSI ($T_3$) | 6 | 5 |
| Irrigation at 0.50 PSI ($T_4$) | 4 | 4 |
| Irrigation at 0.75 PSI ($T_5$) | 3 | 2 |
| Irrigation at 25% depletion of FC ($T_6$) | 7 | 6 |
| Irrigation at 30% depletion of FC ($T_7$) | 5 | 5 |
| Irrigation at 75% depletion of FC ($T_8$) | 2 | 2 |
| Rainfed ($T_9$) | 0 | 0 |

### 3.6.4 *Harvesting and Threshing*

The crop was harvested manually on April 20$^{th}$ in both 2023 and 2024. After harvesting, the crops were tied with labelled ropes and left to dry under the sun. After sun drying, manual threshing was carried out separately and harvested produce obtained from individual plots was weighed and collected in labelled bags. The grain yield was weighed separately after winnowing and cleaning. The straw yield was determined by deducting the grain weight from the total bundle weight and then expressed in tonnes per hectare (t $ha^{-1}$) according to the size of the net plot.

**Plate 3.4: Experimental field during the growth stages**

**Plate 3.5: Experimental field at physiological maturity**

**Plate 3.6: Harvesting and threshing operations during the experiment**

## 3.7 Observations recorded

### 3.7.1 Crop Phenology

#### *3.7.1.1 50% tillering stage (DAS)*

The number of days from sowing till 50 percent of tillers were produced by the crops, was taken as days taken to tillering.

#### *3.7.1.2 50% booting stage (DAS)*

The number of days from sowing until 50 percent of the tillers had swollen, as indicated by the flag leaf, was recorded as the days to booting. This count only included days before the initiation of the awn.

#### *3.7.1.3 50% heading stage (DAS)*

The number of days from sowing until 50 percent of the spikes had emerged from the wheat boots was documented as the days to heading.

#### *3.7.1.4 50% anthesis stage (DAS)*

The number of days from sowing till the anthers came out from 50 percent of the ear.

#### *3.7.1.5 Milking stage (DAS)*

After anthesis, each experimental plot was monitored frequently for milking. From each plot, five spikelets were taken and pressed between the thumb and fingers. The number of days to reach the milking stage was recorded as the date when a milk-like white liquid exuded from four out of five spikelets.

#### *3.7.1.6 Dough stage (DAS)*

After the anthesis, frequent monitoring was done to assess the dough stage. For each plot, five spikelets were taken and pressed between the thumb and fingers. The number of days to reach the dough stage was taken as the date when milk started solidifying.

#### *3.7.1.7 Maturity stage (DAS)*

Daily monitoring was done in each plot after the dough stage. From each plot, ten spikelets were checked randomly. When grains become hard but still 30 to 50% moisture content possessed by grain after pressing between the fingers. The crop gave a yellow appearance from outside of the experimental plots was taken as days to maturity. Similarly, when grains were too hard to crush between the fingers and had a yellow look from the outside of the plot, they took days to harvest.

### 3.7.2 Growth parameters

#### *3.7.2.1 Plant height (cm)*

The height of the wheat plant was quantified from the ground to the tip of the longest leaf. Evaluations were performed on ten randomly selected plants per plot. Data was documented at 30, 60, 90, and 120 days after sowing (DAS) and at harvest. The heights of five plants were measured, averaged, and reported as the mean plant height (cm).

#### *3.7.2.2 Total number of tillers $m^{-2}$*

The total count of tillers per metre of row length was documented at 30, 60, 90 and 120 DAS and at maturity, from two locations within each plot.

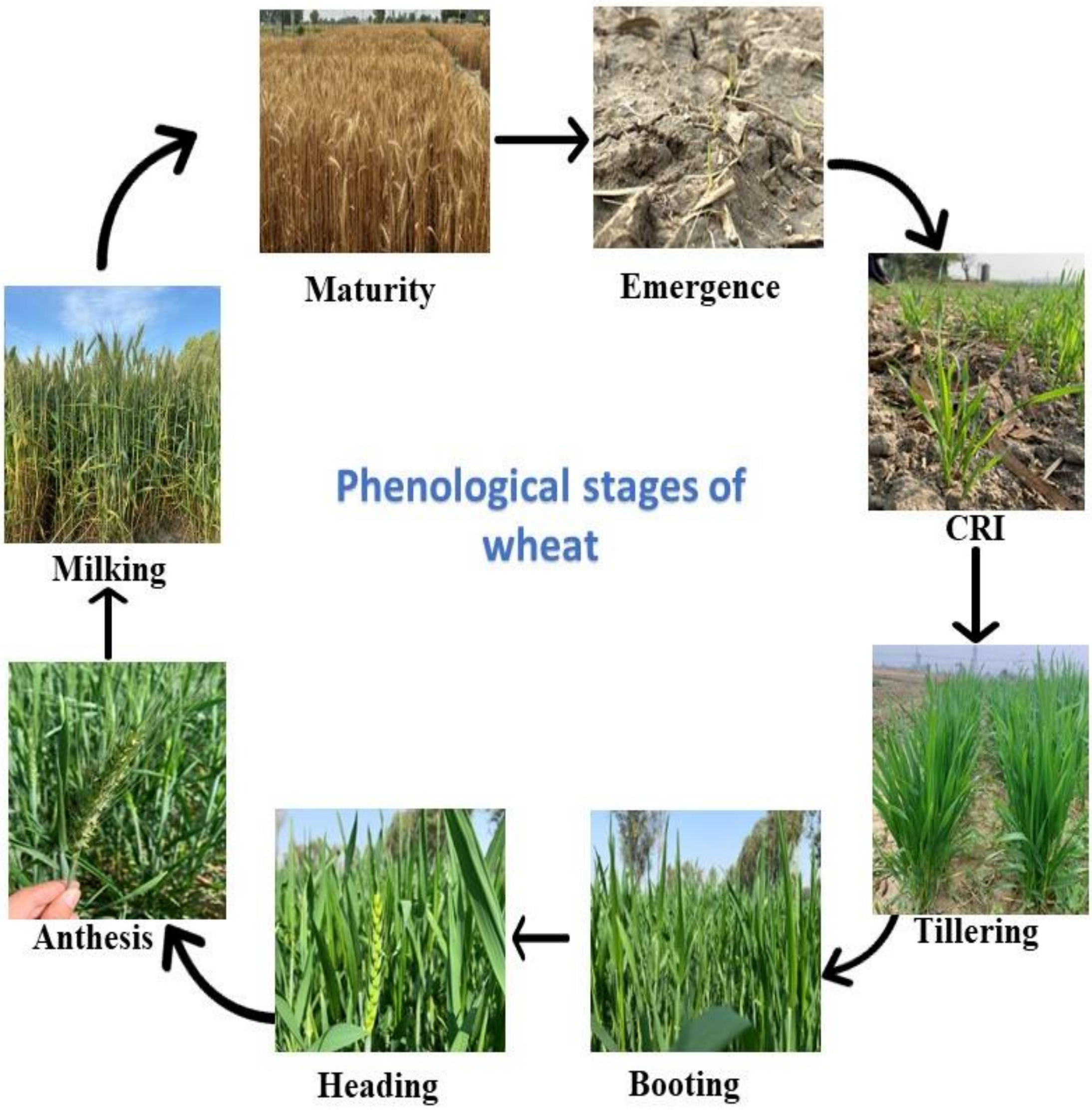



**Plate 3.7: Phenological stages of wheat crop**

*3.7.2.3 Dry matter accumulation (g $m^{-2}$)*

Accumulation of dry matter was assessed from the above-ground part of the plant along a 1-meter row length. Readings were obtained periodically at 30, 60, 90, and 120 DAS. Samples were dried to a consistent weight at 60°C in an oven. The resulting dry weight was averaged and converted into dry weight (g) per square meter.

**Plate 3.8: Measuring the plant height (cm)**

#### *3.7.2.4 Leaf Area Index*

The leaf area index (LAI) was assessed at 30-day intervals, specifically at 30, 60, 90, and 120 DAS. An automated leaf area meter was used to measure the areas of two sample leaves, one for each size group, separately. The mean leaf area value was then multiplied by the total count of leaves in each category, and the results were summed to estimate the total leaf area of the sample. LAI is a unitless parameter.

$$LAI = \frac{Leaf area}{Unit\ land\ area}$$

### 3.7.3 Physiological growth parameters

#### *3.7.3.1 Relative water content (%)*

Leaf relative water content (RWC) was documented at 30-60, 60-90, and 90-120 DAS. Leaf samples were collected, and their fresh weight was recorded immediately to prevent moisture loss. The leaves were immersed in distilled water for 24 hours, after which the turgid weight was recorded, ensuring that excess moisture was removed from the surface beforehand. The leaf samples were oven-dried at 60 °C until a constant dry weight was achieved. RWC was calculated following the method described by Barrs and Weatherley (1962).

$$RWC\ (\%) = \frac{Fresh\ weight - Dry\ weight}{Turgid\ weight - Dry\ weight} \times 100$$

***3.7.3.2 Crop growth rate (g m$^{-2}$ day$^{-1}$)***

Crop growth rate (CGR) refers to the rate at which dry matter is produced per unit area over a specified period. It was determined using the formula provided by Watson, (1947) and denoted in g m$^{-2}$ day$^{-1}$.

$$CGR = \frac{w_2 - w_1}{t_2 - t_1} \times \frac{1}{P}$$

$W_1$ and $W_2$ represent the dry weight of plants at times $t_1$ and $t_2$, respectively, and P is the land area in square meters ($m^2$).

***3.7.3.3 Relative growth rate (g g$^{-1}$ day$^{-1}$)***

It reflects the growth rate per unit of existing dry matter. It is denoted as grams of dry matter produced per gram of existing dry matter per day.

$$RGR = \frac{ln\, W_2 - lnW_1}{t_2 - t_1}$$

$W_1$ and $W_2$ are dry weights of plants at times $t_1$ and $t_2$ respectively and ln is the natural log.

***3.7.3.4 Absolute growth rate (g plant$^{-1}$ day$^{-1}$)***

It reflects the crop's growth rate, indicating whether it is growing faster or slower than normal. It is denoted as grams of dry matter produced per day.

$$AGR = \frac{w_2 - w_1}{t_2 - t_1}$$

$W_1$ and $W_2$ are the dry weight of plants at times $t_1$ and $t_2$ respectively.

***3.7.3.5 Net assimilation rate (g cm$^{-2}$ day$^{-1}$)***

It serves as an indirect indicator of net photosynthetic activity and is expressed as the amount of dry matter accumulated per day per square centimetre of leaf area. To calculate the net assimilation rate (NAR), the total leaf area of the crop was used. NAR was computed at 30-60, 60-90, and 90-120 days using the specified formula and is expressed in grams per square centimetre per day (g cm$^{-2}$ day$^{-1}$).

$$NAR = \frac{(W_2 - W_1) \times (\ln L_2 - \ln L_1)}{(t_2 - t_1) \times (L_2 - L_1)}$$

$W_1$ and $W_2$ are dry weight; $L_1$ and $L_2$ are the leaf area of the plants at times $t_1$ and $t_2$ respectively.

***3.7.3.6 Stress degree days (°C/day)***

The cumulative difference between leaf (canopy) temperature and air temperature reflects the duration and intensity of stress experienced by the crop. Stress Degree Days (SDD) are quantified by summing the differences between canopy and air temperatures over the entire crop growth period (Idso et al., 1977).

$$SDD = \sum_{i=1}^{n} (Tc - T_a)$$

Where, $Tc$ is the canopy temperature and $T_a$ is the air temperature in °C.

**3.7.4 Yield and yield attributing characters**

***3.7.4.1 Effective tillers (m$^{-2}$)***

Effective tillers per meter row length were tallied from two locations within each plot at harvest and then converted to effective tillers per square meter.

***3.7.4.2 Spike length (cm)***

Ear length was calculated from five ear samples selected at random in each experimental plot, excluding the awns. The lengths were then averaged to determine the average ear length.

***3.7.4.3 Number of grains per spike***

Five ears were randomly selected from each plot and manually threshed. The total number of grains per spike was recorded and averaged to determine the mean number of grains per spike.

#### *3.7.4.4 1000-grain weight (g)*

From every plot, a sample of one thousand grains was obtained, and their weight was noted.

#### *3.7.4.5 Grain and straw yield (t ha$^{-1}$)*

Following harvest, the total biomass was weighed in bundles and subsequently threshed to separate the grain from the straw. The weights of both grain and straw were recorded using an electronic balance and converted to yield values expressed in tonnes per hectare.

#### *3.7.4.6 Biological yield (t ha$^{-1}$)*

Upon the completion of the crop harvesting (from the net plot area), bundles were prepared in accordance with the designated treatments. The crop bundles, following a period of sun drying in the field lasting one-week post-harvest, were measured using a spring balance within the field setting. The obtained measurements were subsequently converted to a hectare-based unit and articulated in tonnes per hectare.

#### *3.7.4.7 Harvest index (%)*

The harvest index (HI) is defined as the ratio of economic yield (grain yield) to biological yield (the sum of grain and straw yields) and is expressed as a percentage.

$$HI\ (\%) = \frac{Economic\ Yield\ (grain)}{Biological\ Yield\ (grain + straw)} \times 100$$

### 3.7.5 Irrigation parameters

#### *3.7.5.1 Quantity of irrigation water applied*

The measurement of irrigation water was performed using a 90-degree V-notch weir, with the formula:

$$Q = 0.0138h^{2 \cdot 5}$$

Q = discharge rate (litre/second)

h = head (cm)

$$Total\ volume\ of\ water\ applied\ (VI)(m^3) = \frac{Q\ \times t \times 60\ \times no.of\ irrigations}{1000}$$

t = total time of irrigation water applied (min)

$$Total\ depth\ of\ water\ applied\ (m) = \frac{VI}{Area\ of\ plot}$$

VI = total amount of water applied throughout the entire growing period

***3.7.5.2 Total irrigation water (mm)***

It is defined as the amount of water delivered to each treatment, inclusive of losses through irrigation.

***3.7.5.3 Crop water requirement (mm)***

Its definition is the total amount of water, regardless of source, that a crop needs in a specific amount of time to grow and develop normally under field conditions at a specific location. It is the sum of irrigation water applied along with the effective rainfall (mm).

***3.7.5.4 Irrigation water use efficiency (t ha$^{-1}$ cm)***

The ratio of grain output to the total irrigation depth is known as water use efficiency. It was evaluated using the equation provided by Sharma *et al.,* (2023).

$$Field\ water\ use\ efficiency = \frac{Crop\ yield\ (t\ ha^{-1})}{Total\ depth\ of\ irrigation\ (mm)} \times 100$$

***3.7.5.5 Irrigation water productivity (kg m$^{-3}$):***

The grain yield of a crop that can be produced per unit of total water use is known as total water productivity.

$$Total\ water\ productivity = \frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ water\ use\ (m) \times 10000}$$

**3.7.6 Remote sensing data**

Normalised difference vegetation index (NDVI) and land surface water stress index are the spectrum indices that can be calculated using multispectral Landsat 8 data.

All the images of Landsat-8 archived in Google Earth Engine (GEE) were used to detect NDVI and LSWI of the Phagwara region. GEE is a flexible and strong computation platform that offers simple access to satellite data, processing on the cloud, scalable analysis, and configurable workflows. It makes precise vegetation monitoring fast and effective for users of all skill levels. The satellite in the series, Landsat 8, captures a picture with a temporal resolution of 16 days. A multispectral Landsat 8 image consists of two thermal and nine spectral bands. All spectral bands, except for the panchromatic band (Band 8), have a spatial resolution of 30 meters, while the panchromatic band has a resolution of 15 m. NDVI and LSWI were monitored from November to April for both *rabi* seasons, 2022-23 and 2023-24.

#### *3.7.6.1 Normalised difference vegetation index (NDVI)*

It is a crucial vegetation index widely employed in global studies of climatic and environmental changes (Bhandari *et al.,* 2012). It is calculated using the ratio of canopy reflectance in the red (Band 4) and near-infrared (Band 5) bands (Nageswara *et al.,* 2005). It can be calculated using the formula given by Tucker,1979.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

#### *3.7.6.2 Land surface water index (LSWI)*

Shortwave infrared (SWIR) (Band 6) and near-infrared (NIR) (Band 5) are used to calculate the land surface water index (LSWI). In the SWIR, liquid water absorbs a large amount of light, and the LSWI is sensitive to the overall water content in vegetation (Chandrasekar *et al.,* 2010).

$$LSWI = \frac{NIR - SWIR}{NIR + SWIR}$$

### 3.7.7 Soil studies

Soil samples were obtained from the experimental plots using a soil auger at a depth of 0 to 15 cm for subsequent analysis. The samples were then labelled and stored appropriately.

### *3.7.7.1 Soil pH and electrical conductivity (EC)*

Samples of dried soil weighing 20 g were obtained and put into a 100 ml beaker. 40 ml (soil: water in 1:2 ratio) of distilled water was added and stirred well with a glass rod and kept undisturbed for an hour. pH meter was calibrated by using three buffer solutions (4, 7 & 9.2 pH). Using a pH meter, the pH of the soil suspension was determined. EC was also recorded from the prepared suspension by using a conductivity meter (Jackson, 1973).

### *3.7.7.2 Organic carbon (%)*

Using the fast titration method devised by Walkley & Black, (1934) and the protocol outlined by Jackson, (1973), the soil's organic carbon content was determined.

### *3.7.7.3 Available N (kg ha$^{-1}$)*

Available soil N was determined using the alkaline permanganate method as described by Subbiah & Asija (1956).


**Plate 3.9: Recording pH using a soil pH meter**

**Procedure**

20 g of soil was weighed out and added to Kjeldahl's distillation assembly's distillation flask. Once this flask was assembled, 100 millilitres of 0.32% $KMnO_4$ solution was added to it. Two drops of methyl red indicator were added to a 250 ml

conical flask that had 25 ml of N/50 $H_2SO_4$ pipetted out of it. Make sure the delivery tube of the distillation apparatus is positioned beneath this conical flask so that it dips deeply into the flask's contents. Make sure the delivery tube of the distillation apparatus is positioned beneath this conical flask so that it dips deeply into the flask's contents. Distillation was then initiated, and roughly 150 ml of the distillate was collected. This was followed by a wet litmus paper test to confirm that ammonia was not coming out from the delivery tube.

The available N content in the soil was quantified by titrating the distillate collected in a conical flask with N/50 NaOH solution, and determining the volume of NaOH required to reach the endpoint.

#### *3.7.7.4 Available $P_2O_5$ (kg $ha^{-1}$)*

Using Jackson's (1973) description of Olsen's method, the amount of available phosphorus in the soil was calculated.

**Procedure of extraction:**

50 million litres of Olsen's extract are added to a 250-millilitre flask or shaking bottle containing 2.5 grams of soil and 0.5 grams of phosphorus-free activated charcoal. Whatman filter paper No. 1 is used to filter the contents after they have been shaken for 30 minutes on a mechanical shaker. In addition, a blank was run side by side.

**Procedure**

In a 50 ml volumetric flask, 10 ml of the extract is transferred, and 1-2 drops of the 2,4-dinitrophenol indicator are added. Subsequently, 5 N $H_2SO_4$ is added to adjust the pH to 3.5. The endpoint should be colourless. After the pH is adjusted, 50 millilitres of distilled water and 8 millilitres of ascorbic acid solution are added to finish the volume. With the aid of a colourimeter and a 660 nm wavelength or red filter, the intensity of the colour was measured after 30 minutes and before two hours of colour development. The instrument was first adjusted to zero reading using a blank. The phosphorus content of the extract is determined by comparing the reading to the phosphorus standard curve.

### *3.7.7.5 Available $K_2O$ (kg ha$^{-1}$)*

Available soil $K_2O$ was determined by extraction with a neutral normal ammonium acetate solution at a 1:5 soil-to-extractant ratio. The potassium concentration in the extract was measured using a flame photometer, following the procedure described by Jackson (1973).

**Procedure:**

5 g soil and 25 ml of neutral 1 N ammonium acetate are taken in a shaking bottle on a horizontal shaker and shaken for 5 minutes. Then the solution is filtered through Whatman filter paper No. 1. The flame photometer's K content is ascertained following the required calibration and standardisation of the devices using 10, 20, and 30 ppm K solution.

### *3.7.7.6 Bulk density (g/cc):*

Soil bulk density (ρb) was determined using the core sampler method, as described by Singh *et al.* (1980). The soil samples were oven-dried at 105°C until a constant weight was achieved. Bulk density was then calculated using the following formula:

$$Bulk\ density\ (\rho b) = \frac{Oven\ dry\ weight\ of\ soil}{Volume\ of\ soil}$$

**Plate 3.10: Performing the soil analysis**

### 3.7.8 Economic analysis

The cost of cultivation and gross returns (` $ha^{-1}$) for the various treatments were calculated based on the prevailing market prices of inputs and outputs. The determination of net returns (` $ha^{-1}$) involved deducting the total cultivation cost of each treatment from the gross income derived from the corresponding treatment. Furthermore, an analysis of the benefit-cost ratio was performed to evaluate the economic feasibility of the diverse treatments.

***3.7.8.1 Gross returns (` $ha^{-1}$)***

The economic returns for each treatment were determined by multiplying the crop yield with the market price in effect.

***3.7.8.2 Net returns (` $ha^{-1}$)***

Net returns were calculated by subtracting total variable costs from gross returns.

***3.7.8.3 Benefit cost ratio***

The benefit-cost ratio was determined by dividing the gross returns by the total variable costs for each treatment.

### 3.8 Statistical analysis:

The significance of treatment effects was assessed using the 'F' test (Fisher, 1958). The standard errors of differences between treatment groups and their interactions were calculated at a 5 per cent probability level when the 'F' value was significant. Treatment means are presented with both original values and transformed values in parentheses. Data for various characteristics were analyzed using analysis of variance (ANOVA) as outlined by Gomez & Gomez, (1984). ANOVA tables were prepared for each character in the following manner.

*CHAPTER 4*

# *RESULTS AND DISCUSSIONS*

This chapter presents the results from the experiment titled "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)" through appropriate tables and figures. Additionally, pertinent scientific explanations and supporting evidence from existing literature have been provided to clarify the cause-and-effect relationships observed in the experimental results.

## *I RESULTS*

## 4.1 Growth parameters

### 4.1.1 Crop phenology

#### *50% tillering stage (DAS)*

The tillering stage progresses through the advancement of the fifth leaf stage. Tillers are shoots that emerge laterally from the base of the plant's stem. The data regarding the duration of days required for wheat to reach maximum tillering is outlined in the provided table 4.1.

During the 2022–23 growing period, the longest duration required for wheat to reach the tillering stage was observed under the recommended irrigation treatment ($T_1$), with a total of 49 days, whereas the shortest duration (46 days) was recorded under rainfed conditions ($T_9$). A comparable trend persisted in the subsequent year (2023–24), wherein wheat plants irrigated according to the $T_1$, and $T_6$ irrigation scheduling methods exhibited a tillering stage duration of 49 days. Conversely, a reduction in the duration to 47 days was noted under rainfed conditions ($T_9$). However, statistical analysis indicated no significant differences among treatments in either year. The pooled analysis corroborated these findings, demonstrating that wheat plants subjected to $T_9$ conditions consistently reached the tillering stage within the shortest duration (47 days), while those irrigated based on $T_1$ and $T_6$ treatments required the longest duration (49 days).

***50% booting stage (DAS)***

The initiation of the booting stage commences with the flag leaf achieving full visibility. The stem, in its elongated state, propels the ear to emerge from the sheath of the flag leaf. The boot stage signifies the culmination of vegetative growth and subsequently transitions into the reproductive phase. The determination of the potential quantity of grains is established during the booting stage.

The results presented in Table 4.1 demonstrate that irrigation regimes significantly affected the number of days required to reach the booting stage in wheat across both crop seasons. In the 2022–2023 season, treatments $T_1$ (recommended irrigation) and $T_6$ (irrigation at 25% depletion of field capacity) each required 80 days to reach the booting stage, representing the maximum duration among all treatments. This was followed by treatment T7 (irrigation at 30% depletion of field capacity), which recorded 79 days. In the 2023–2024 season, a similar trend was observed, with $T_1$ and $T_6$ taking the longest duration (83 days) to reach the booting stage, which was significantly higher than the other treatments. Conversely, the rainfed treatment ($T_9$) consistently exhibited the shortest duration to booting, requiring only 75 days in both seasons. The pooled analysis corroborated the findings of individual years, with the highest number of days observed in $T_1$, statistically at par with $T_6$ and $T_7$, while the minimum duration to booting was recorded in $T_9$ (75 days).

***50% heading stage (DAS)***

The heading stage, characterized by the emergence of the ear from the flag leaf sheath until complete ear emergence, was significantly influenced by irrigation regimes across both cropping seasons, as shown in Table 4.1. In the 2022–2023 season, the maximum number of days to reach the heading stage was recorded in treatment $T_1$ (recommended irrigation), with 92 days, which was significantly at par with $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC), both of which required 91 days. In contrast, the minimum duration to heading was observed in treatment $T_9$ (rainfed), with the crop reaching this stage in 85 days, significantly earlier than in the other treatments. During the 2023–2024 season, a similar pattern was observed. The crop in treatment $T_1$ took the longest time (93 days) to attain the heading stage, which was statistically comparable to $T_6$, while the shortest duration (84 days) was again noted in $T_9$. The pooled analysis reflected a consistent trend across both years, with the highest number of days to heading recorded in $T_1$ (93 days), statistically similar to $T_6$ and $T_7$, and the lowest in $T_9$ (84 days).

***50% anthesis stage (DAS)***

The stage of flowering, known as anthesis, commences after heading. During this stage, pollen is discharged from the anthers. When approximately 50% of the plant population has reached the point where their flowers have opened and the anthers have started to protrude out of the spikelet, it is the anthesis stage of wheat. The anthesis stage holds significant importance in the field of agronomy as it is during this stage that the final number of grains per ear is determined**.** The data in table 4.1 shows that the count of days required for the crop to reach the anthesis stage is significantly swayed by different irrigation treatments.

In the 2022–2023 season, the maximum number of days to reach the 50% anthesis stage was recorded under recommended irrigation treatment ($T_1$), requiring 110 days. This was followed by treatments $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC), which required 109 and 107 days, respectively. In contrast, the shortest duration to anthesis was observed under the rainfed condition ($T_9$), with the crop reaching this stage in 95 days. A similar trend was observed during the 2023–2024 season, wherein treatment $T_1$ recorded the highest number of days to anthesis (114 days), significantly exceeding the other treatments, and was statistically at par with $T_6$ (111 days). The minimum duration to anthesis in the second year was again recorded in the rainfed treatment ($T_9$), with 97 days. The pooled analysis confirmed the significant influence of irrigation scheduling on the timing of anthesis, with trends consistent across both seasons.

***Milking stage (DAS)***

The milking stage in wheat commences immediately after the completion of anthesis and is characterized by the accumulation of a pale, milky fluid within the developing grains. This stage precedes the dough stage, during which the fluid solidifies into grain tissue. In the 2022–2023 season, the shortest duration to reach the milking stage was observed under rainfed conditions ($T_9$), with the crop attaining this stage in 106 days. In contrast, the recommended irrigation treatment ($T_1$) and irrigation at 25% depletion of FC ($T_6$) required 123 and 121 days, respectively, to reach this stage, with the difference between the two being statistically non-significant (Table 4.2). During the 2023–2024 season, a similar pattern was observed, with treatment $T_1$ taking the longest time (128 days) to reach the milking stage, which was significantly higher than the 112 days recorded under rainfed conditions ($T_9$). The pooled analysis revealed a significant influence of irrigation scheduling on the time to reach the milking stage. Treatment $T_1$ exhibited the maximum duration (125 days), whereas the minimum (109 days) was recorded under $T_9$, highlighting the pronounced effect of limited water availability on accelerating crop phenology.

***Dough stage (DAS)***

The wheat kernels reach full formation during the dough stage because of the solidification of milk. Although the grain may exhibit minimal deformation upon compression, there is no apparent presence of liquid.

The data presented in Table 4.2 demonstrate a significant effect of irrigation scheduling treatments on the number of days required for wheat to reach the dough stage across both cropping seasons. In 2022–2023, the maximum duration to attain the dough stage was recorded under the recommended irrigation treatment ($T_1$), with 141 days, which was significantly greater than the 115 days observed under rainfed conditions ($T_9$). A similar trend was observed during the 2023–2024 season, where treatment $T_1$ again required the longest time (143 days), significantly exceeding the duration under $T_9$ (117 days). Treatments $T_6$ (140 days) and $T_7$ (137 days) also required extended durations to reach the dough stage and were statistically comparable to $T_1$. The pooled data analysis further confirmed the significant impact of irrigation regimes, with the highest number of days to reach the dough stage recorded in $T_1$ (142 days), and the lowest in $T_9$ (116 days). A clear inverse relationship was observed between water availability and the time required to reach the dough stage, with increasing water stress accelerating crop phenological progression from recommended irrigation ($T_1$) to rainfed conditions ($T_9$), where rainfall was the sole moisture source.

***Maturity stage (DAS)***

At the stage of maturity, the movement of photosynthates and water ceases towards the kernels, resulting in the absence of any further deformation of grains upon pressure. Harvesting is carried out once the crop attains the optimal moisture content (18-20%) necessary for the harvesting process. The analysis indicated that the different irrigation scheduling regimes had a consequential impact in both years (Table 4.2).

During the 2022–23 growing season, the longest duration required for wheat to reach maturity was recorded under fully recommended irrigation ($T_1$), with a total of 148 days, whereas the shortest duration (123 days) was observed under rainfed conditions ($T_9$). A similar trend persisted in the subsequent year (2023–24), wherein wheat plants cultivated under $T_1$ conditions required a maximum of 150 days to attain maturity, a duration that was significantly greater compared to $T_9$, where maturity was achieved within 124 days. The pooled analysis corroborated these findings, indicating that the highest number of days to reach maturity stage was recorded under $T_1$, which was statistically comparable to treatments $T_6$ and $T_7$, while the shortest duration was consistently observed under $T_9$.

**Table 4.1: Effect of irrigation scheduling methods on wheat phenology**

| Treatments | Tillering (50%) | | | Booting (50%) | | | Heading (50%) | | | Anthesis (50%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 49 | 49 | 49 | 80 | 83 | 82 | 92 | 93 | 93 | 110 | 114 | 113 |
| Irrigation at CRI and Flowering stages ($T_2$) | 48 | 47 | 47 | 78 | 79 | 79 | 88 | 91 | 90 | 102 | 106 | 104 |
| Irrigation at 0.25 PSI ($T_3$) | 47 | 48 | 47 | 78 | 80 | 79 | 89 | 92 | 91 | 107 | 109 | 108 |
| Irrigation at 0.50 PSI ($T_4$) | 48 | 48 | 48 | 77 | 77 | 77 | 88 | 89 | 88 | 102 | 105 | 103 |
| Irrigation at 0.75 PSI ($T_5$) | 48 | 47 | 48 | 76 | 76 | 76 | 86 | 87 | 86 | 98 | 101 | 99 |
| Irrigation at 25% depletion of FC ($T_6$) | 49 | 49 | 49 | 80 | 83 | 81 | 91 | 93 | 92 | 109 | 111 | 110 |
| Irrigation at 30% depletion of FC ($T_7$) | 48 | 49 | 48 | 79 | 80 | 80 | 91 | 92 | 92 | 107 | 108 | 107 |
| Irrigation at 75% depletion of FC ($T_8$) | 48 | 47 | 47 | 76 | 76 | 77 | 84 | 86 | 85 | 97 | 100 | 98 |
| Rainfed ($T_9$) | 46 | 47 | 47 | 75 | 75 | 75 | 85 | 84 | 84 | 95 | 97 | 96 |
| **SEm+** | **0.7** | **0.6** | **0.5** | **0.8** | **0.8** | **0.7** | **0.6** | **1.8** | **1.0** | **1.8** | **2.0** | **1.7** |
| **C.D (p= 0.05)** | **NS** | **NS** | **NS** | **2.4** | **2.4** | **1.9** | **1.8** | **5.3** | **3.0** | **5.4** | **5.9** | **5.1** |

**Table 4.2: Effect of irrigation scheduling methods on wheat phenology**

| Treatments | Milking | | | Dough | | | Maturity | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 123 | 128 | 125 | 141 | 143 | 142 | 148 | 150 | 149 |
| Irrigation at CRI and Flowering stages ($T_2$) | 113 | 124 | 118 | 125 | 131 | 129 | 133 | 139 | 136 |
| Irrigation at 0.25 PSI ($T_3$) | 118 | 126 | 123 | 130 | 136 | 133 | 140 | 143 | 141 |
| Irrigation at 0.50 PSI ($T_4$) | 111 | 124 | 117 | 126 | 130 | 128 | 137 | 137 | 137 |
| Irrigation at 0.75 PSI ($T_5$) | 107 | 122 | 115 | 123 | 129 | 126 | 130 | 133 | 132 |
| Irrigation at 25% depletion of FC ($T_6$) | 121 | 128 | 125 | 139 | 140 | 140 | 146 | 149 | 147 |
| Irrigation at 30% depletion of FC ($T_7$) | 119 | 128 | 123 | 135 | 137 | 136 | 143 | 146 | 144 |
| Irrigation at 75% depletion of FC ($T_8$) | 107 | 118 | 112 | 120 | 120 | 120 | 128 | 127 | 128 |
| Rainfed ($T_9$) | 106 | 112 | 109 | 115 | 117 | 116 | 123 | 124 | 123 |
| **SEm+** | **1.9** | **2.6** | **1.5** | **2.1** | **2.3** | **1.9** | **4.2** | **4.6** | **2.5** |
| **C.D (p= 0.05)** | **5.7** | **7.7** | **4.4** | **6.3** | **7.0** | **5.6** | **12.4** | **13.5** | **7.3** |

### *4.1.2 Plant height (cm)*

The height of plant is a key growth parameter that significantly sways both the total production of dry matter and the crop yield. Plant height surged with the crop's duration, reaching its maximum at harvest. Plant height data were recorded periodically at 30, 60, 90, and 120 DAS, as well as at harvest. The outcomes revealed that, in both years, the height of wheat plant varied dramatically with varying irrigation levels, except for 30 DAS (Table 4.3).

In the 2022–23 growing season, irrigation schedules exhibited no significant effect on plant height at 30 days after sowing (DAS). However, the tallest plants (18.5 cm) were recorded under treatment $T_1$ (recommended irrigation), while the shortest (16.5 cm) were observed under rainfed conditions ($T_9$). As the crop advanced through subsequent growth stages, the maximum plant heights at 60 DAS (42.4 cm), 90 DAS (89.0 cm), 120 DAS (99.7 cm), and harvest (104.1 cm) were attained under treatment $T_1$, with values that were significantly greater than those recorded under other irrigation regimes. Statistical analysis indicated that treatments $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC) were comparable to $T_1$. Conversely, plants grown under $T_9$ (rainfed conditions) exhibited the lowest recorded heights, measuring 33.2 cm at 60 DAS, 69.0 cm at 90 DAS, 75.3 cm at 120 DAS, and 81.2 cm at harvest, which were significantly lower than those observed under alternative irrigation treatments.

During the following growing season, irrigation scheduling techniques had no significant effect on plant height of wheat at 30 DAS. However, the tallest plants (26.9 cm) were recorded under treatment $T_1$, whereas the shortest (26.1 cm) were observed under $T_9$ (rainfed conditions). At 60 DAS (50.5 cm), 90 DAS (93.1 cm), 120 DAS (101.7 cm), and harvest (107.7 cm), plants grown under treatment $T_1$ exhibited a statistically significant increase in height and were comparable to those under treatment $T_7$. In contrast, the minimum plant heights recorded under $T_9$ were 40.6 cm at 60 DAS, 71.7 cm at 90 DAS, 80.1 cm at 120 DAS, and 83.6 cm at harvest, which were significantly lower than those observed under alternative irrigation treatments to those in $T_1$.

**Table 4.3: Effect of irrigation scheduling methods on wheat plant height (cm)**

| Treatments | 30 DAS | | | 60 DAS | | | 90 DAS | | | 120 DAS | | | Harvest | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 18.5 | 26.9 | 22.7 | 42.4 | 50.5 | 46.6 | 89.0 | 93.1 | 91.0 | 99.7 | 101.7 | 100.7 | 104.1 | 107.7 | 105.9 |
| Irrigation at CRI and Flowering stages ($T_2$) | 17.6 | 26.6 | 21.1 | 36.3 | 46.4 | 41.3 | 78.7 | 82.4 | 80.5 | 84.8 | 96.9 | 90.8 | 91.4 | 98.8 | 95.1 |
| Irrigation at 0.25 PSI ($T_3$) | 16.8 | 26.8 | 21.8 | 35.9 | 45.5 | 40.7 | 80.9 | 83.4 | 82.1 | 87.8 | 97.7 | 92.7 | 94.3 | 100.7 | 97.5 |
| Irrigation at 0.50 PSI ($T_4$) | 16.7 | 26.6 | 21.8 | 35.6 | 45.4 | 40.5 | 79.6 | 82.7 | 81.2 | 86.5 | 97.1 | 91.8 | 93.9 | 99.3 | 96.6 |
| Irrigation at 0.75 PSI ($T_5$) | 16.6 | 26.2 | 21.4 | 34.8 | 45.3 | 40.0 | 72.2 | 78.3 | 75.2 | 81.5 | 88.3 | 84.9 | 87.4 | 91.7 | 89.5 |
| Irrigation at 25% depletion of FC ($T_6$) | 18.4 | 26.7 | 22.6 | 37.4 | 47.3 | 42.4 | 81.7 | 85.6 | 83.7 | 95.9 | 98.9 | 97.4 | 98.4 | 102.5 | 100.4 |
| Irrigation at 30% depletion of FC ($T_7$) | 17.5 | 26.7 | 22.2 | 39.4 | 50.2 | 45.1 | 83.6 | 91.0 | 87.3 | 98.6 | 100.3 | 99.4 | 101.2 | 104.6 | 102.9 |
| Irrigation at 75% depletion of FC ($T_8$) | 16.6 | 26.2 | 21.4 | 34.8 | 41.5 | 38.2 | 72.3 | 77.1 | 74.7 | 80.3 | 87.7 | 84.0 | 87.4 | 90.0 | 88.7 |
| Rainfed ($T_9$) | 16.5 | 26.1 | 21.3 | 33.2 | 40.6 | 36.9 | 69.0 | 71.7 | 70.3 | 75.3 | 80.1 | 77.7 | 81.2 | 83.6 | 82.4 |
| **SEm+** | **0.9** | **1.2** | **0.8** | **1.8** | **2.1** | **1.6** | **3.9** | **4.2** | **0.9** | **4.6** | **3.6** | **2.6** | **3.8** | **4.2** | **2.6** |
| **C.D (p= 0.05)** | **NS** | **NS** | **NS** | **5.2** | **6.2** | **4.8** | **11.5** | **12.3** | **8.3** | **13.6** | **10.5** | **7.7** | **9.8** | **12.2** | **7.6** |

Consistent with the results observed across both years, the pooled analysis revealed a significant effect of irrigation scheduling on wheat plant height, except at 30 DAS. In treatment $T_1$, plant height was recorded as 46.6 cm at 60 DAS, 91.0 cm at 90 DAS, 100.7 cm at 120 DAS, and 105.9 cm at harvest, all of which were significantly higher when compared to the plant heights observed in treatment $T_9$, which measured 36.9 cm at 60 DAS, 70.3 cm at 90 DAS, 77.7 cm at 120 DAS, and 82.4 cm at harvest. Plant heights in treatments $T_7$ (irrigation at 30% depletion of FC) and $T_6$ (irrigation at 25% depletion of FC) were found to be statistically similar to those in treatment $T_1$.

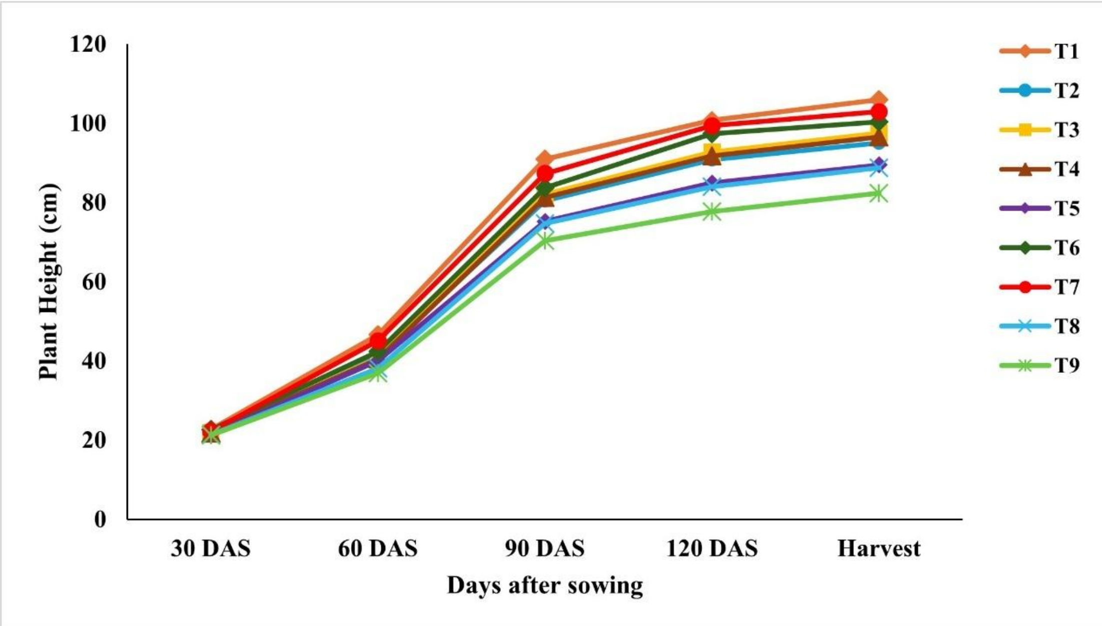



**Fig 4.1: Effect of irrigation scheduling methods on plant height of wheat (pooled)**

### *4.1.3 Number of tillers ($m^{-2}$)*

The number of tillers is a critical aspect in crop growth, serving a significant purpose in achieving adequate ground coverage and efficient utilization of solar radiation, ultimately impacting grain yield. The tiller count was highest at 60 DAS, aligning with the peak tillering phase of wheat, and then reduced due to the death of the tillers. Data regarding the number of tillers is provided in table 4.4.

During the 2022–23 growing season, irrigation scheduling methods had no significant influence on tiller density at 30 DAS. However, the highest tiller count (267.8 $m^{-2}$) was recorded under treatment $T_1$, whereas the lowest (240.1 $m^{-2}$) was observed under rainfed conditions ($T_9$). The application of recommended irrigation ($T_1$) resulted in a significantly higher tiller count at 60 DAS (459.2 $m^{-2}$), 90 DAS (425.4 $m^{-2}$), and in the number of effective tillers (396.4 $m^{-2}$) compared to other irrigation scheduling methods. Treatments $T_7$ (445.6 and 410.3 $m^{-2}$) and $T_6$ (434.9 and 390.2 $m^{-2}$) exhibited statistically similar results to $T_1$ at both 60 and 90 DAS. Furthermore, the effective tiller count for $T_6$ and $T_7$ was statistically at par with $T_1$. In contrast, the lowest tiller densities were recorded under $T_9$, with significantly reduced counts at 60 DAS (351.0 $m^{-2}$), 90 DAS (328.1 $m^{-2}$), and in the effective tillers count (302.4 $m^{-2}$) when compared to all other irrigation scheduling methods. During the 2023–24 growing season, tiller density at 30 DAS did not exhibit statistically significant differences across irrigation treatments. However, the highest tiller count (278.6 $m^{-2}$) was recorded under treatment $T_1$, whereas the lowest (245.5 $m^{-2}$) was observed under rainfed conditions ($T_9$). At later growth stages, maximum tiller density was attained under $T_1$, with 480.5 $m^{-2}$ at 60 DAS, which was statistically comparable to $T_7$ (30% depletion of FC), recording 474.0 $m^{-2}$ at 60 DAS and 430 $m^{-2}$ at 90 DAS. Conversely, plants grown under rainfed conditions ($T_9$) exhibited a significantly reduced tiller count of 365.4 $m^{-2}$ and 340.4 $m^{-2}$ at 60 and 90 DAS, respectively, compared to other irrigation scheduling methods.

The highest number of effective tillers (416.5 $m^{-2}$) was also observed under $T_1$, which was statistically superior to other irrigation treatments, whereas the lowest effective tiller count (317.2 $m^{-2}$) was recorded under $T_9$. Statistical analysis indicated that treatments $T_6$ and $T_7$ were comparable to $T_1$ in terms of effective tiller count. Pooled analysis further confirmed that irrigation scheduling had no significant effect on tiller density at 30 DAS. However, at 60 DAS (469.8 $m^{-2}$) and 90 DAS (436.2 $m^{-2}$), significantly higher tiller counts were recorded under $T_1$, whereas the lowest values were observed under $T_9$ (358.2 $m^{-2}$ at 60 DAS and 335.0 $m^{-2}$ at 90 DAS). The highest pooled effective tiller count (406.5 $m^{-2}$) was documented under $T_1$, whereas the lowest (309.8 $m^{-2}$) was recorded under $T_9$. Additionally, treatments $T_6$ and $T_7$ remained statistically comparable to $T_1$ across tiller count assessments at 60 and 90 DAS, as well as effective tiller density.

**Table 4.4: Effect of irrigation scheduling methods on number of tillers ($m^{-2}$) of wheat**

| Treatments | 30 DAS | | | 60 DAS | | | 90 DAS | | | Effective tillers | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** |
| Recommended irrigation ($T_1$) | 267.8 | 278.6 | 273.2 | 459.2 | 480.5 | 469.8 | 425.4 | 436.1 | 431.2 | 396.4 | 416.5 | 406.5 |
| Irrigation at CRI and Flowering stages ($T_2$) | 257.9 | 266.5 | 262.2 | 408.8 | 437.5 | 423.2 | 371.3 | 379.7 | 375.7 | 342.1 | 368.1 | 355.1 |
| Irrigation at 0.25 PSI ($T_3$) | 258.6 | 265.4 | 262.0 | 400.4 | 427.4 | 413.9 | 376.5 | 402.8 | 389.7 | 356.3 | 381.1 | 368.7 |
| Irrigation at 0.50 PSI ($T_4$) | 252.6 | 262.0 | 257.3 | 395.9 | 422.3 | 409.2 | 369.0 | 380.5 | 374.8 | 352.8 | 374.2 | 363.5 |
| Irrigation at 0.75 PSI ($T_5$) | 249.9 | 253.2 | 250.0 | 389.1 | 413.2 | 401.2 | 350.9 | 376.0 | 364.4 | 330.6 | 334.0 | 337.5 |
| Irrigation at 25% depletion of FC ($T_6$) | 262.8 | 270.3 | 266.5 | 434.9 | 460.6 | 447.9 | 390.2 | 415.8 | 403.0 | 369.9 | 389.2 | 379.6 |
| Irrigation at 30% depletion of FC ($T_7$) | 259.5 | 266.8 | 263.2 | 445.6 | 474.0 | 459.8 | 410.3 | 430.0 | 420.5 | 378.0 | 409.2 | 393.6 |
| Irrigation at 75% depletion of FC ($T_8$) | 242.2 | 249.4 | 245.8 | 372.9 | 388.9 | 380.9 | 346.6 | 364.4 | 355.5 | 324.4 | 333.1 | 328.6 |
| Rainfed ($T_9$) | 240.1 | 245.5 | 242.8 | 351.0 | 365.4 | 358.2 | 328.1 | 340.4 | 335.0 | 302.4 | 317.2 | 309.8 |
| **SEm+** | **12.5** | **15.9** | **9.29** | **21.2** | **23.2** | **16.8** | **19.8** | **19.6** | **12.4** | **15.2** | **21.5** | **13.1** |
| **C.D (p= 0.05)** | **NS** | **NS** | **NS** | **62.1** | **67.7** | **49.1** | **57.7** | **57.1** | **36.3** | **44.7** | **62.7** | **38.2** |

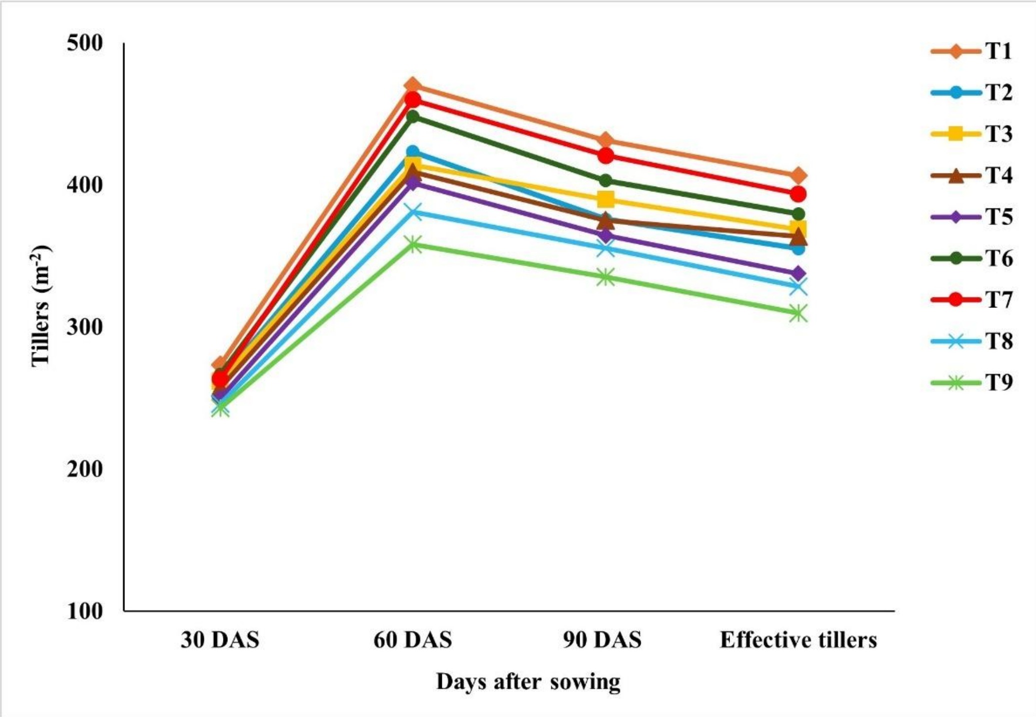



**Fig 4.2: Effect of irrigation scheduling methods on the number of tillers ($m^{-2}$) of wheat (pooled)**

### *4.1.4 Dry matter accumulation (g $m^{-2}$)*

Dry matter accumulation is an essential measure for the progression of crop development and its capacity to be converted into tangible economic returns. Over the two-year study, a significant accumulation of dry matter was discerned between 60 & 90 DAS and is shown in table 4.5.

During the 2022–23 cropping season, irrigation scheduling methods had no significant effect on dry matter accumulated in wheat at 30 DAS. However, the highest dry matter accumulation (42.2 g $m^{-2}$) was recorded under treatment $T_1$ (recommended irrigation), whereas the lowest (35.9 g $m^{-2}$) was observed under rainfed conditions ($T_9$). At later growth stages, maximum dry matter was attained under $T_1$, with values of 185.7 g $m^{-2}$ at 60 DAS, 607.6 g $m^{-2}$ at 90 DAS, and 794.7 g $m^{-2}$ at 120 DAS. Statistical analysis indicated that treatments $T_7$ (irrigation at 30% depletion of FC) and $T_6$ (irrigation at 25% depletion of FC) were comparable to $T_1$ from 60 DAS until harvest. Conversely, plants grown under $T_9$ exhibited the lowest dry matter accumulation, recording 144.7 g $m^{-2}$ at 60 DAS, 518.1 g $m^{-2}$ at 90 DAS, and 653.7 g $m^{-2}$ at 120 DAS. In the subsequent growing season (2023–2024), irrigation scheduling methods significantly influenced accumulation of dry matter during all the growth stages, with the exception of 30 DAS. The highest dry matter accumulation (44.9 g $m^{-2}$) was recorded under $T_1$, while the lowest (35.3 g $m^{-2}$) was observed under $T_9$. Among all treatments, the maximum dry matter accumulation occurred in $T_1$ (recommended irrigation), reaching 231.5 g $m^{-2}$ at 60 DAS, 629.8 g $m^{-2}$ at 90 DAS, and 819.5 g $m^{-2}$ at 120 DAS. Treatments $T_7$ (irrigation at 30% depletion of FC) and $T_6$ (irrigation at 25% depletion of FC) remained statistically comparable to $T_1$. In contrast, the lowest DMA values were recorded under $T_9$ (rainfed) across all growth stages, with 156.6 g $m^{-2}$ at 60 DAS, 524.4 g $m^{-2}$ at 90 DAS, and 670.5 g $m^{-2}$ at 120 DAS.

The pooled analysis confirmed the trends observed in both years, indicating that irrigation scheduling significantly influenced dry matter accumulation at later growth stages (60, 90, and 120 DAS), as well as at harvest. The highest amount of dry matter accumulation was observed for $T_1$ at 30 DAS (43.6 g $m^{-2}$), 60 DAS (208.6 g $m^{-2}$), 90 DAS (618.7 g $m^{-2}$), and 120 DAS (807.1 g $m^{-2}$), which was significantly higher than $T_9$, where values of 35.6 g $m^{-2}$, 150.6 g $m^{-2}$, 521.3 g $m^{-2}$, and 662.1 g $m^{-2}$ were recorded at 30, 60, 90, and 120 DAS, respectively. Additionally, $T_7$ and $T_6$ were found to be statistically comparable to $T_1$ across all measured parameters.

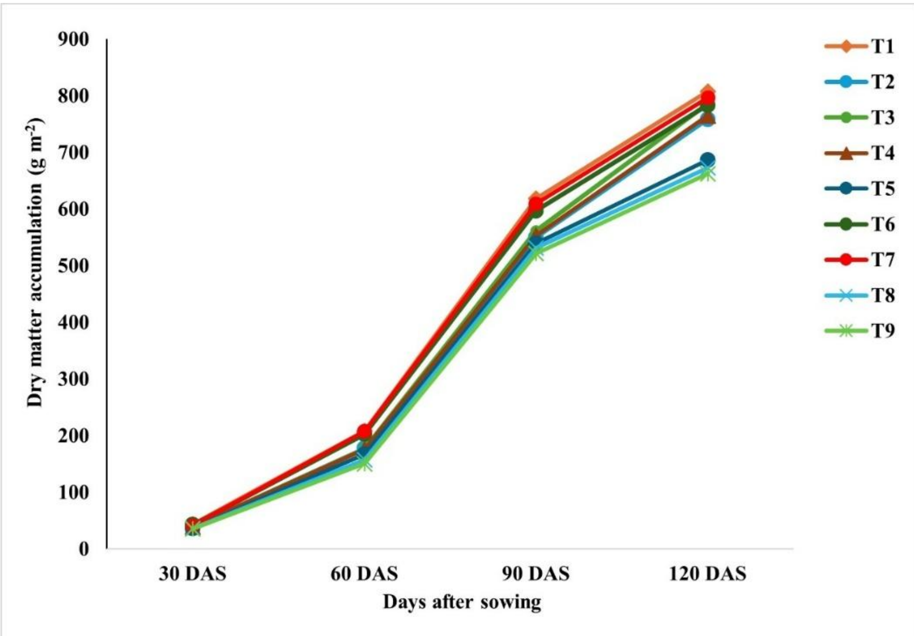



**Fig 4.3: Effect of irrigation scheduling methods on dry matter accumulation (g $m^{-2}$) of wheat (pooled)**

**Table 4.5: Effect of irrigation scheduling methods on dry matter accumulation (g $m^{-2}$) of wheat**

| Treatments | 30 DAS | | | 60 DAS | | | 90 DAS | | | 120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 42.2 | 44.9 | 43.6 | 185.7 | 231.5 | 208.6 | 607.6 | 629.8 | 618.7 | 794.7 | 819.5 | 807.1 |
| Irrigation at CRI and Flowering stages ($T_2$) | 36.8 | 41.7 | 39.2 | 160.1 | 194.9 | 177.5 | 540.3 | 559.6 | 550.0 | 748.0 | 768.6 | 758.3 |
| Irrigation at 0.25 PSI ($T_3$) | 36.8 | 41.4 | 39.1 | 158.4 | 195.1 | 176.7 | 550.4 | 572.3 | 561.4 | 769.4 | 802.1 | 785.7 |
| Irrigation at 0.50 PSI ($T_4$) | 36.7 | 40.9 | 38.8 | 157.7 | 194.1 | 175.9 | 542.6 | 564.4 | 553.5 | 756.1 | 773.3 | 764.7 |
| Irrigation at 0.75 PSI ($T_5$) | 35.8 | 37.4 | 36.6 | 152.6 | 182.2 | 167.4 | 531.2 | 547.5 | 539.3 | 677.4 | 695.4 | 686.4 |
| Irrigation at 25% depletion of FC ($T_6$) | 41.5 | 43.6 | 42.6 | 183.0 | 221.6 | 202.3 | 575.5 | 618.6 | 597.0 | 767.6 | 799.2 | 783.4 |
| Irrigation at 30% depletion of FC ($T_7$) | 38.5 | 43.2 | 40.8 | 185.0 | 230.2 | 207.6 | 594.8 | 624.2 | 609.5 | 782.0 | 810.3 | 796.2 |
| Irrigation at 75% depletion of FC ($T_8$) | 36.4 | 36.5 | 36.4 | 149.2 | 166.4 | 157.8 | 523.8 | 538.8 | 531.3 | 663.7 | 681.1 | 672.4 |
| Rainfed ($T_9$) | 35.9 | 35.3 | 35.6 | 144.7 | 156.6 | 150.6 | 518.1 | 524.4 | 521.3 | 653.7 | 670.5 | 662.1 |
| **SEm+** | **2.2** | **3.7** | **2.1** | **9.9** | **16.1** | **9.4** | **20.5** | **24.5** | **18.2** | **30.2** | **34.2** | **26.2** |
| **C.D (p= 0.05)** | **NS** | **NS** | **NS** | **29.09** | **46.9** | **27.5** | **59.9** | **72.7** | **53.3** | **88.3** | **99.8** | **76.6** |

### *4.1.5 Leaf Area Index*

The leaf area index (LAI) serves as a descriptor of the plant canopy, quantifying the photosynthetically active leaf area. The data presented in Table 4.6 reveal that LAI was significantly influenced by different irrigation scheduling methods at all growth stages, except at 30 DAS, during both years of study. In 2022–23, at 30 DAS, the highest LAI (0.81) was recorded under the recommended irrigation schedule ($T_1$), while the lowest (0.74) was observed under the rainfed condition ($T_9$), though differences were not statistically significant. At 60, 90, and 120 DAS, treatment $T_1$ consistently produced the maximum LAI values of 2.58, 4.40, and 4.12, respectively. These were followed by $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC), which were statistically comparable to $T_1$. In contrast, the lowest LAI values were recorded under $T_9$, with 2.10 at 60 DAS, 3.40 at 90 DAS, and 3.23 at 120 DAS.

A similar trend was observed in the 2023–2024 season, where differences in LAI at 30 DAS were non-significant, with the highest value recorded under treatment $T_1$ (0.83) and the lowest under treatment $T_9$ (0.76). At 60, 90, and 120 DAS, $T_1$ again exhibited the highest LAI values (2.84, 4.62, and 4.36), followed closely by $T_7$ (2.71, 4.50, and 4.26), which was statistically at par with $T_1$. The lowest LAI values during these stages were recorded in the rainfed regime ($T_9$), with 2.43 at 60 DAS, 3.80 at 90 DAS, and 3.47 at 120 DAS. Pooled analysis over the two years confirmed that irrigation scheduling had no significant effect on LAI at 30 DAS. However, from 60 DAS onward, $T_1$ consistently resulted in significantly higher values of LAI (2.71 at 60 DAS, 4.51 at 90 DAS, and 4.25 at 120 DAS), with $T_7$ and $T_6$ being statistically similar across all stages. The lowest LAI values in the pooled analysis were observed under the rainfed treatment ($T_9$), with 2.27, 3.60, and 3.35 at 60, 90, and 120 DAS, respectively.

**Table 4.6: Effect of irrigation scheduling methods on leaf area index of wheat**

| Treatments | 30 DAS | | | 60 DAS | | | 90 DAS | | | 120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** |
| Recommended irrigation ($T_1$) | 0.81 | 0.83 | 0.82 | 2.58 | 2.84 | 2.71 | 4.40 | 4.62 | 4.51 | 4.12 | 4.36 | 4.25 |
| Irrigation at CRI and Flowering stages ($T_2$) | 0.77 | 0.80 | 0.78 | 2.27 | 2.60 | 2.43 | 4.00 | 4.09 | 4.05 | 3.55 | 3.83 | 3.70 |
| Irrigation at 0.25 PSI ($T_3$) | 0.76 | 0.81 | 0.78 | 2.12 | 2.62 | 2.37 | 3.87 | 4.13 | 4.00 | 3.72 | 3.85 | 3.78 |
| Irrigation at 0.50 PSI ($T_4$) | 0.75 | 0.79 | 0.77 | 2.11 | 2.52 | 2.32 | 3.80 | 4.07 | 3.93 | 3.43 | 3.74 | 3.59 |
| Irrigation at 0.75 PSI ($T_5$) | 0.74 | 0.77 | 0.76 | 2.10 | 2.49 | 2.30 | 3.53 | 3.93 | 3.75 | 3.32 | 3.60 | 3.46 |
| Irrigation at 25% depletion of FC ($T_6$) | 0.77 | 0.81 | 0.80 | 2.33 | 2.69 | 2.52 | 4.19 | 4.46 | 4.33 | 3.77 | 4.19 | 4.01 |
| Irrigation at 30% depletion of FC ($T_7$) | 0.81 | 0.82 | 0.82 | 2.37 | 2.71 | 2.55 | 4.24 | 4.50 | 4.38 | 3.90 | 4.26 | 4.04 |
| Irrigation at 75% depletion of FC ($T_8$) | 0.74 | 0.79 | 0.76 | 2.11 | 2.54 | 2.33 | 3.63 | 3.93 | 3.78 | 3.39 | 3.60 | 3.50 |
| Rainfed ($T_9$) | 0.74 | 0.76 | 0.75 | 2.10 | 2.43 | 2.27 | 3.40 | 3.80 | 3.60 | 3.23 | 3.47 | 3.45 |
| **SEm+** | **0.02** | **0.02** | **0.01** | **0.07** | **0.08** | **0.06** | **0.11** | **0.12** | **0.07** | **0.12** | **0.11** | **0.09** |
| **C.D (p= 0.05)** | **NS** | **NS** | **NS** | **0.22** | **0.23** | **0.18** | **0.34** | **0.33** | **0.22** | **0.32** | **0.32** | **0.29** |

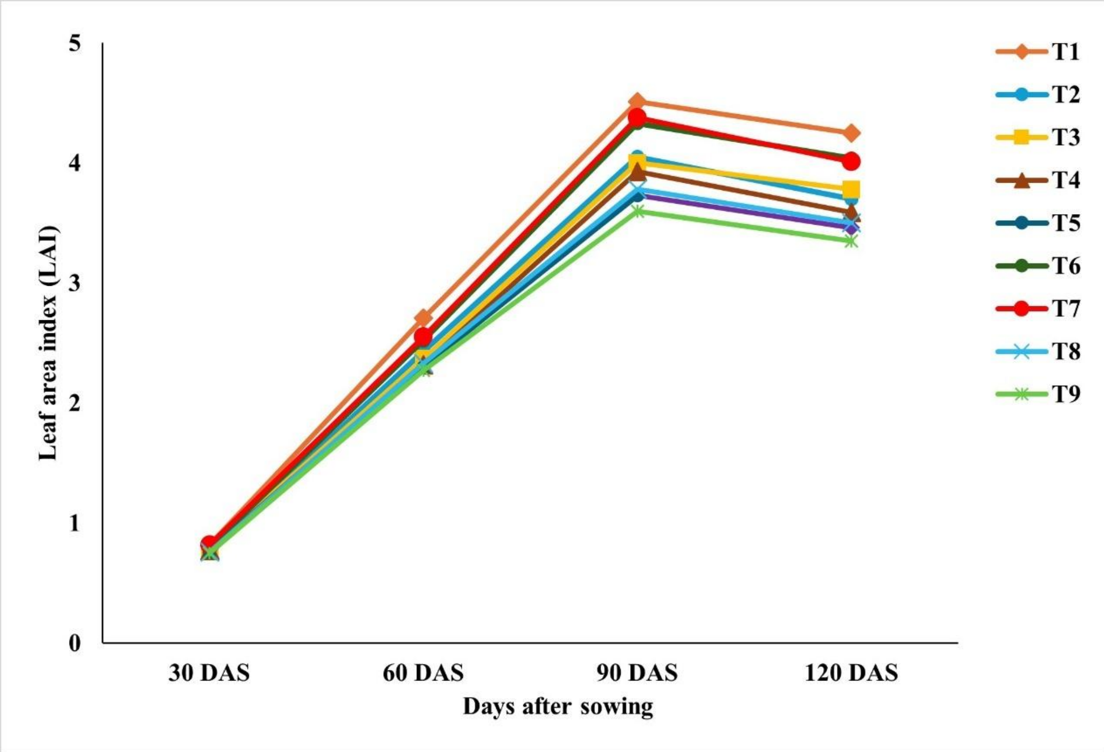



**Fig 4.4: Effect of irrigation scheduling methods on leaf area index of wheat (pooled)**

## 4.2 Physiological Parameters

### *4.2.1 Relative water content (%)*

The relative water content (RWC) serves as a significant parameter signifying the level of water pressure experienced by plants. It contributes to a more profound comprehension of the water movement within the soil-plant-atmosphere system (SPEC). The leaf RWC specifically highlights the difference between the water received by leaves and the transpiration rate (Lugojan & Cicula, 2011). Data regarding RWC is exhibited in table 4.7.

During 2022-23, a significant effect of irrigation scheduling was observed during 30-60, 60-90 and 90-120 DAS. At 30-60 DAS, the highest RWC of 85.8% was observed in the recommended irrigation treatment ($T_1$), which was significantly at par with 83.9% under irrigation at 25% depletion of FC ($T_6$) and 82.3% under irrigation at 30% depletion of FC ($T_7$). During 60-90 and 90-120 DAS trends were similar, where RWC of 83.6% and 83.1% respectively were observed when the recommended irrigation regime ($T_1$) was followed. Irrigation at 25% of depletion of FC and 30% RWC was observed to be at par with $T_1$ both at 60-90 and 90-120 DAS. The lower value of RWC was observed at 30-60 (72.6%), 60-90 (67.4%) and 90-120 DAS (64.7%), respectively in treatment $T_9$ (rainfed).

In the 2023–24 growing season, the highest relative water content (RWC) during the 30–60 DAS period was observed under the recommended irrigation regime ($T_1$), recording a value of 88.6%. This was followed by irrigation treatments at 25% and 30% depletion of field capacity ($T_6$ and $T_7$), and irrigation at 0.25 PSI ($T_3$), which recorded RWC values of 86.6%, 86.2%, and 82.5%, respectively. A similar trend in RWC was observed during the subsequent growth stages (60–90 and 90–120 DAS). In contrast, the rainfed treatment ($T_9$) exhibited significantly lower RWC values of 75.8%, 70.4%, and 68.4% during 30–60, 60–90, and 90–120 DAS, respectively.

Pooled data analysis indicated that irrigation scheduling methods statistically had a significant effect on RWC from 30 to 120 DAS period. The recommended irrigation regime ($T_1$) consistently maintained higher RWC values across all growth stages—87.2% (30–60 DAS), 84.2% (60–90 DAS), and 83.6% (90–120 DAS)—which were significantly superior when compared with other treatments. Conversely, the lowest RWC values were recorded under the rainfed regime ($T_9$), with 74.2%, 68.9%, and 66.6% during 30–60, 60–90, and 90–120 DAS, respectively.

**Table 4.7: Effect of irrigation scheduling methods on relative water content (%) of wheat**

| Treatments | 30-60 DAS | | | 60-90 DAS | | | 90-120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 85.8 | 88.6 | 87.2 | 83.6 | 84.8 | 84.2 | 83.1 | 84.2 | 83.6 |
| Irrigation at CRI and Flowering stages ($T_2$) | 77.8 | 80.1 | 79.0 | 71.7 | 76.7 | 74.2 | 71.7 | 73.7 | 72.7 |
| Irrigation at 0.25 PSI ($T_3$) | 78.5 | 82.5 | 80.5 | 76.0 | 77.0 | 76.5 | 74.0 | 74.1 | 74.1 |
| Irrigation at 0.50 PSI ($T_4$) | 75.8 | 81.3 | 78.6 | 75.0 | 75.5 | 75.2 | 69.6 | 71.4 | 71.0 |
| Irrigation at 0.75 PSI ($T_5$) | 75.7 | 79.4 | 77.5 | 67.1 | 71.5 | 69.3 | 66.3 | 69.8 | 68.0 |
| Irrigation at 25% depletion of FC ($T_6$) | 83.9 | 86.6 | 85.3 | 82.7 | 85.7 | 84.2 | 81.7 | 84.2 | 82.9 |
| Irrigation at 30% depletion of FC ($T_7$) | 82.3 | 86.2 | 84.3 | 80.4 | 82.3 | 81.4 | 78.3 | 81.0 | 79.7 |
| Irrigation at 75% depletion of FC ($T_8$) | 73.9 | 78.6 | 76.3 | 69.8 | 71.0 | 70.4 | 65.6 | 68.6 | 67.1 |
| Rainfed ($T_9$) | 72.6 | 75.8 | 74.2 | 67.4 | 70.4 | 68.9 | 64.7 | 68.4 | 66.6 |
| **SEm+** | **2.6** | **2.4** | **1.7** | **1.9** | **2.0** | **1.6** | **2.4** | **2.1** | **1.6** |
| **C.D (p= 0.05)** | **7.7** | **7.1** | **4.9** | **5.4** | **5.8** | **4.6** | **6.9** | **6.1** | **4.8** |

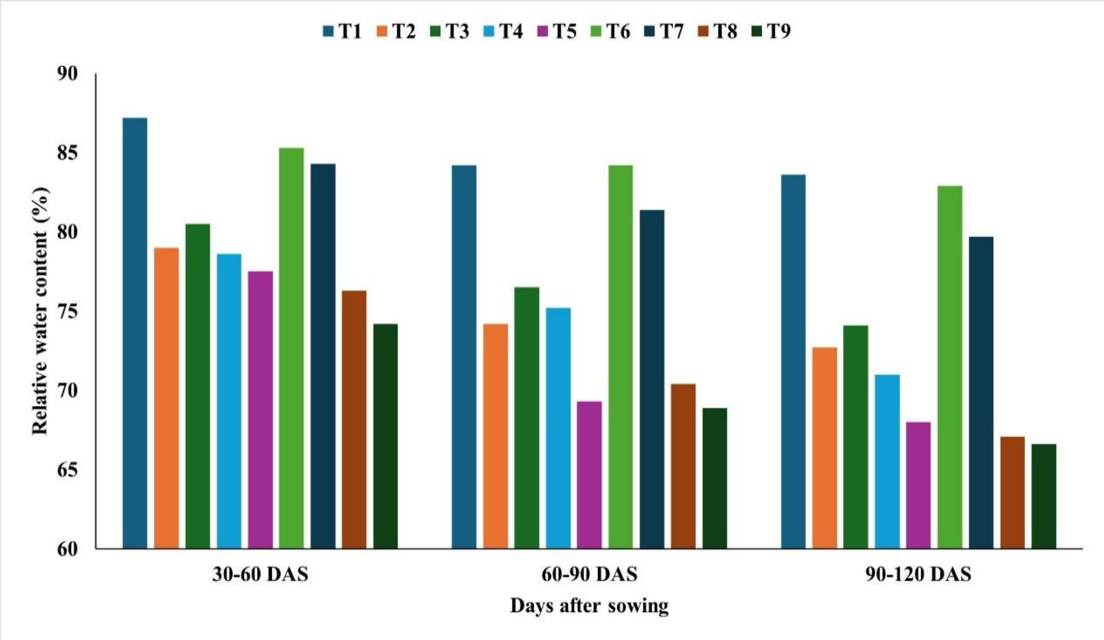



**Fig 4.5: Effect of irrigation scheduling methods on relative water (%) content of wheat (pooled)**

### *4.2.2 Crop growth rate (g m$^{-2}$ day$^{-1}$)*

Crop Growth Rate (CGR) is a key metric that indicates the rate of dry matter accumulation per unit area, making it a crucial variable in field analysis. The CGR is regulated by canopy, photosynthesis, and respiration, thereby representing a significant aspect of crop growth. Under various growing environments, the CGR initiates from a minimal level, eventually reaching a specific maximum point before declining thereafter. The data concerning the CGR of wheat was documented at three different stages: 30-60, 60-90, and 90-120 DAS is presented in table 4.8. CGR of wheat demonstrated its lowest value between 30-60 DAS, followed by a gradual increase from 60-90 DAS, and then a subsequent decline beginning at 90-120 DAS. CGR was significantly affected by irrigation scheduling methods implemented during both the 2022–2023 and 2023–2024 growing seasons.

During the initial cropping period, the highest crop growth rate (CGR) of 5.9 g m$^{-2}$ day$^{-2}$ was observed between 30-60 days DAS in the recommended irrigation treatment ($T_1$), followed by 5.1 g m$^{-2}$ day$^{-2}$ in $T_6$, and the lowest value of 1.9 g m$^{-2}$ day$^{-2}$ in the rainfed treatment ($T_9$). In the 60-90 DAS phase, the CGR reached its maximum at 17.2 g $m^{-2}$ $day^{-2}$ in $T_1$, with $T_6$ at 16.6 g $m^{-2}$ $day^{-2}$ and $T_7$ at 16.2 g $m^{-2}$ $day^{-2}$, while the lowest rate was recorded in $T_9$ at 9.9 g $m^{-2}$ $day^{-2}$ under rainfed conditions. Between 90-120 DAS, the highest CGR of 10.4 g $m^{-2}$ $day^{-2}$ was observed in the recommended irrigation treatment ($T_1$), which was statistically similar to $T_6$ at 10.2 g $m^{-2}$ $day^{-2}$. In contrast, the CGR declined to 3.32 g $m^{-2}$ $day^{-1}$ in the rainfed treatment ($T_9$).

In the 2023-24 growing season, the highest CGR during the 30-60, 60-90, and 90-120 DAS periods were recorded in the $T_1$ treatment group, with values of 6.5, 19.5, and 13.6 g $m^{-2}$ $day^{-2}$, respectively. These values showed statistical similarity to those of $T_6$, which had CGR values of 6.5, 17.5, and 12.3 g $m^{-2}$ $day^{-2}$, respectively. In contrast, the lowest CGR was observed in $T_9$, with values of 1.2, 9.7, and 5.4 g $m^{-2}$ $day^{-2}$. Similar trends were observed in the pooled data analysis, where the highest CGR was recorded during the 30-60 DAS (6.2 g $m^{-2}$ $day^{-2}$), 60-90 DAS (18.3 g $m^{-2}$ $day^{-2}$), and 90-120 DAS (12.0 g $m^{-2}$ $day^{-2}$) periods. These values were statistically similar to those of $T_6$ across all growth phases. Conversely, the lowest CGR values were observed in $T_9$, with 1.5 g $m^{-2}$ $day^{-2}$ during 30-60 DAS, 9.8 g $m^{-2}$ $day^{-2}$ during 60-90 DAS, and 4.4 g $m^{-2}$ $day^{-2}$ during 90-120 DAS.

**Table 4.8: Effect of irrigation scheduling methods on CGR (g $m^{-2}$ $day^{-1}$) of wheat**

| Treatments | 30-60 DAS | | | 60-90 DAS | | | 90-120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 5.9 | 6.5 | 6.2 | 17.2 | 19.5 | 18.3 | 10.4 | 13.6 | 12.0 |
| Irrigation at CRI and Flowering stages ($T_2$) | 4.3 | 4.4 | 4.4 | 13.4 | 12.4 | 12.9 | 4.1 | 5.8 | 5.0 |
| Irrigation at 0.25 PSI ($T_3$) | 3.6 | 4.0 | 3.8 | 13.9 | 14.8 | 14.4 | 5.9 | 8.3 | 7.1 |
| Irrigation at 0.50 PSI ($T_4$) | 3.3 | 4.0 | 3.6 | 11.1 | 12.5 | 11.8 | 4.7 | 6.8 | 5.7 |
| Irrigation at 0.75 PSI ($T_5$) | 3.3 | 3.5 | 3.4 | 10.5 | 11.0 | 10.8 | 3.3 | 5.7 | 4.5 |
| Irrigation at 25% depletion of FC ($T_6$) | 5.1 | 6.5 | 5.8 | 16.6 | 17.5 | 17.1 | 10.2 | 12.3 | 11.3 |
| Irrigation at 30% depletion of FC ($T_7$) | 4.8 | 5.3 | 5.0 | 16.2 | 15.1 | 15.7 | 9.3 | 10.9 | 10.1 |
| Irrigation at 75% depletion of FC ($T_8$) | 3.0 | 3.4 | 3.2 | 10.3 | 10.7 | 10.5 | 3.9 | 5.6 | 4.7 |
| Rainfed ($T_9$) | 1.3 | 1.9 | 1.5 | 9.9 | 9.7 | 9.8 | 3.3 | 5.4 | 4.4 |
| **SEm+** | **0.2** | **0.2** | **0.2** | **1.0** | **1.4** | **0.9** | **0.5** | **1.3** | **0.6** |
| **C.D (p= 0.05)** | **0.5** | **0.6** | **0.5** | **2.9** | **4.1** | **2.7** | **1.6** | **3.7** | **1.82** |

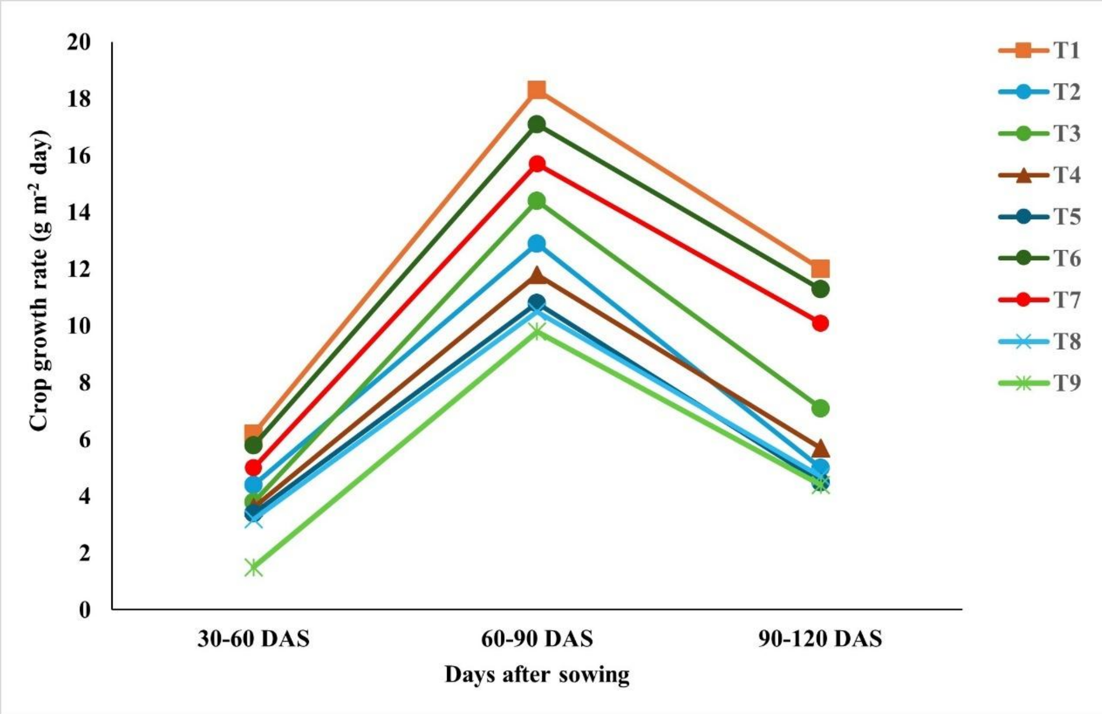



**Fig 4.6: Effect of irrigation scheduling methods on CGR (g m$^{-2}$ day$^{-1}$) of wheat (pooled)**

### *4.2.3 Relative growth rate (g g$^{-1}$ day$^{-1}$)*

The relative growth rate (RGR) in wheat exhibited an initial high value which gradually declined over time, with much of this reduction being ascribed to an escalation in self-shading among the canopy leaves. The RGR data was collected at intervals of 30-60, 60-90, and 90-120 DAS. Analysis of the data revealed a significant impact of diverse irrigation scheduling patterns on the relative growth rate of wheat across both cropping seasons (2022-23 and 2023-24) (Table 4.9).

During the first growing season, the RGR of 58 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$ was recorded between 30-60 DAS under the recommended irrigation treatment ($T_1$), followed by $T_6$ (55 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$) and $T_7$ (54 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$). The lowest RGR value of 18 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$ was observed in $T_9$ (rainfed). The peak RGR values of 72 and 55 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$ were recorded during the 60-90 and 90-120 DAS periods, respectively, in $T_1$ (recommended irrigation). Conversely, $T_9$ (rainfed) exhibited the lowest RGR values during 60-90 DAS (33 g g$^{-1}$ day$^{-1}$× 10$^{-3}$) and 90-120 DAS (14 g g$^{-1}$ day$^{-1}$ × 10$^{-3}$). In the 2023-24 growing season, the highest RGR was recorded in $T_1$ during 30-60 DAS (61 g

$g^{-1}$ $day^{-1} \times 10^{-3}$), 60-90 DAS (91 g $g^{-1}$ $day^{-1} \times 10^{-3}$), and 90-120 DAS (63 g $g^{-1}$ $day^{-1} \times 10^{-3}$). These values were significantly higher than those in all other treatments, but statistically at par to $T_6$ (irrigation at depletion at 25% FC). The lowest RGR in 2023-24 was observed in $T_9$, with values of 22, 43, and 17 g $g^{-1}$ $day^{-1} \times 10^{-3}$ during 30-60, 60-90, and 90-120 DAS, respectively. When considering the pooled data, the highest RGR in $T_1$ was recorded at 30-60 DAS (59 g $g^{-1}$ $day^{-1} \times 10^{-3}$), 60-90 DAS (81 g $g^{-1}$ $day^{-1} \times 10^{-3}$), and 90-120 DAS (59 g $g^{-1}$ $day^{-1} \times 10^{-3}$). The RGR in $T_6$ was significantly at par to $T_1$ across all growth phases. The minimum RGR was observed in $T_9$ (rainfed), with values of 22, 38, and 17 g $g^{-1}$ $day^{-1} \times 10^{-3}$ during 30-60, 60-90, and 90-120 DAS, respectively.

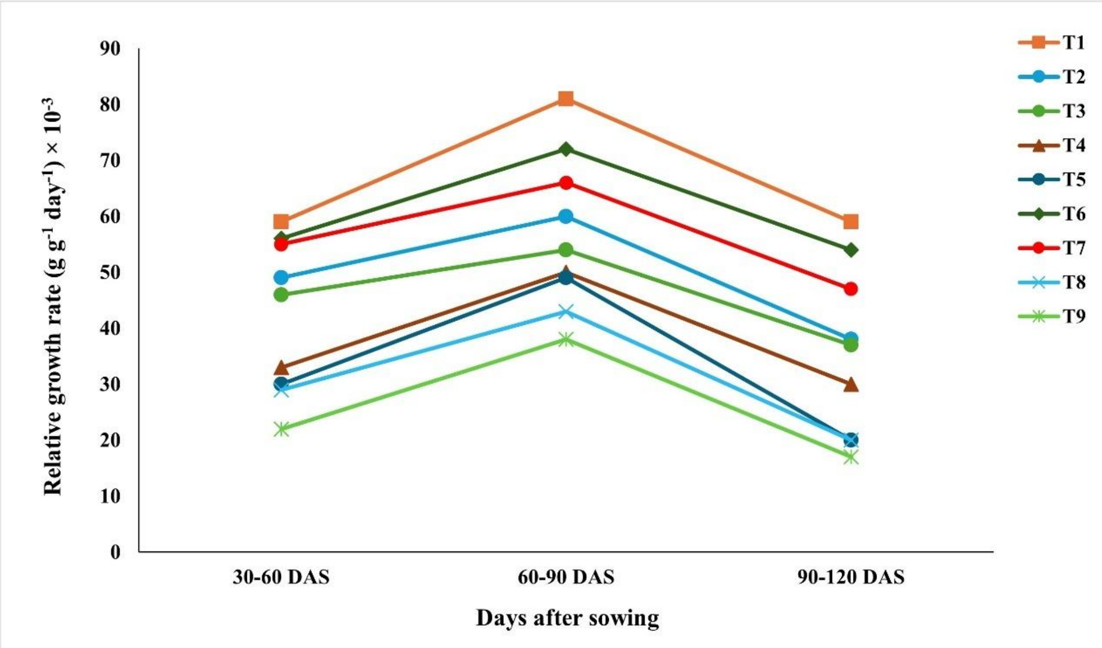



**Fig 4.7: Effect of irrigation scheduling methods on RGR (g $g^{-1}$ $day^{-1}$) × $10^{-3}$ of wheat (pooled)**

**Table 4.9: Effect of irrigation scheduling methods on RGR (g $g^{-1}$ $day^{-1}$) × $10^{-3}$ of wheat**

| Treatments | 30-60 DAS | | | 60-90 DAS | | | 90-120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 58 | 61 | 59 | 72 | 91 | 81 | 55 | 63 | 59 |
| Irrigation at CRI and Flowering stages ($T_2$) | 46 | 52 | 49 | 58 | 62 | 60 | 35 | 42 | 38 |
| Irrigation at 0.25 PSI ($T_3$) | 44 | 49 | 46 | 52 | 56 | 54 | 33 | 40 | 37 |
| Irrigation at 0.50 PSI ($T_4$) | 31 | 35 | 33 | 49 | 52 | 50 | 26 | 34 | 30 |
| Irrigation at 0.75 PSI ($T_5$) | 27 | 33 | 30 | 48 | 50 | 49 | 15 | 26 | 20 |
| Irrigation at 25% depletion of FC ($T_6$) | 55 | 57 | 56 | 65 | 79 | 72 | 47 | 60 | 54 |
| Irrigation at 30% depletion of FC ($T_7$) | 54 | 56 | 55 | 62 | 71 | 66 | 43 | 50 | 47 |
| Irrigation at 75% depletion of FC ($T_8$) | 26 | 32 | 29 | 40 | 46 | 43 | 19 | 21 | 20 |
| Rainfed ($T_9$) | 18 | 26 | 22 | 33 | 43 | 38 | 14 | 18 | 17 |
| **SEm+** | **7** | **6** | **6** | **3** | **5** | **3** | **8** | **9** | **6** |
| **C.D (p= 0.05)** | **20** | **17** | **16** | **10** | **16** | **10** | **24** | **27** | **18** |

### *4.2.4 Absolute growth rate (g plant$^{-1}$day $^{-1}$)*

The utilization of absolute growth rate (AGR) is widespread in the growth assessment of cultivated crops, with these physiological factors serving as the most effective indicators of the overall productivity of the crop. The data regarding the AGR of wheat was documented during the 30-60, 60-90, and 90-120 DAS. During the 30-60 DAS time frame, the AGR of wheat exhibited its minimum value, which then demonstrated a gradual rise leading up to the 60-90 DAS period, followed by a subsequent decrease. The absolute growth rate was notably influenced by various irrigation regimes (Table 4.10).

In the 2022-23 growing season, AGR during the 30-60 DAS was highest under recommended irrigation ($T_1$), with a value of 64 g plant$^{-1}$ day$^{-1}$, and was significantly at par with $T_6$ (56 g plant$^{-1}$ day$^{-1}$). Similarly, during the 60-90 DAS and 90-120 DAS periods, the highest AGR values were recorded in $T_1$, with 381 and 126 g plant$^{-1}$ day$^{-1}$, respectively, and these values were statistically comparable to those of $T_6$ (irrigation at 25% depletion of FC), which had AGR values of 317 and 115 g plant$^{-1}$ day$^{-1}$, respectively. The minimal AGR was noted in $T_9$ (27, 115, and 38 g plant$^{-1}$ day$^{-1}$) for the periods of 30-6 0, 60-90, and 90-120 DAS respectively.

In the 2023-24 growing season, similar to the previous year, the highest AGR values were observed under treatment $T_1$ (recommended irrigation) during the 30-60 (95 g plant$^{-1}$ day$^{-1}$), 60-90 (393 g plant$^{-1}$ day$^{-1}$), and 90-120 DAS (152 g plant$^{-1}$ day$^{-1}$) periods. The AGR values observed under $T_1$ were significantly at par with $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC). These trends were consistent in the pooled data analysis, where $T_1$ exhibited the highest AGR during the 30-60 DAS (77 g plant$^{-1}$ day$^{-1}$), 60-90 DAS (387 g plant$^{-1}$ day$^{-1}$), and 90-120 DAS (140 g plant$^{-1}$ day$^{-1}$) periods. Conversely, treatment $T_9$ (rainfed) recorded the lowest AGR values of 32, 118, and 49 g plant$^{-1}$ day$^{-1}$ during the 30–60, 60–90, and 90–120 DAS intervals, respectively. These values were significantly lower compared to other treatments, except $T_8$ (irrigation at 75% depletion of FC).

**Table 4.10: Effect of irrigation scheduling methods on AGR (g plant$^{-1}$ day $^{-1}$) × $10^{-3}$ of wheat**

| Treatments | 30-60 DAS | | | 60-90 DAS | | | 90-120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** |
| Recommended irrigation ($T_1$) | 64 | 90 | 77 | 381 | 393 | 387 | 126 | 152 | 140 |
| Irrigation at CRI and Flowering stages ($T_2$) | 53 | 60 | 57 | 225 | 229 | 227 | 62 | 64 | 63 |
| Irrigation at 0.25 PSI ($T_3$) | 44 | 55 | 50 | 240 | 254 | 247 | 88 | 93 | 91 |
| Irrigation at 0.50 PSI ($T_4$) | 39 | 53 | 46 | 183 | 181 | 182 | 60 | 64 | 62 |
| Irrigation at 0.75 PSI ($T_5$) | 38 | 50 | 44 | 177 | 180 | 178 | 48 | 62 | 55 |
| Irrigation at 25% depletion of FC ($T_6$) | 56 | 75 | 65 | 317 | 329 | 323 | 115 | 138 | 127 |
| Irrigation at 30% depletion of FC ($T_7$) | 56 | 69 | 63 | 248 | 259 | 253 | 102 | 122 | 112 |
| Irrigation at 75% depletion of FC ($T_8$) | 36 | 45 | 40 | 152 | 175 | 163 | 46 | 61 | 54 |
| Rainfed ($T_9$) | 27 | 36 | 32 | 115 | 120 | 118 | 38 | 60 | 49 |
| **SEm+** | **5** | **10** | **6** | **23** | **42** | **28** | **20** | **19** | **11** |
| **C.D (p= 0.05)** | **16** | **29** | **18** | **66** | **123** | **82** | **59** | **39** | **31** |

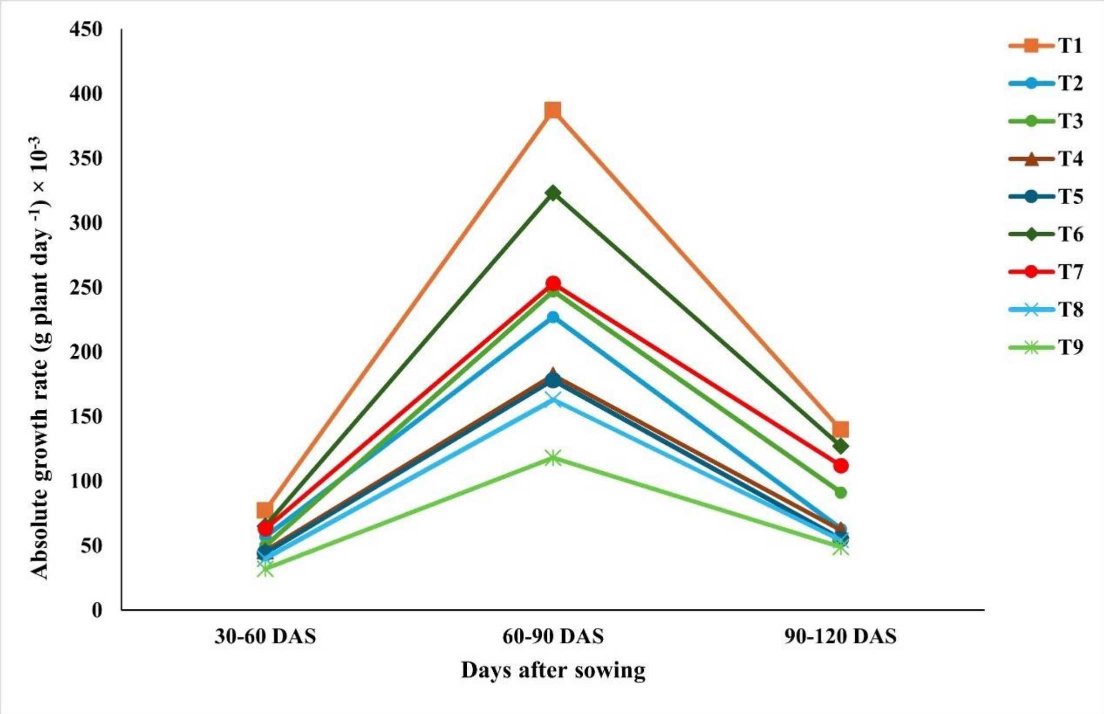



**Fig 4.8: Effect of irrigation scheduling methods on AGR (g plant$^{-1}$ day $^{-1}$) × $10^{-3}$ of wheat (pooled)**

### *4.2.5 Net assimilation rate (g cm$^{-2}$ day$^{-1}$)*

Data on the net assimilation rate (NAR) are presented in Table 4.11, highlighting the significant effect of different irrigation scheduling methods on NAR during the 30-60, 60-90, and 90-120 DAS. In the 2022-23 growing season, the highest NAR value of 5.8 g cm$^{-2}$ day$^{-1}$ was observed in treatment $T_1$ (recommended irrigation) during the 30-60 DAS, which was statistically similar to $T_6$ (5.1 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$). In contrast, the lowest NAR of 2.2 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$ was recorded in the rainfed treatment ($T_9$). During the 60-90 DAS and 90-120 DAS, the maximum NAR values were observed in $T_1$ (20 and 8.3 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$), while $T_9$ exhibited the lowest NAR values (6.7 and 0.08 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$), with NAR in $T_1$ being significantly higher compared to other treatments. In the 2023-24 growing season, notably higher NAR values were observed in $T_1$ (recommended irrigation) during the 30-60 DAS (6.7 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$), 60-90 DAS (22.0 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$), and 90-120 DAS (9.7 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$) periods. In contrast, $T_9$ (rainfed) showed the lowest NAR values, with 2.6, 6.5, and 2.4 g cm$^{-2}$ day$^{-1}$ × $10^{-3}$ during the respective periods.

**Table 4.11: Effect of irrigation scheduling methods on NAR (g cm$^{-2}$ day$^{-1}$) × 10$^{-3}$ of wheat**

| Treatments | 30-60 DAS | | | 60-90 DAS | | | 90-120 DAS | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 5.8 | 6.7 | 6.3 | 20.0 | 22.0 | 21.2 | 8.3 | 9.7 | 9.0 |
| Irrigation at CRI and Flowering stages ($T_2$) | 3.8 | 5.1 | 4.5 | 11.9 | 8.20 | 10.1 | 2.6 | 3.5 | 3.1 |
| Irrigation at 0.25 PSI ($T_3$) | 3.7 | 4.8 | 4.3 | 12.6 | 10.4 | 11.5 | 2.7 | 3.6 | 3.2 |
| Irrigation at 0.50 PSI ($T_4$) | 3.0 | 4.1 | 3.6 | 10.6 | 7.7 | 9.2 | 2.6 | 2.7 | 2.7 |
| Irrigation at 0.75 PSI ($T_5$) | 2.8 | 3.4 | 3.1 | 9.3 | 6.8 | 8.1 | 2.4 | 2.6 | 2.6 |
| Irrigation at 25% depletion of FC ($T_6$) | 5.1 | 6.5 | 5.8 | 18.3 | 20.9 | 19.7 | 6.5 | 9.5 | 8.0 |
| Irrigation at 30% depletion of FC ($T_7$) | 4.7 | 6.2 | 5.5 | 12.9 | 13.4 | 13.2 | 2.8 | 6.1 | 4.5 |
| Irrigation at 75% depletion of FC ($T_8$) | 2.7 | 2.7 | 2.7 | 9.2 | 7.1 | 8.1 | 2.1 | 2.5 | 2.3 |
| Rainfed ($T_9$) | 2.2 | 2.6 | 2.5 | 6.7 | 6.5 | 6.6 | 0.8 | 2.4 | 1.6 |
| **SEm+** | **1.0** | **1.0** | **1.0** | **1.4** | **2.0** | **1.0** | **1.0** | **2.0** | **1.0** |
| **C.D (p= 0.05)** | **2.0** | **2.1** | **1.4** | **4.0** | **7.0** | **4.0** | **3.0** | **4.0** | **2.0** |

These trends were consistent in the pooled data analysis, where the highest NAR values were again recorded in $T_1$ during the 30-60 DAS (6.3 g $cm^{-2}$ $day^{-1}$ × $10^{-3}$), 60-90 DAS (21.2 g $cm^{-2}$ $day^{-1}$ × $10^{-3}$), and 90-120 DAS (9.0 g $cm^{-2}$ $day^{-1}$ × $10^{-3}$) periods, while the lowest NAR values were observed in $T_9$ (2.5, 6.6, and 1.6 g $cm^{-2}$ $day^{-1}$ × $10^{-3}$, respectively).

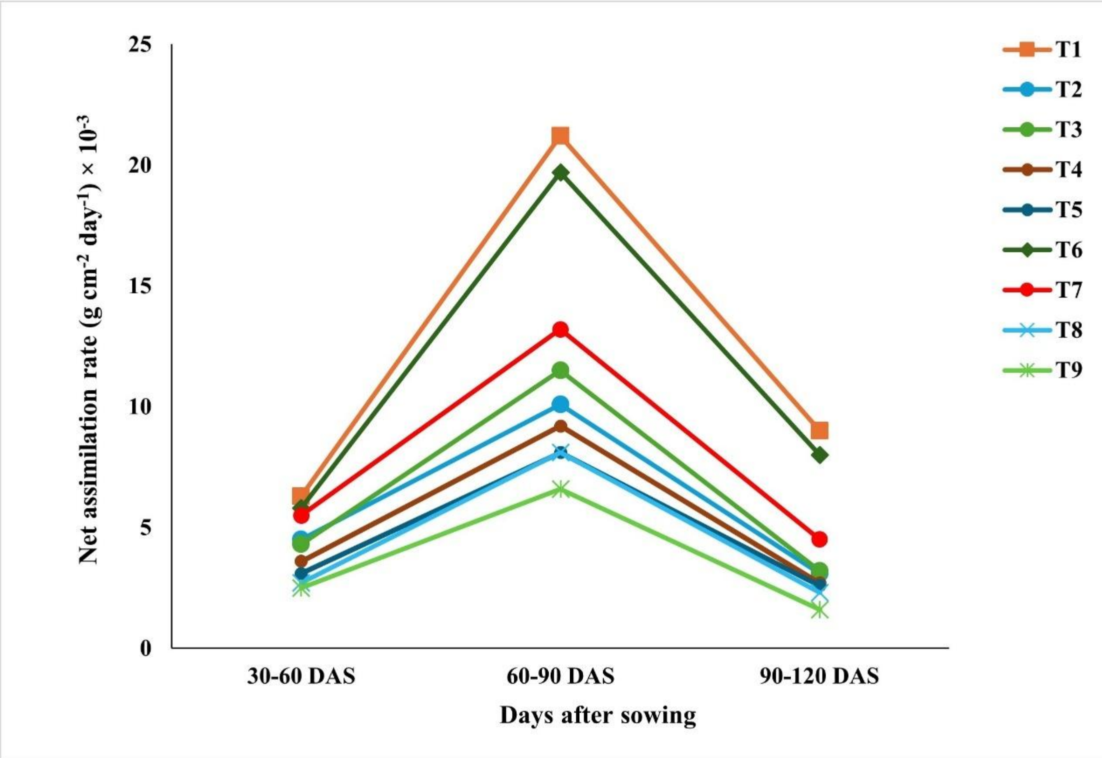



**Fig 4.9: Effect of irrigation scheduling on NAR (g $cm^{-2}$ $day^{-1}$) × $10^{-3}$ of wheat (pooled)**

### *4.2.6 Stress degree days* (°C/day)

During the wheat growing seasons of 2022–23 and 2023–24, cumulative stress degree days (SDD) exhibited considerable variation across growth stages and treatments ($T_3$, $T_4$, and $T_5$) as shown in Table 4.12. Overall, the 2023–24 season was cooler than 2022–23, as reflected by SDD values. During the tillering–jointing stage, $T_3$ and $T_4$ recorded negative SDD values in both years, indicative of cooler canopy temperatures, while $T_4$ experienced milder cool conditions closer to optimal thermal ranges during vegetative growth. In contrast, $T_5$ exhibited positive SDD values in both years during this stage, reflecting heat stress conditions where canopy temperatures exceeded critical thresholds, potentially increasing transpiration demand and adversely affecting early vegetative growth. A similar pattern was observed during the booting stage. At the heading–flowering stage, $T_3$ shifted from mild heat stress in 2022–23, as indicated by positive SDD, to significant cool stress in 2023–24, reflected by negative SDD values. $T_4$ consistently recorded negative SDD during this stage across both years, indicating cooler conditions. Notably, $T_5$ maintained high positive SDD in both seasons during heading–flowering, highlighting substantial heat stress during this critical reproductive phase. During the grain filling stage, $T_3$ and $T_4$ again experienced negative SDD values, whereas $T_5$ consistently recorded positive SDD, suggesting persistent heat stress during grain development.

**Table 4.12 Effect of irrigation scheduling on SDD (°C/day) of wheat**

| **Growth stages** | **Days after sowing (DAS)** | **Irrigation at 0.25 PSI ($T_3$)** | | **Irrigation at 0.50 PSI ($T_4$)** | | **Irrigation at 0.75 PSI ($T_5$)** | |
|---|---|---|---|---|---|---|---|
| | | **2022-23** | **2023-24** | **2022-23** | **2023-24** | **2022-23** | **2023-24** |
| Tillering–Jointing | 60–75 DAS | -30.80 | -51.70 | -10.50 | -14.00 | 14.20 | 17.8 |
| Booting | 75–90 DAS | -20.63 | -63.38 | -4.78 | -11.23 | -6.40 | -7.53 |
| Heading-Flowering | 90–105 DAS | 6.98 | -39.9 | -31.00 | -19.62 | 35.00 | 36.18 |
| Grain Filling | 105–120 DAS | -11.98 | -55.7 | -20.00 | -19.78 | 6.00 | 5.92 |

## 4.3 Yield and Yield attributes

### *4.3.1 Spike length (cm)*

The length of spike is a key characteristic of yield in wheat, as it affects the grain count per spike. The quantity of grains produced by each spike exhibits a direct correlation with the length of the spike in the wheat plant. A longer spike typically accommodates more grains per spike, leading to a hike in overall yield of grain. The spike length was significantly inveigled by different irrigation scheduling methods throughout both cropping years (Table 4.13).

During the 2022–23 growing season, irrigation scheduling methods had a significant influence on wheat spike length at harvest. The longest spike length (11.1 cm) was recorded under the recommended irrigation treatment ($T_1$), followed by $T_7$ (10.8 cm). Statistical analysis indicated that treatments $T_7$, $T_6$, and $T_4$ were significantly at par with $T_1$, whereas the shortest spike length (9.6 cm) was observed under rainfed conditions ($T_9$). A similar trend persisted in the subsequent growing season (2023–24), wherein $T_1$ exhibited the maximum spike length (11.3 cm), followed closely by $T_7$ (11.2 cm). Additionally, treatments $T_7$, $T_6$, and $T_4$ remained statistically comparable to $T_1$. Conversely, plants subjected to rainfed conditions ($T_9$) developed the shortest spikes, measuring 9.8 cm. The pooled analysis reaffirmed these findings, demonstrating that spike length was significantly influenced by irrigation scheduling. The longest spike (11.2 cm) was recorded under $T_1$ and was found to be statistically at par with $T_6$, $T_7$ and $T_4$, whereas the shortest spike length (9.7 cm) was consistently observed under $T_9$.

### *4.3.2 Number of grains per spike*

The grains per spike is yet another crucial facet adding to the grain yield of wheat. The potential quantity of grains per ear is determined during the booting stage, whereas its actual quantity is ascertained during the flowering or anthesis stage. A higher count of grains per spike signifies the favorable conditions prevailing during the flowering stage. Stress during the course of flowering stage can interfere with pollination, resulting in a reduced grain count per spike. The grain count in wheat was significantly altered by the various irrigation scheduling methods in both years (Table 4.13).

During the 2022–23 growing season, the lowest number of grains per spike (40.4) was recorded under rainfed conditions ($T_9$), whereas the highest grain count (50.0) was observed under recommended irrigation ($T_1$). Treatments $T_7$ (48.4) and $T_4$ (47.4) were found to be statistically comparable to $T_1$.

**Table 4.13: Effect of irrigation scheduling methods on yield characters of wheat**

| Treatments | Spike length (cm) | | | Number of grains per spike | | | 1000-grain weight (g) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 11.1 | 11.3 | 11.2 | 50.0 | 50.8 | 50.4 | 48.3 | 48.6 | 48.5 |
| Irrigation at CRI and Flowering stages ($T_2$) | 10.2 | 10.4 | 10.4 | 44.6 | 45.7 | 45.2 | 45.6 | 46.2 | 45.9 |
| Irrigation at 0.25 PSI ($T_3$) | 10.6 | 10.9 | 10.7 | 46.9 | 47.0 | 46.9 | 46.1 | 46.6 | 46.3 |
| Irrigation at 0.50 PSI ($T_4$) | 10.7 | 10.9 | 10.8 | 47.4 | 47.7 | 47.6 | 46.7 | 47.0 | 46.8 |
| Irrigation at 0.75 PSI ($T_5$) | 10.1 | 10.2 | 10.2 | 44.3 | 45.4 | 44.8 | 42.7 | 43.7 | 43.2 |
| Irrigation at 25% depletion of FC ($T_6$) | 10.6 | 10.8 | 10.7 | 47.1 | 47.8 | 47.4 | 47.0 | 47.3 | 47.1 |
| Irrigation at 30% depletion of FC ($T_7$) | 10.8 | 11.2 | 11.0 | 48.4 | 50.0 | 49.2 | 47.2 | 47.5 | 47.3 |
| Irrigation at 75% depletion of FC ($T_8$) | 10.0 | 10.1 | 10.1 | 43.9 | 44.0 | 44.0 | 41.8 | 42.1 | 41.9 |
| Rainfed ($T_9$) | 9.6 | 9.8 | 9.7 | 40.4 | 40.6 | 40.5 | 40.1 | 41.0 | 40.5 |
| **SEm+** | **0.3** | **0.3** | **0.2** | **1.6** | **1.9** | **1.4** | **1.7** | **1.5** | **1.3** |
| **C.D (p= 0.05)** | **0.8** | **0.9** | **0.6** | **4.5** | **5.6** | **4.2** | **4.9** | **4.5** | **3.8** |

In the following year (2023–24), a similar trend persisted, with the highest number of grains per spike (50.8) recorded under $T_1$, followed by $T_7$ (50.0 grains) and $T_4$ (47.7 grains), both of which were statistically comparable to $T_1$. Conversely, the lowest grain count (40.6) was documented under rainfed conditions ($T_9$). The pooled analysis further corroborated these findings, indicating a significant effect of irrigation scheduling methods on grain number. The maximum number of grains per spike (50.4) was recorded under $T_1$, whereas the lowest count (40.5) was observed under $T_9$. Additionally, treatments $T_7$ and $T_4$ remained statistically similar to $T_1$ in comparison to other irrigation scheduling methods.

### *4.3.3 1000-grain weight (g)*

The 1000-grain weight serves as an indicator of the crop's capacity to effectively transport photosynthates from various origins to the sink, which in this case refers to the grains. In 2022-23, the 1000-grain weight of wheat was significantly inveigled by the various irrigation regimes (Table 4.13).

During the 2022–23 growing season, the implementation of recommended irrigation ($T_1$) across various growth stages resulted in the highest 1000-grain weight (48.3 g), followed by $T_7$ (47.2 g), $T_6$ (47.0 g), and $T_4$ (46.7 g). The lowest 1000-grain weight (40.1 g) was recorded under rainfed conditions ($T_9$). Statistical analysis revealed that all irrigation scheduling methods were comparable, except for $T_5$, $T_8$, and $T_9$, which exhibited significantly lower grain weights when compared to other irrigation scheduling methods. In the 2023–24 season, the maximum 1000-grain weight (48.6 g) was recorded under $T_1$, followed by $T_7$ (47.5 g), $T_6$ (47.3 g), and $T_4$ (47.0 g). The lowest test weight (41.0 g) was documented under $T_9$. Furthermore, treatments $T_5$, $T_8$ and $T_9$ were found to be statistically similar in terms of 1000-grain weight but remained significantly lower than other irrigation treatments. The pooled analysis reaffirmed these findings, indicating that the highest 1000-grain weight (48.5 g) was recorded under $T_1$, followed closely by $T_7$ (47.3 g). In contrast, the lowest test weight (40.5 g) was consistently observed under $T_9$. Additionally, treatments $T_5$, $T_8$, and $T_9$ continued to exhibit significantly lower grain weights compared to other irrigation scheduling methods.

### *4.3.4 Grain Yield (t ha$^{-1}$)*

Grain yield represents the most critical agronomic parameter in wheat cultivation, as it directly reflects the effectiveness of crop management strategies, particularly irrigation practices. The principal aim of modifying crop practices and optimizing irrigation schedules is to enhance grain yield while concurrently improving water use efficiency. Key yield-contributing components in wheat include the number of effective tillers, spike length and grains per spike.

A detailed examination of the grain yield data depicted in Table 4.14 indicates that irrigation scheduling methods exerted a statistically significant effect on grain yield across the two study years. In the 2022–2023 growing season, the highest grain yield (5.9 t ha$^{-1}$) was recorded under the recommended irrigation regime ($T_1$). Treatments $T_7$ (irrigation at 30% depletion of FC) and $T_4$ (irrigation at 0.50 PSI) produced yields of 5.7 t ha$^{-1}$ and 5.5 t ha$^{-1}$, respectively, which were statistically comparable to $T_1$. In the subsequent season (2023–2024), the maximum grain yield of 6.1 t ha$^{-1}$ was again observed under the recommended irrigation treatment ($T_1$). Similar yield performance was recorded under $T_7$ (5.9 t ha$^{-1}$) and $T_4$ (5.8 t ha$^{-1}$), with no statistically significant differences from $T_1$. Conversely, the lowest yields were consistently observed under rainfed conditions ($T_9$), with values of 2.4 t ha$^{-1}$ and 3.6 t ha$^{-1}$ in 2022–2023 and 2023–2024, respectively. Pooled analysis across both years confirmed the significant impact of irrigation treatments on grain yield. The highest average grain yield (6.0 t ha$^{-1}$) was achieved under the recommended irrigation regime ($T_1$), while the lowest yield (3.0 t ha$^{-1}$) was documented under rainfed conditions ($T_9$).

### *4.3.5 Straw Yield (t ha$^{-1}$)*

Irrigation practices had a notable impact on straw production over the two years. A rise in straw output was noted from the initial to the subsequent year (Table 4.14). Treatment $T_1$, with the recommended irrigation, achieved the maximum straw yield of 7.4 t ha$^{-1}$. This was followed by $T_7$ (irrigation at 30% depletion of FC), yielding 7.3 t ha$^{-1}$, and treatment $T_5$, with irrigation at 0.50 PSI, which produced a yield of 7.0 t ha$^{-1}$. An observed reduction in straw yield was noted specifically at 75% depletion of FC

($T_8$) and 0.75 PSI ($T_5$), compared to alternative irrigation practices. Rainfed treatment ($T_9$) recorded the lowest straw yield at 4.2 t $ha^{-1}$, which was significantly lower compared to the other treatments. In the year 2023-24, the results mirrored those of the previous year, with the highest straw yield recorded in $T_1$ (7.8 t $ha^{-1}$), which was statistically similar to $T_7$ (7.6 t $ha^{-1}$) and $T_4$ (7.5 t $ha^{-1}$). The value of 5.7 t $ha^{-1}$ was documented in $T_9$ and was the lowest among all the treatments. In the pooled analysis, $T_1$ exhibited a higher straw yield of 7.6 t $ha^{-1}$, compared to the minimum yield of 4.9 t $ha^{-1}$ recorded in treatment $T_9$.

### *4.3.6 Biological Yield (t $ha^{-1}$)*

Biological yield signifies the comprehensive accumulation of dry matter within a given crop. A substantial biological yield indicates the presence of a robust crop with significant capabilities to generate both elevated grain and straw yields. A significant effect of irrigation scheduling was observed on biological yield during both years 2022-23 and 2023-24 (Table 4.14). During 2022-23, the maximum biological yield of 13.3 t $ha^{-1}$ was observed under recommended irrigation treatment ($T_1$) which was followed by $T_7$ (12.9 t $ha^{-1}$), $T_4$ (12.6 t $ha^{-1}$). Significantly the lowest biological yield of 6.6 t $ha^{-1}$ was observed under the rainfed conditions ($T_9$). In the year 2023-24, the results were similar to the previous year, where the significantly higher biological yield (13.9 t $ha^{-1}$) was observed when recommended irrigation was followed ($T_1$). It was statistically similar to when irrigation was applied at 30% depletion of FC (13.5 t $ha^{-1}$), 25% depletion of FC (13.3 t $ha^{-1}$) and 0.50 PSI (13.3 t $ha^{-1}$). A biological yield of 9.3 t $ha^{-1}$ was observed under rainfed ($T_9$) treatment was applied which was significantly lower when compared to all the treatments. In the pooled analysis, a significantly increased biological yield of 13.6 t $ha^{-1}$ was detected under treatment $T_1$, and the least yield (7.9 t $ha^{-1}$) was documented under rainfed ($T_9$) treatment.

**Table 4.14: Effect of irrigation scheduling methods on yield (t ha$^{-1}$) and harvest index (%) of wheat**

| Treatments | Grain Yield (t ha$^{-1}$) | | | Straw Yield (t ha$^{-1}$) | | | Biological Yield (t ha$^{-1}$) | | | Harvest Index (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 5.9 | 6.1 | 6.0 | 7.4 | 7.8 | 7.6 | 13.3 | 13.9 | 13.6 | 44.2 | 44.1 | 44.2 |
| Irrigation at CRI and Flowering stages ($T_2$) | 4.9 | 4.4 | 4.7 | 6.7 | 6.4 | 6.5 | 11.6 | 10.8 | 11.2 | 42.7 | 40.8 | 41.8 |
| Irrigation at 0.25 PSI ($T_3$) | 5.1 | 5.5 | 5.3 | 6.4 | 7.5 | 7.0 | 11.5 | 12.9 | 12.2 | 44.0 | 42.3 | 43.1 |
| Irrigation at 0.50 PSI ($T_4$) | 5.5 | 5.8 | 5.7 | 7.0 | 7.5 | 7.3 | 12.6 | 13.3 | 12.9 | 44.0 | 43.6 | 43.8 |
| Irrigation at 0.75 PSI ($T_5$) | 3.7 | 4.1 | 3.9 | 4.9 | 6.3 | 5.6 | 8.6 | 10.4 | 9.5 | 42.5 | 39.6 | 41.1 |
| Irrigation at 25% depletion of FC ($T_6$) | 5.3 | 5.8 | 5.6 | 6.9 | 7.6 | 7.2 | 12.3 | 13.3 | 12.8 | 43.5 | 43.4 | 43.4 |
| Irrigation at 30% depletion of FC ($T_7$) | 5.7 | 5.9 | 5.8 | 7.3 | 7.6 | 7.4 | 12.9 | 13.5 | 13.2 | 44.0 | 43.7 | 43.8 |
| Irrigation at 75% depletion of FC ($T_8$) | 2.6 | 3.7 | 3.2 | 4.4 | 6.0 | 5.2 | 7.0 | 9.7 | 8.3 | 37.2 | 38.6 | 37.9 |
| Rainfed ($T_9$) | 2.4 | 3.6 | 3.0 | 4.2 | 5.7 | 4.9 | 6.6 | 9.3 | 7.9 | 36.9 | 38.2 | 37.5 |
| **SEm+** | **0.2** | **0.3** | **0.2** | **0.4** | **0.3** | **0.2** | **0.5** | **0.5** | **0.3** | **1.5** | **1.9** | **1.2** |
| **C.D (p= 0.05)** | **0.6** | **0.8** | **0.5** | **1.1** | **1.0** | **0.6** | **1.5** | **1.4** | **0.8** | **4.3** | **NS** | **3.3** |

### *4.3.7 Harvest Index (%)*

Harvest index (HI) is the correlation between the economic and the biological yield of the crop. It signifies the reproductive competency of the plant. The higher value of the HI indicated that there is an additional physiological capacity of the crop to mobilize the photosynthates and thus translocate into the economic parts. The data in Table 4.14 indicate that during the 2022–2023 cropping season, HI was significantly affected by the various irrigation scheduling treatments. In contrast, during the 2023–24 season, the effect of these treatments on HI was statistically non-significant. In 2022–23, the highest HI (44.2 %) was recorded under the recommended irrigation schedule ($T_1$), followed closely by treatments $T_4$ (44.0 %) and $T_7$ (44.0 %), all of which were statistically at par with $T_1$. The lowest HI was observed under the rainfed condition ($T_9$), with a value of 36.9 %. In 2023–24, treatment $T_1$ (recommended irrigation) again recorded the highest HI (44.1 %), whereas the lowest HI (38.2 %) was associated with the rainfed treatment ($T_9$); however, the differences among treatments were not statistically significant in this year.

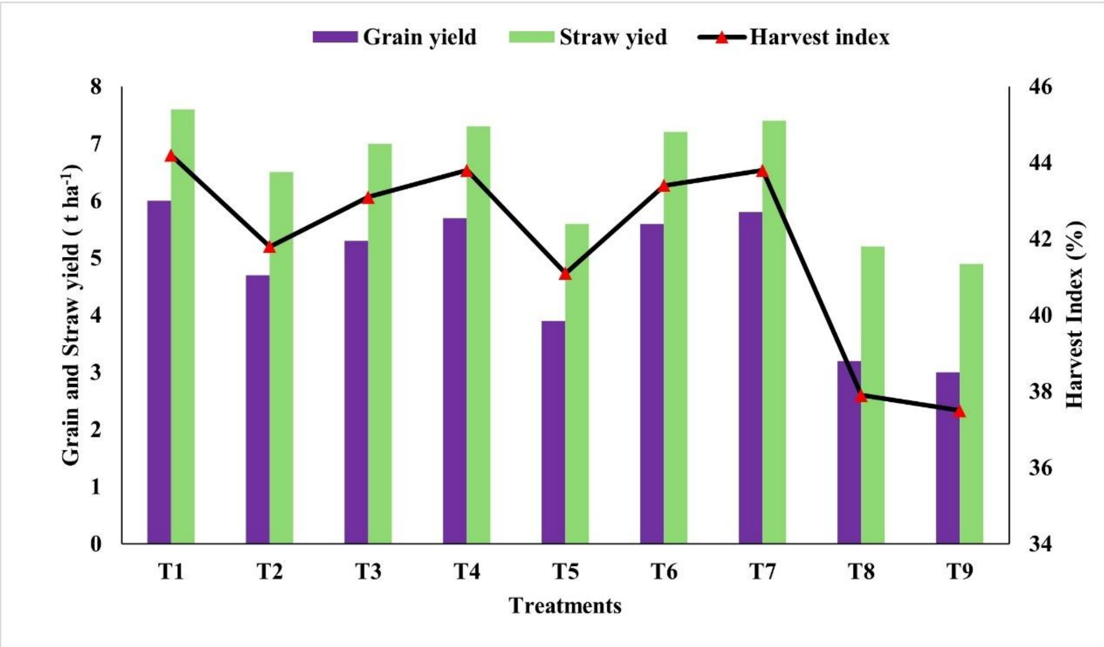



**Fig 4.10: Effect of irrigation scheduling methods on grain yield (t ha$^{-1}$), straw yield (t ha$^{-1}$) and harvest index (%) of wheat (pooled)**

The pooled analysis followed a similar pattern, with the maximum HI (44.2 %) under $T_1$ and the minimum (37.5 %) under $T_9$. Notably, $T_9$ exhibited a significantly lower HI compared to most treatments, except for $T_8$.

## 4.4 Irrigation parameters

### *4.4.1 Total Irrigation Requirement (mm)*

The total irrigation water requirement (TWR) exhibited variation across different irrigation regimes, as presented in Table 4.15. In the 2022–23 cropping season, the highest TWR was recorded under treatment $T_6$ (irrigation scheduled at 25% depletion of FC), amounting to 876 mm. This was followed by $T_3$ (irrigation at 0.25 PSI), which recorded a TWR of 814 mm. In contrast, during the 2023–24 season, the overall irrigation requirement was lower compared to the previous year. The highest TWR in this season was observed in $T_1$ (recommended irrigation), amounting to 683 mm, followed by $T_7$ (irrigation at 30% depletion of FC) with 667 mm. Based on the pooled analysis of data across both years, the highest average TWR was noted under $T_6$ (irrigation at 25% depletion of FC), amounting to 759 mm. This was followed by $T_3$, where irrigation was applied at 0.25 PSI, with an average TWR of 796 mm.

Effective rainfall (ER) was recorded at a higher level during the 2022–23 cropping season, amounting to 96 mm, whereas a slightly lower value of 87 mm was observed in 2023–24. The pooled analysis across both years indicated an average ER of 92 mm.

### *4.4.2 Crop Water Requirement (mm)*

The crop water requirement (CWR) data is provided in table 4.15. During the year 2022-23, the maximum CWR (972 mm) was recorded when irrigation was applied at 25% depletion of FC ($T_6$) followed by treatment $T_3$ (910 mm). Whereas in the year 2023-24, the highest CWR was estimated as 865 mm when irrigation was applied at 0.25 PSI ($T_3$), it was followed by recommended irrigation schedule (770 mm), irrigation at 30% depletion of FC (754 mm) and irrigation at 25% FC (731 mm). In both years, the minimum crop water requirement was recorded as 96 mm and 87 mm under the rainfed irrigation scheduling ($T_9$).

The pooled analysis of the two-year data revealed that the highest crop water requirement was observed with irrigation at 0.25 PSI (888 mm), followed by irrigation at 25% depletion of FC (851 mm) and 30% depletion of FC (829 mm).

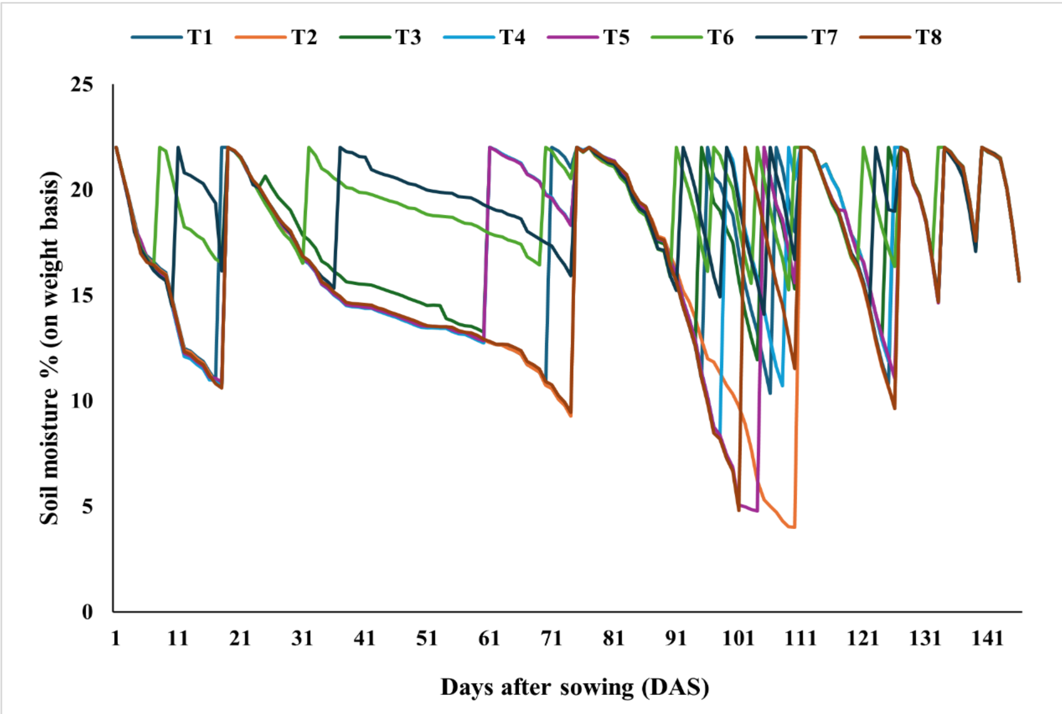



**Fig. 4.11 Trend of soil moisture levels in the effective root zone under different treatments throughout the wheat growing period**

**Table 4.15: Effect of irrigation scheduling methods on total irrigation requirement, effective rainfall and crop water requirement in wheat**

| Treatments | Total Irrigation Requirement (mm) | | | Effective Rainfall (mm) | | | Crop Water Requirement (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 706 | 683 | 695 | 96 | 87 | 92 | 802 | 770 | 786 |
| Irrigation at CRI and Flowering stages ($T_2$) | 620 | 215 | 417 | 96 | 87 | 92 | 716 | 302 | 509 |
| Irrigation at 0.25 PSI ($T_3$) | 814 | 778 | 796 | 96 | 87 | 92 | 910 | 865 | 888 |
| Irrigation at 0.50 PSI ($T_4$) | 653 | 582 | 618 | 96 | 87 | 92 | 749 | 669 | 709 |
| Irrigation at 0.75 PSI ($T_5$) | 541 | 558 | 549 | 96 | 87 | 92 | 637 | 645 | 641 |
| Irrigation at 25% depletion of FC ($T_6$) | 876 | 644 | 760 | 96 | 87 | 92 | 972 | 731 | 851 |
| Irrigation at 30% depletion of FC ($T_7$) | 807 | 667 | 737 | 96 | 87 | 92 | 903 | 754 | 829 |
| Irrigation at 75% depletion of FC ($T_8$) | 637 | 596 | 617 | 96 | 87 | 92 | 734 | 683 | 708 |
| Rainfed ($T_9$) | ----- | ----- | ----- | 96 | 87 | 92 | 96 | 87 | 92 |

### *4.4.3 Irrigation water use efficiency (t ha$^{-1}$ cm)*

The irrigation water use efficiency (IWUE) data for the irrigation treatments are endorsed in table 4.16. It was observed that IWUE values varied between 0.040 and 0.083 t ha$^{-1}$ cm in 2022-23 and between 0.062 and 0.206 t ha$^{-1}$ cm in 2023-24. This indicates that lower irrigation treatments led to increased IWUE values. During the year 2022-23, the highest IWUE was calculated for the treatment where irrigation was applied at 0.50 PSI ($T_4$) i.e. 0.085 t ha$^{-1}$ cm and was followed by 0.083 t ha$^{-1}$ cm for the recommended irrigation regime ($T_1$). In 2023-24, the highest IWUE of 0.206 t ha$^{-1}$ cm was observed where irrigation was applied at CRI and flowering growth stages ($T_2$).

It was followed by irrigation applied at 0.50 PSI (0.100 t ha$^{-1}$ cm) and recommended irrigation where IWUE of 0.090 t ha$^{-1}$ cm was achieved. The lowest value of IWUE for both years was 0.040 t ha$^{-1}$ cm and 0.062 t ha$^{-1}$ cm which resulted when irrigation was applied when there was a 75% depletion of FC ($T_7$). During the pooled analysis, the highest IWUE of 0.143 t ha$^{-1}$ cm was observed under treatment $T_2$ (irrigation at CRI and flowering stage). A IWUE value of 0.092 t ha$^{-1}$ cm was observed at 0.50 PSI irrigation regime ($T_4$). The minimum value of IWUE (0.051 t ha$^{-1}$ cm) was under rainfed ($T_9$) treatment. Irrigation scheduling with irrigation applied at CRI and flowering ($T_2$) achieved the highest IWUE, as it used less irrigation water compared to the other treatments. Furthermore, recommended irrigation and irrigation applied at 0.50 PSI ($T_4$), where IWUE was observed to be significantly higher than other irrigation scheduling methods.

### *4.4.4 Irrigation water productivity (kg m$^{-3}$)*

Irrigation water productivity (IWP) reflects the quantity of grain yield that can be generated from each unit of overall water consumption (Table 4.16). The peak irrigation water productivity recorded during the year 2022-23 was noted under treatment $T_4$ (0.50 PSI) at a rate of 0.848 kg m$^{-3}$, followed closely by treatment $T_1$ (recommended irrigation) at 0.832 kg m$^{-3}$. The minimum value observed was 0.404 kg m$^{-3}$, which occurred under treatment $T_8$, where irrigation was administered at 75% depletion of field capacity (FC). Nevertheless, in the subsequent year 2023-24, the highest water productivity was realized under treatment $T_2$ (2.057 kg m$^{-3}$), with $T_4$

(0.997 kg $m^{-3}$) and treatment $T_1$ (0.895 kg $m^{-3}$) following. In the pooled analysis, the highest water productivity was recorded in $T_2$ (1.426 kg $m^{-3}$), succeeded by $T_4$ (0.923 kg $m^{-3}$). Conversely, the least productivity was noted for $T_8$ (0.507 kg $m^{-3}$).

#### *4.4.5 Amount of water required to produce 1 kg of wheat (liters)*

The quantity of water necessary to produce 1 kg of wheat grain (Table 4.16) was minimal under treatment $T_4$ (1179 liters) for the *rabi* season of 2022-23, with treatment $T_1$ (recommended irrigation) following closely at 1202 liters. Conversely, treatment $T_8$ (irrigation at 75% depletion of FC) demonstrated the highest water consumption, amounting to 2472 liters. In the subsequent agricultural year of 2023-24, the treatment that required the least volume of water was $T_2$ (486 liters) per kg of wheat, succeeded by $T_4$ (1003 liters) and $T_6$ (1112 liters). The greatest water requirements were noted under treatment $T_8$ (1603 liters). These findings were substantiated through pooled analysis, which revealed that $T_2$ (irrigation at CRI and flowering) exhibited the lowest water utilization (871 liters), followed by $T_4$ (1091 liters), while $T_8$ (2037 liters) necessitated the highest water volume.

#### *4.4.6 Water saving (%)*

Water saving (%) has been calculated when compared to treatment $T_1$ for both the years i.e., 2022-23 and 2023-24 (Table 4.16). During the first year, the maximum water saving was observed under PSI-based treatment $T_5$ (23 %) followed by $T_4$ (7 %). Among the soil moisture depletion-based treatments, the water saving of 10 % in $T_8$. However, during the subsequent year, the highest water saving of 69 % was observed under treatment $T_2$ (irrigation at CRI and flowering stages) followed by PSI-based irrigation scheduling methods i.e., $T_5$ (18 %) and $T_4$ (15 %). Among the soil moisture depletion methods, the maximum water saving of 11 % was observed under $T_8$. Similarly, in pooled analysis, the water saving observed under $T_2$ was quantified at 40 %, representing the most significant level of savings observed. Among the PSI-based treatments, the highest water saving of 21 % was achieved in $T_5$ followed by $T_4$ (11 %). For the soil moisture depletion methods, the highest was achieved in $T_9$ (10 %).

**Table 4.16: Effect of irrigation scheduling methods on IWUE, irrigation water productivity, amount of water required to produce 1 kg of wheat and water saving in wheat**

| Treatments | Irrigation water use efficiency ($t\ ha^{-1}\ cm$) | | | Irrigation water productivity ($kg\ m^{-3}$) | | | Amount of water required to produce 1 kg of wheat (litres) | | | Water saving (%) over $T_1$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 0.083 | 0.090 | 0.086 | 0.832 | 0.895 | 0.863 | 1202 | 1117 | 1160 | ----- | ----- | ---- |
| Irrigation at CRI and Flowering stages ($T_2$) | 0.080 | 0.206 | 0.143 | 0.796 | 2.057 | 1.426 | 1257 | 486 | 871 | 12 | 69 | 40 |
| Irrigation at 0.25 PSI ($T_3$) | 0.062 | 0.070 | 0.066 | 0.621 | 0.700 | 0.660 | 1612 | 1429 | 1520 | -15 | -14 | -15 |
| Irrigation at 0.50 PSI ($T_4$) | 0.085 | 0.100 | 0.092 | 0.848 | 0.997 | 0.923 | 1179 | 1003 | 1091 | 7 | 15 | 11 |
| Irrigation at 0.75 PSI ($T_5$) | 0.068 | 0.074 | 0.071 | 0.676 | 0.740 | 0.708 | 1479 | 1351 | 1415 | 23 | 18 | 21 |
| Irrigation at 25% depletion of FC ($T_6$) | 0.061 | 0.090 | 0.075 | 0.610 | 0.879 | 0.744 | 1640 | 1112 | 1376 | -24 | 4 | -10 |
| Irrigation at 30% depletion of FC ($T_7$) | 0.071 | 0.088 | 0.079 | 0.706 | 0.879 | 0.793 | 1416 | 1137 | 1277 | -14 | 2 | -6 |
| Irrigation at 75% depletion of FC ($T_8$) | 0.040 | 0.062 | 0.051 | 0.404 | 0.610 | 0.507 | 2472 | 1603 | 2037 | 10 | 11 | 10 |
| Rainfed ($T_9$) | ---- | ----- | ----- | ---- | ---- | ------ | ---- | ---- | ------ | ----- | ----- | ---- |

## 4.5 Soil moisture stress relationship with plant water status based on remote sensing techniques

### *4.5.1 False color composite (FCC)*

False colour composite (FCC) imagery serves as a valuable tool for evaluating the vitality of vegetation, necessitating the consultation of pivotal remote sensing research that elucidates the interactions between vegetation and various spectral bands. FCC images are extensively employed in environmental research due to their capacity to improve the representation of vegetation health, particularly through the incorporation of the Near Infrared (NIR) spectral band. FCC was created to visualize vegetation, urban areas along with water bodies present in interest. In FCC, various spectral bands are allocated to the red, green, and blue colour channels to accentuate specific characteristics, such as vegetation and water bodies. FCC was created for both the rabi season of 2022-23 and 2023-23 as shown in Fig. 4.12 and 4.13.

In the context of the year 2022-23, specifically during November 2022 the vegetation present in the designated area during that temporal interval is observed to exhibit a hue of red. In contrast, the remainder of the area is characterized by shades of blue and cyan, which serve to denote regions of buildup as well as fallow land or those locales wherein the germination of crops has not yet occurred. From December through February, the augmentation of bright red hues signifies an enhancement in vegetation coverage when juxtaposed with November, attributable to the elevated reflectance of the near infrared (NIR) band. Nevertheless, in March, the subdued red colouration denotes that the agricultural vegetation is reaching its maturation phase, resulting in a marginal reduction in the reflectance of the NIR band. In April, the diminishing proportion of red colouration suggests that the harvesting of the crops has transpired, as evidenced by the illustration presenting cyan or yellow tones.

In the year 2023-24, the month of November exhibited a character analogous to that of the preceding year, as this month signifies the commencement of the rabi season. As we transition into December, the expansion of the area occupied by vegetation is represented in a vivid red hue, attributable to the elevated reflectance of near infrared (NIR), which indicates the presence of dense and thriving vegetation.

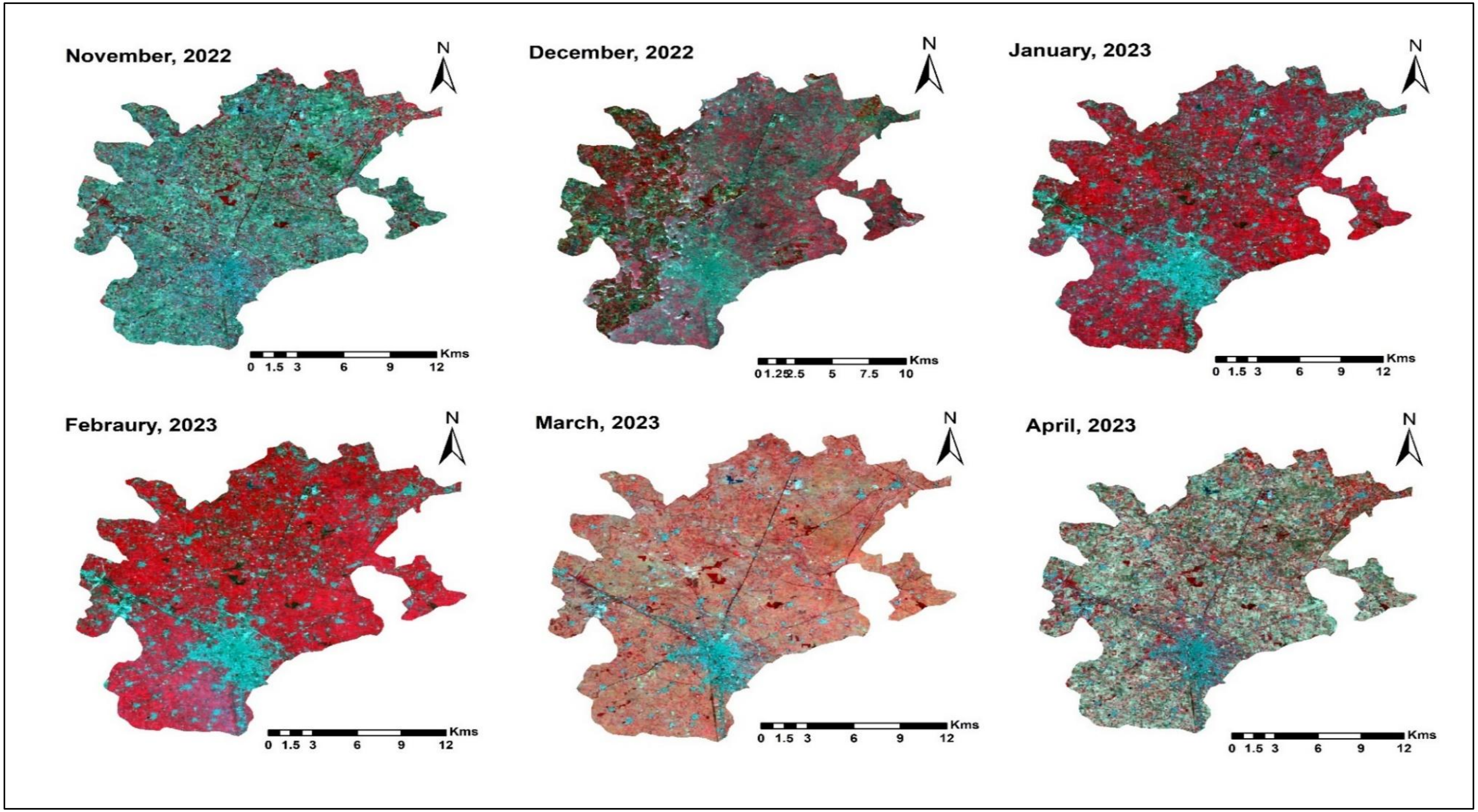



**Fig. 4.12 False color composite (FCC) of Phagwara for the *rabi* season of 2022-23**

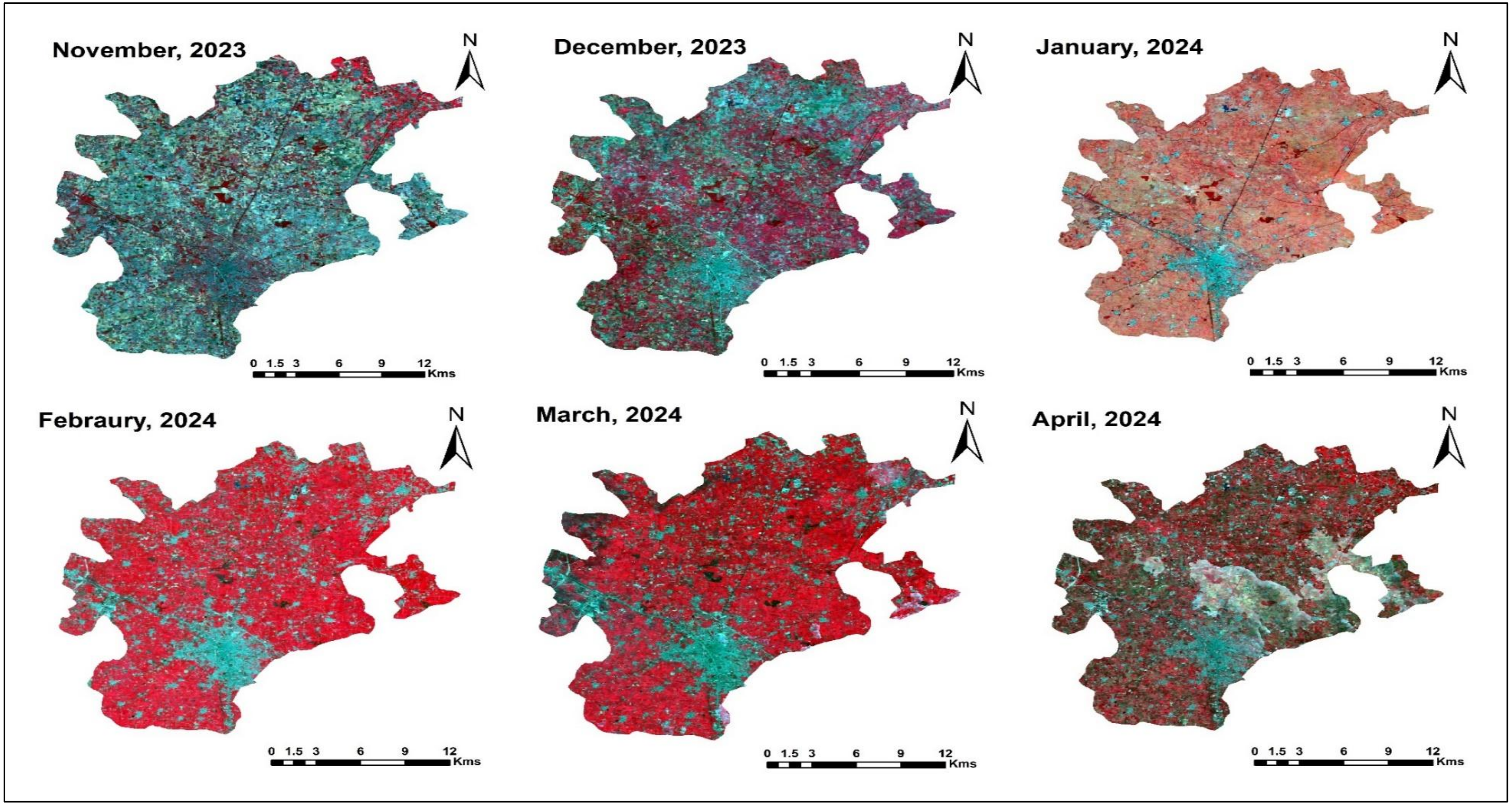



**Fig. 4.13 False colour composite (FCC) of Phagwara for the *rabi* season of 2023-24**

Nonetheless, in January, the hue tends to exhibit a lighter shade of red, a phenomenon that can be ascribed to a diminished reflectance of the near-infrared (NIR) band; this occurrence may be linked to the lower ambient temperatures prevalent during this time frame, which consequently attenuated the metabolic processes of the plant, resulting in a decline in chlorophyll concentration and, hence, a reduction in NIR reflectance. As we progress from February to March, when the temperature tends to become optimum for plant growth, the vegetation appears to be in bright red. The softer crimson hue of April suggests that the foliage is getting closer to maturity.

#### *4.5.2 Normalized difference vegetation index*

The normalized difference vegetation index (NDVI) is a commonly utilized metric obtained from satellite imagery for the evaluation of vegetation health and density. The relationship between spectral variability and variations in the pace of vegetation development has been extensively studied using the NDVI (Gandhi *et al.,* 2015). Ranging from -1 to 1, NDVI values serve as indicators of vegetation health and density, with elevated values suggesting more robust vegetation. The influence of water stress on vegetation manifests in diverse manners, and NDVI provides a means to indirectly evaluate the repercussions of water stress on vegetation. Fig. 4.14 and 4.16 represent the values of the NDVI in the Phagwara block during the *rabi* season where most of the area is grown with wheat crops. In the year 2022-23 (Fig.4.14), the findings suggest that in November, NDVI varied between -0.303 and 0.778. As shown in this month most of the area has been shown in yellow color where NDVI values ranged from 0.252 to 0.396. The recorded values in December and January fell within the range of -0.242 to 0.703 and -0.219 to 0.747, respectively. In November the NDVI was still very low, near land level, and the wheat had just been seeded. The results of the analysis for February and March showed values varying from -0.072 to 0.738 and 0.002 to 0.775, respectively. April's NDVI values fall between -0.298 and 0.795. Since this month is a crop harvest, most of the region is covered in yellow, with NDVI values ranging from 0.323 to 0.460, which shows a decline in NDVI values as crops approach senescence and their chlorophyll content decreases.

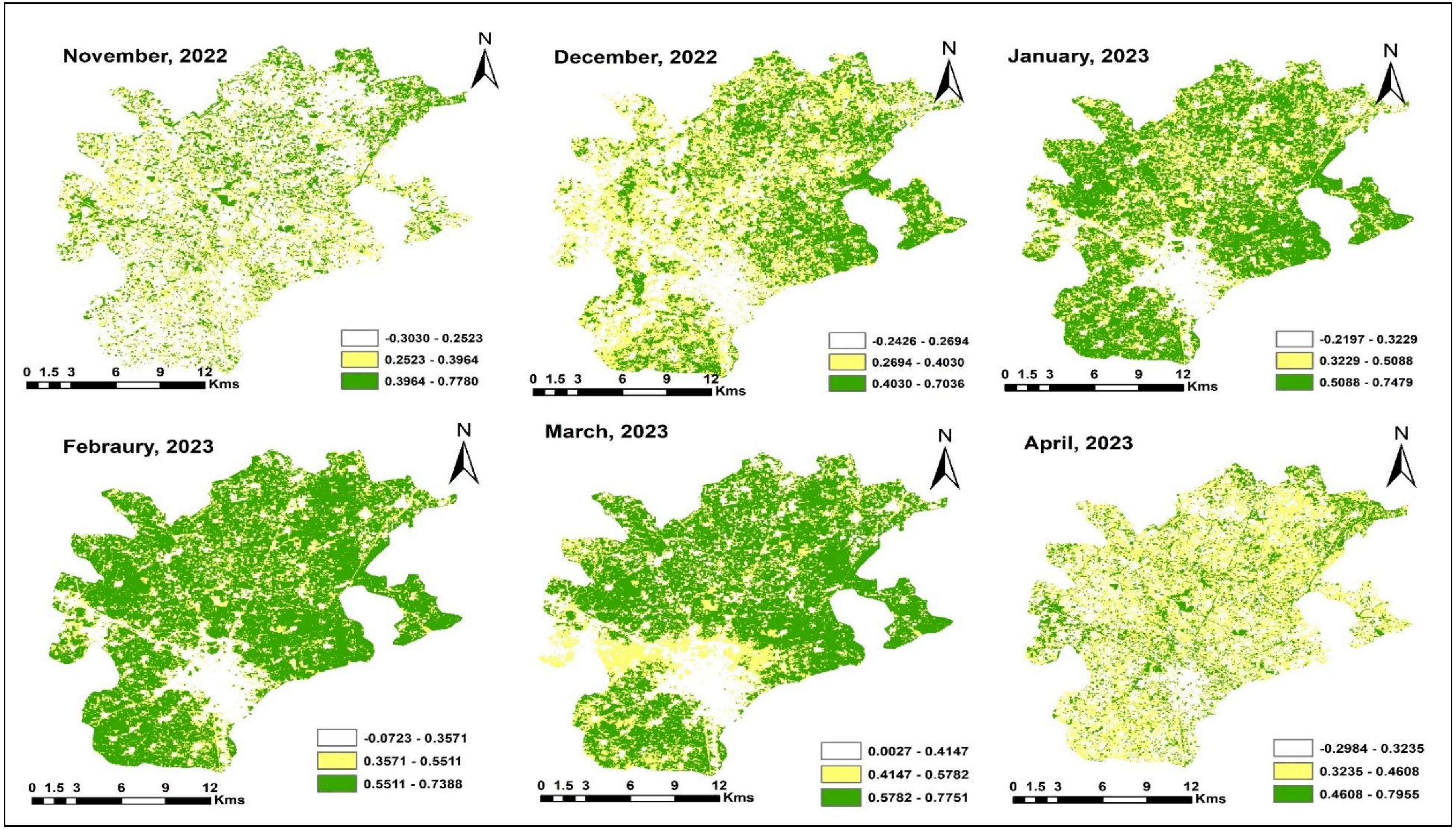



**Fig. 4.14 NDVI of Phagwara for the *rabi* season of 2022-23**

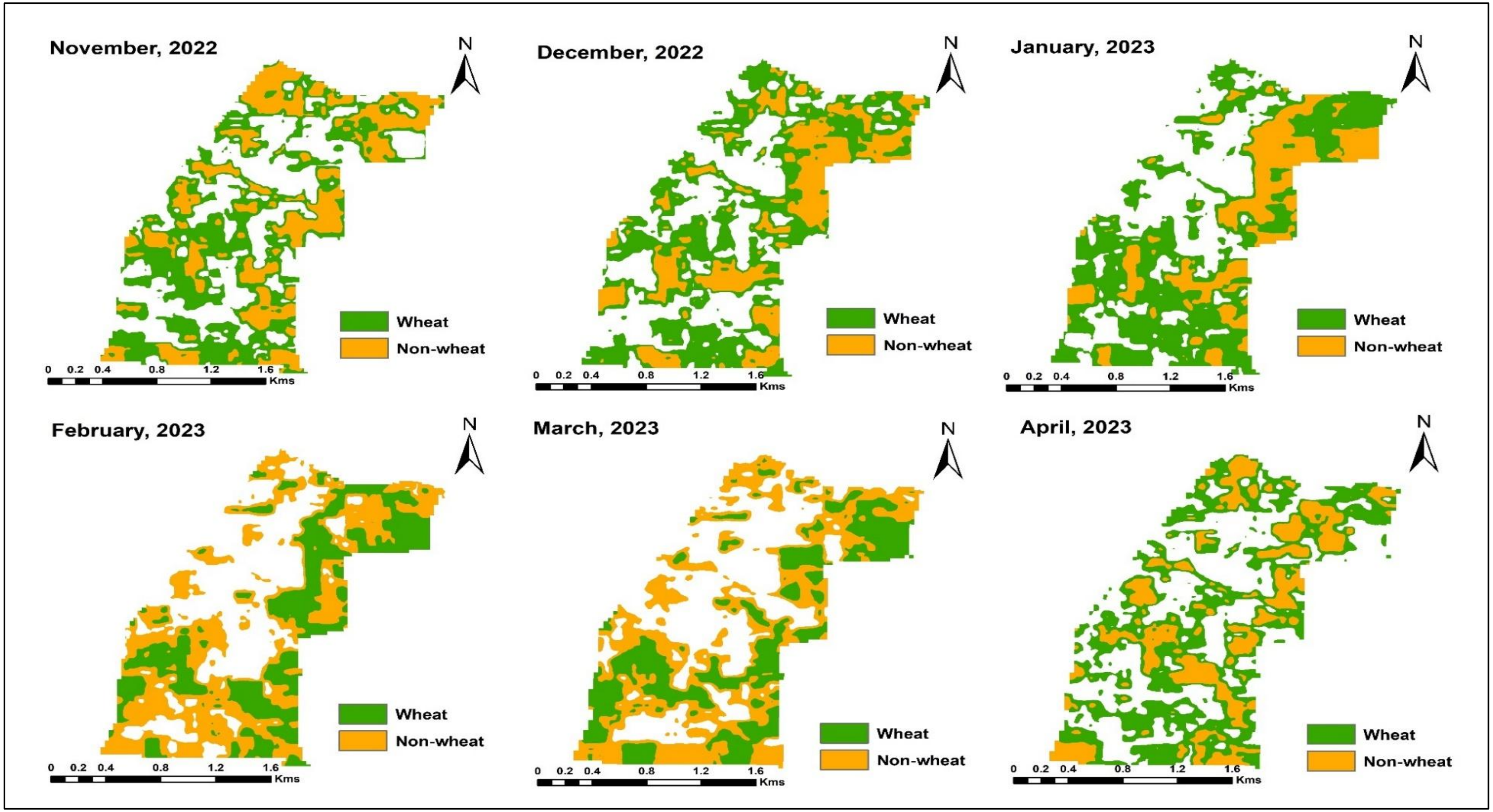



**Fig. 4.15 NDVI of study area for the *rabi* season of 2022-23**

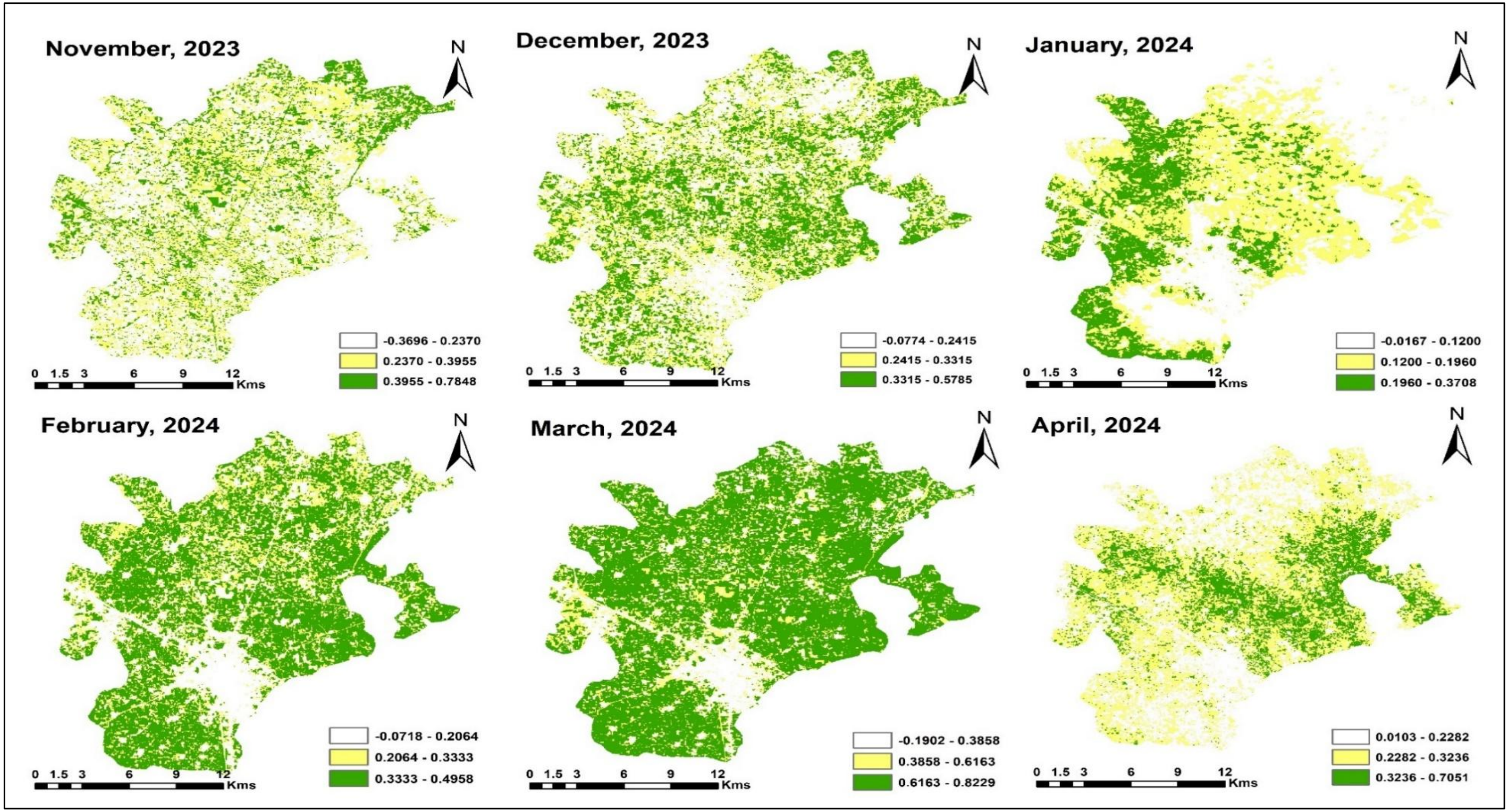



**Fig. 4.16 NDVI of Phagwara for the *rabi* season of 2023-24**

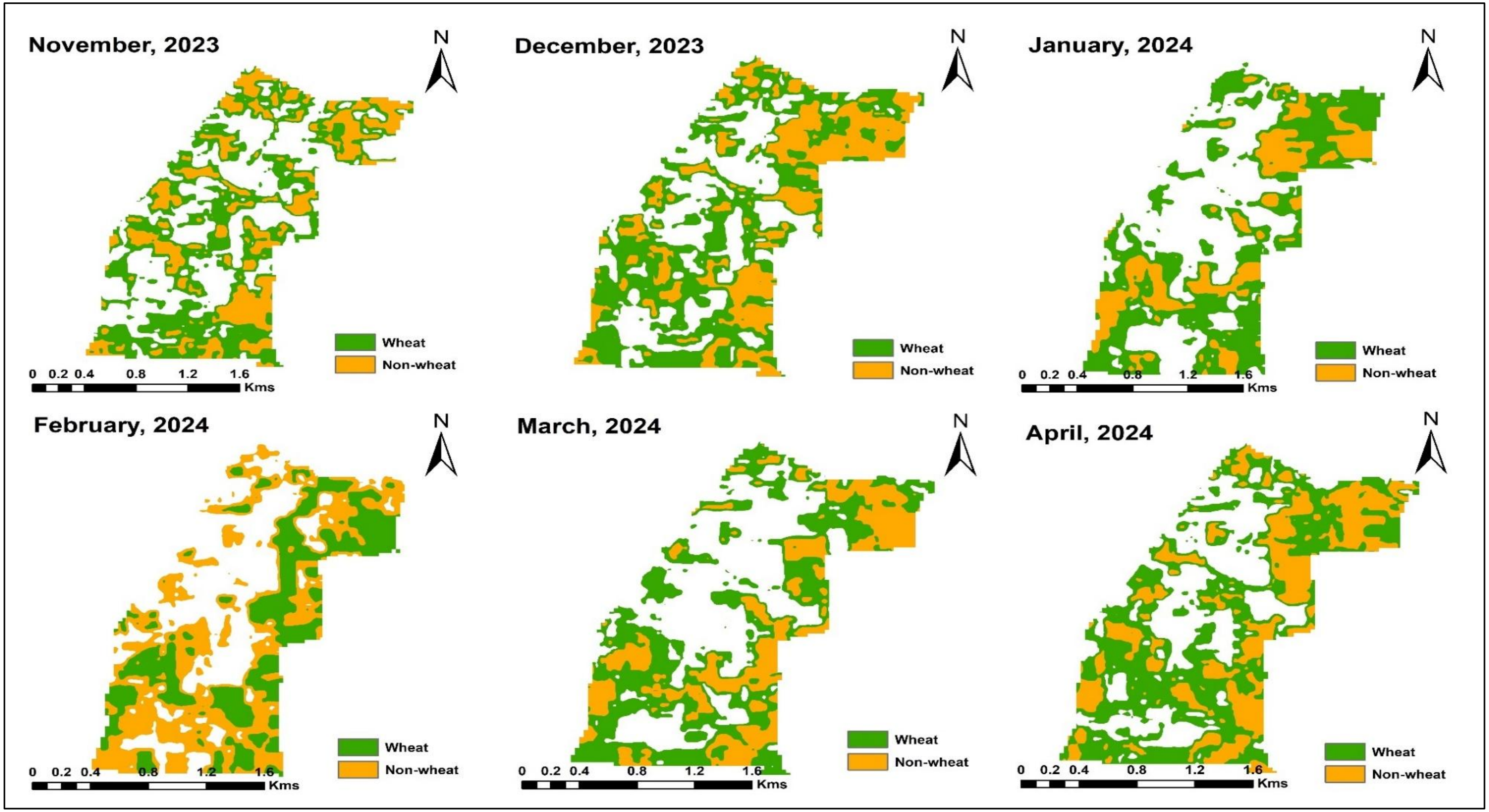



**Fig. 4.17 NDVI of the study area for the *rabi* season of 2023-24**

The examination of the NDVI index for the *rabi* season 2023-24 (Fig. 4.16) reveals that in November, the values varied from -0.369 to 0.784. In December, the range extends from -0.077 to 0.578. The range for January falls between -0.016 to 0.370, -0.071 to 0.495 for February, -0.190 to 0.822 for March, and 0.010 to 0.705 for April. Similar trends were observed for NDVI for the study area for the year 2023-24 (Fig. 4.16). The spectral curve of wheat provides valuable information about the plant's health, water content, and growth stage for the Phagwara region along with the study area as shown in Fig. 4.18 to 4.21.

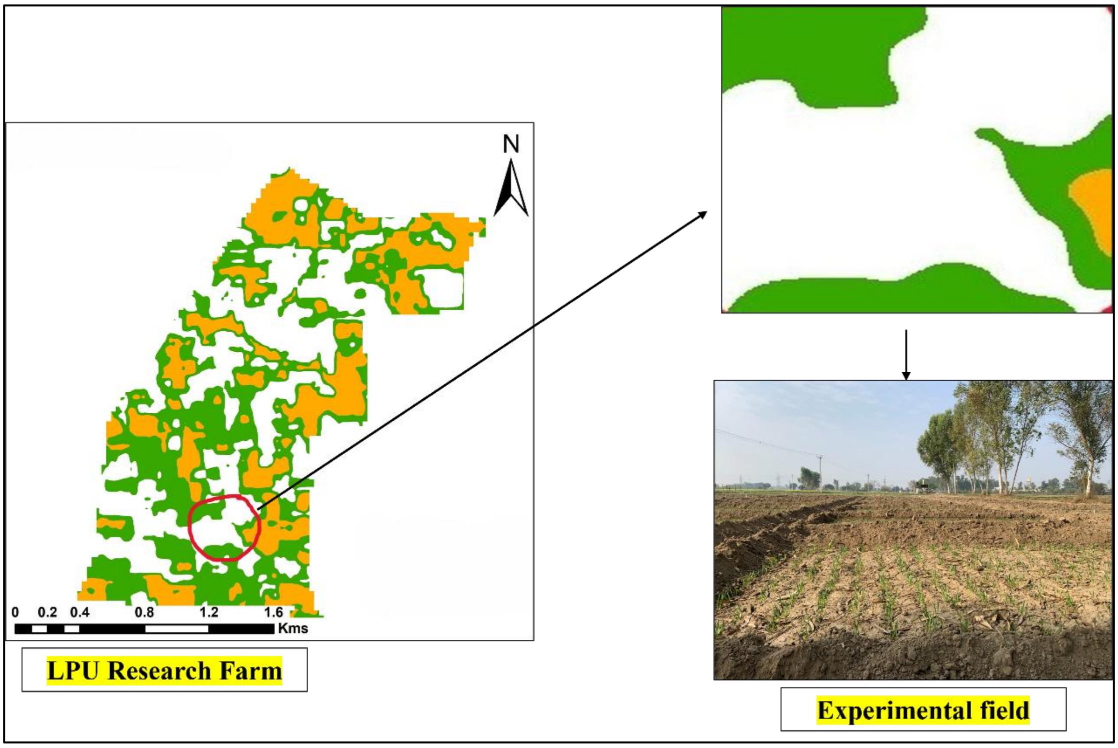



**Fig. 4.18 Map for study area**

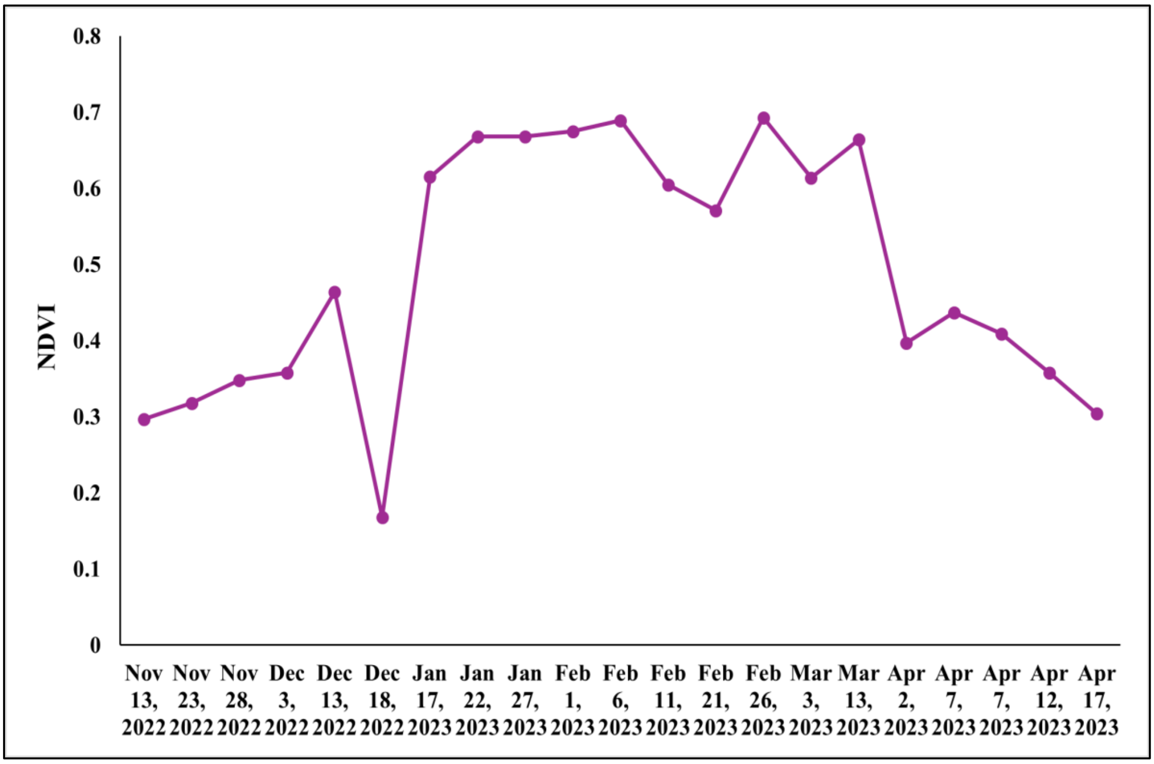



**Fig. 4.19 Spectral curve of wheat for Phagwara during 2022-23**

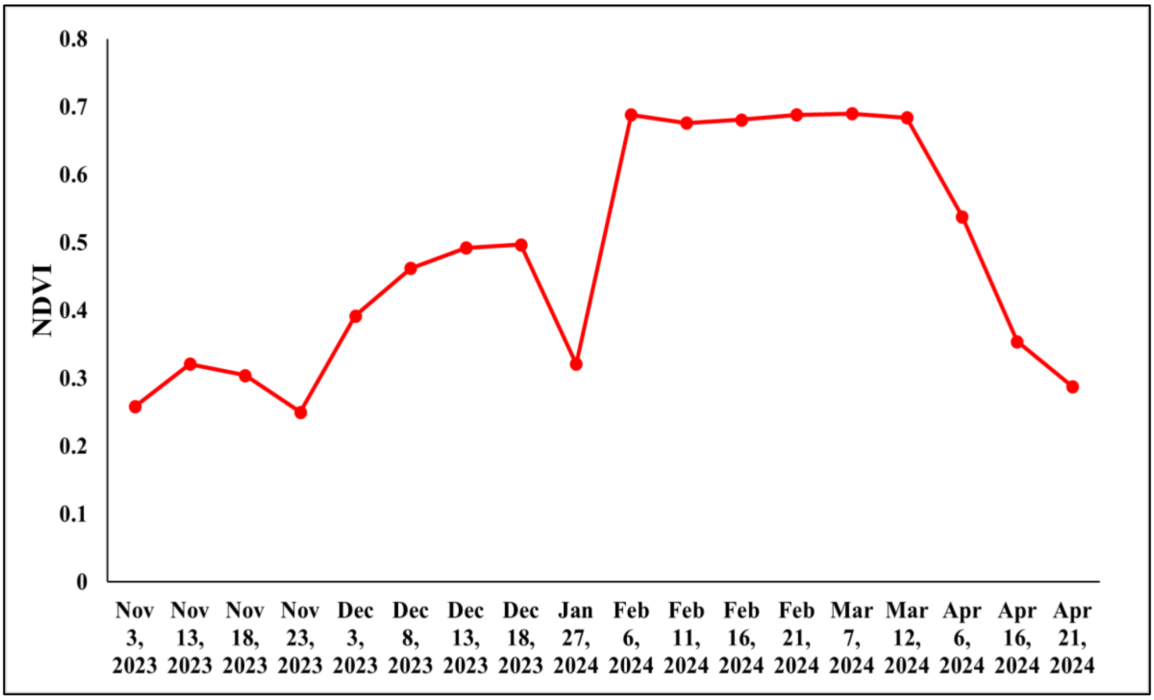



**Fig. 4.20 Spectral curve of wheat for Phagwara during 2023-24**

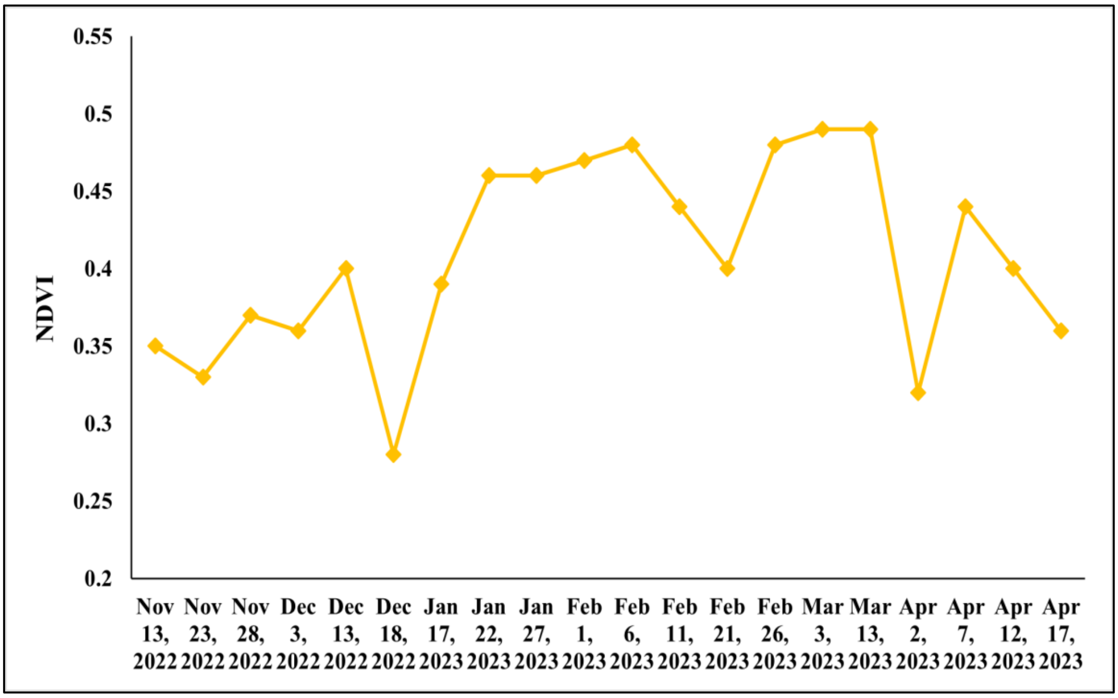



**Fig. 4.21 Spectral curve of wheat for study area during 2022-23**

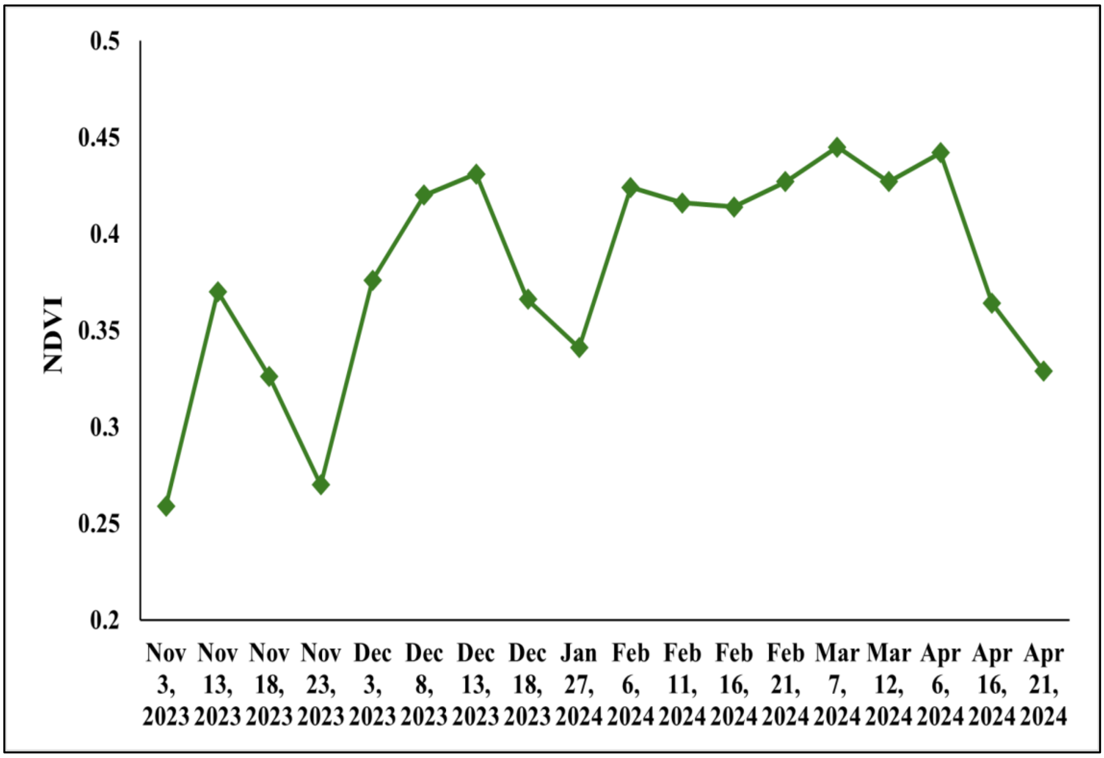



**Fig. 4.22 Spectral curve of wheat for study area during 2023-24**

### 4.5.3 *Land surface water index*

The land surface water index (LSWI) is an additional index derived from remote sensing data, which holds significance in the evaluation of water stress experienced by crops. LSWI computation involves the utilization of near-infrared (NIR) and shortwave infrared (SWIR) bands captured through satellite imaging. This index serves to quantify the water content present on the Earth's surface, where elevated LSWI values signify moist conditions while decreased values indicate dry conditions. During the period spanning from 2022 to 2023 (Fig. 4.22), the LSWI exhibited a range of values between -0.350 to 0.807 in November, and between -0.611 to 0.941 in December. In January, the LSWI demonstrated a range from -0.331 to 0.787, with values observed between -0.744 and 0.674 in February. The range for March was between -0.0711 to 0.618 and in April it lies between -0.421 to 0.730.

In 2023-24 (Fig. 4.23), the LSWI value fluctuates within the range of -0.556 to 0.827 in November, and -0.380 to 0.652 in December. During January, the LSWI value varied from -0.422 to 0.589, while in February, it showed a range of -0.407 to 0.747, and in March, it ranged between -0.358 to 0.799. In April, the values range between -0.405 to 0.874.

### *4.6 Economics*

The production economics of wheat, assessed across two consecutive cropping seasons (2022–23 and 2023–24) under various irrigation scheduling strategies, are presented in Table 4.17 & 4.18. The variation in total cost of cultivation among treatments was primarily attributed to differences in irrigation levels, which represent a significant proportion of production expenditure. During 2022–23, the maximum gross return (`151,553 ha$^{-1}$) was recorded under the recommended irrigation schedule ($T_1$), followed by `164,932 ha$^{-1}$ in 2023–24 under the same treatment. In contrast, the lowest gross returns were observed under rainfed conditions ($T_9$), amounting to `66,888 ha$^{-1}$ and `102,037 ha$^{-1}$ during 2022–23 and 2023–24, respectively. The pooled data analysis indicated the highest gross return (`158,242 ha$^{-1}$) under $T_1$ and the lowest (`84,462 ha$^{-1}$) under $T_9$.

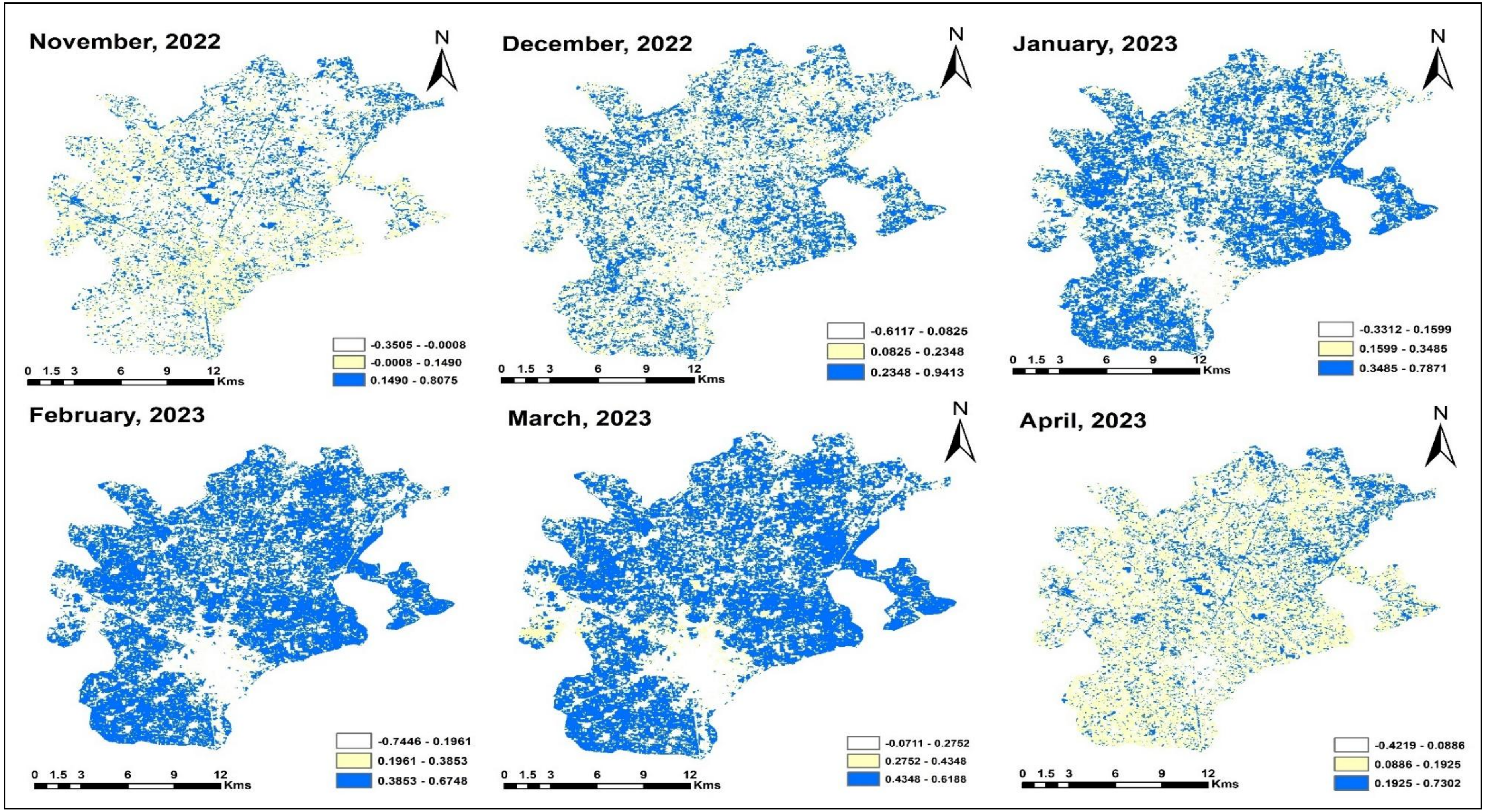



**Fig. 4.23 LSWI of Phagwara for *rabi* season of 2022-23**

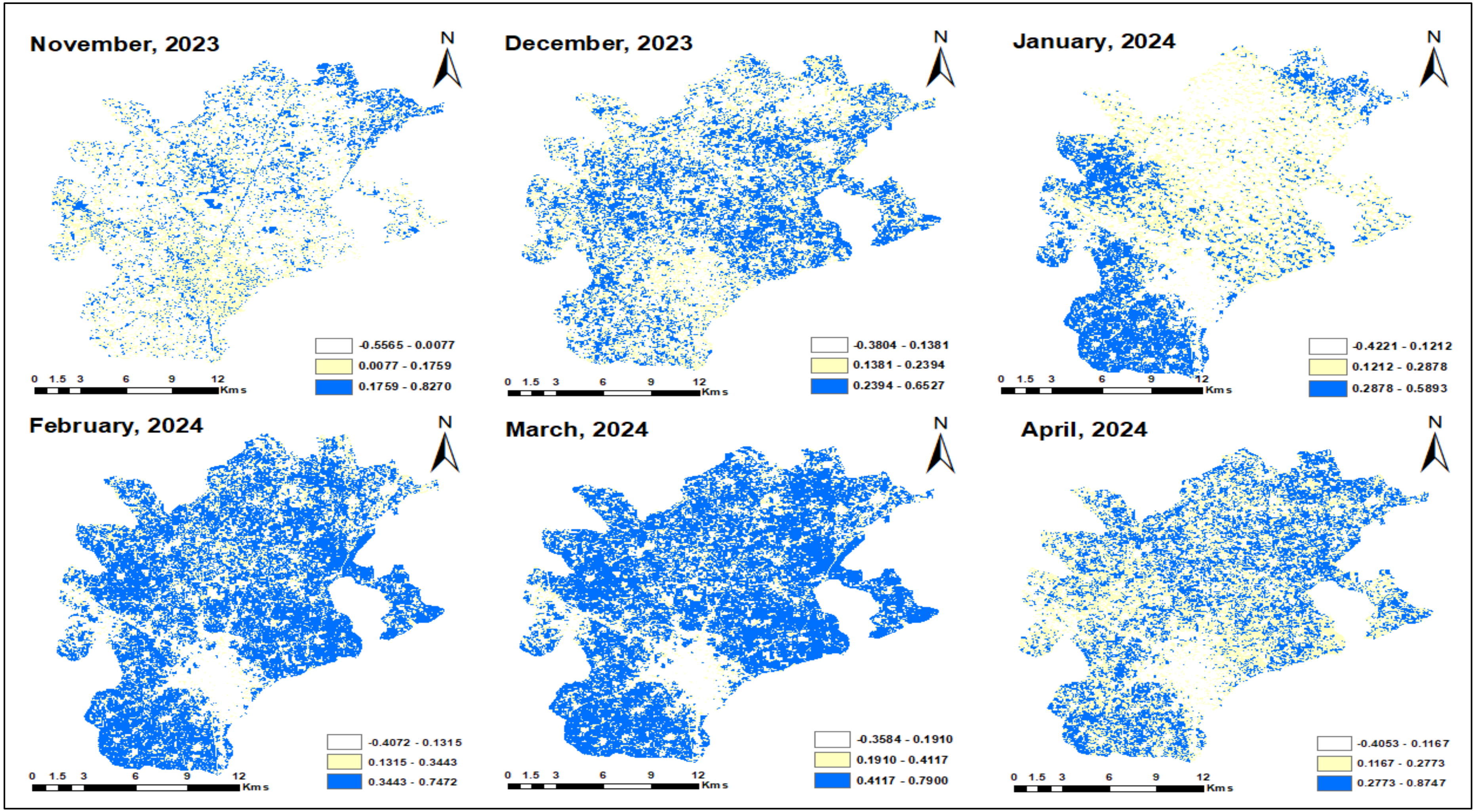



**Fig. 4.24 LSWI of Phagwara for *rabi* season of 2023-24**

Net returns followed a similar trend to gross returns (Table 4.17). The maximum net return was achieved under $T_1$, with values of `101,264 ha$^{-1}$ in 2022–23 and `112,459 ha$^{-1}$ in 2023–24. The lowest net returns were recorded under $T_9$ (`18,600 ha$^{-1}$ and `51,949 ha$^{-1}$ in the respective years). The pooled analysis reflected the highest net return of `106,862 ha$^{-1}$ under $T_1$, and the lowest (`35,274 ha$^{-1}$) under $T_9$. When net returns were analysed relative to water use, during 2022–23, $T_1$ continued to provide the highest economic return (`101,264 ha$^{-1}$). However, in 2023–24, treatment $T_4$ (irrigation at 0.50 PSI) yielded the highest net return (`120,636 ha$^{-1}$), surpassing all other treatments. This pattern was also evident in the pooled analysis, with $T_4$ producing the highest net return (`108,788 ha$^{-1}$), while $T_9$ consistently resulted in the lowest economic benefit (`35,274 ha$^{-1}$).

The benefit-cost (B:C) ratio (Table 4.18), which reflects the economic efficiency of irrigation scheduling methods, varied from 0.4 to 2.0 in 2022–23 and from 1.1 to 2.4 in 2023–24. The highest B:C ratio of 2.0 in 2022–23 was observed in $T_1$ (recommended irrigation) and $T_4$ (0.50 PSI) and were observed to be similar, whereas the lowest was under $T_9$ (rainfed). In the 2023–24 season, highest B: C ratio of 2.3 was observed in $T_2$ (irrigation at CRI and flowering stages), and lowest of 1.1 was achieved in $T_9$. Pooled data analysis showed that $T_4$ achieved the maximum B:C ratio (2.2), while the minimum (0.8) was associated with the rainfed treatment ($T_9$). This indicates that strategic irrigation management, particularly treatments $T_2$ and $T_4$, substantially enhances economic returns and water use efficiency in wheat cultivation.

**Table 4.17: Effect of irrigation scheduling methods on economic feasibility**

| Treatments | Gross returns (` $ha^{-1}$) (a) | | | Cost of cultivation (` $ha^{-1}$) (b) | | | Net returns (` $ha^{-1}$) (c) (c= a-b) | | | Net returns (` $ha^{-1}$) (based on water saving) (d) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** | **2022-23** | **2023-24** | **Pooled** |
| Recommended irrigation ($T_1$) | 151553 | 164932 | 158243 | 50289 | 52474 | 51381 | 101264 | 112459 | 106862 | ----- | ----- | ----- |
| Irrigation at CRI and Flowering stages ($T_2$) | 129381 | 122787 | 126084 | 48999 | 50939 | 49969 | 80383 | 71849 | 76116 | 90209 | 121094 | 105652 |
| Irrigation at 0.25 PSI ($T_3$) | 130831 | 149384 | 140107 | 50589 | 52631 | 51610 | 80242 | 96753 | 88498 | 67965 | 83345 | 75655 |
| Irrigation at 0.50 PSI ($T_4$) | 143272 | 157045 | 150159 | 49989 | 51989 | 50989 | 93283 | 105057 | 99170 | 100275 | 120636 | 110455 |
| Irrigation at 0.75 PSI ($T_5$) | 95993 | 116089 | 106041 | 49689 | 51639 | 50664 | 46304 | 64450 | 55377 | 57103 | 76312 | 66707 |
| Irrigation at 25% depletion of FC ($T_6$) | 138699 | 156953 | 147826 | 50769 | 52339 | 51554 | 87930 | 104615 | 96272 | 66779 | 108398 | 87589 |
| Irrigation at 30% depletion of FC ($T_7$) | 147301 | 158951 | 153126 | 50569 | 52384 | 51476 | 96732 | 106567 | 101650 | 82856 | 109087 | 95972 |
| Irrigation at 75% depletion of FC ($T_8$) | 71940 | 105761 | 88851 | 49289 | 51289 | 50289 | 22652 | 54473 | 38562 | 24835 | 60338 | 42586 |
| Rainfed ($T_9$) | 66888 | 102037 | 84463 | 47400 | 48600 | 48000 | 19488 | 53437 | 36463 | ----- | ----- | ----- |

**Table 4.18: Effect of irrigation scheduling methods on economic feasibility**

| Treatments | B:C ratio (e) (e=c/b) | | | B:C ratio (f) (f=d/b) | | |
|---|---|---|---|---|---|---|
| | 2022-23 | 2023-24 | Pooled | 2022-23 | 2023-24 | Pooled |
| Recommended irrigation ($T_1$) | 2.0 | 2.1 | 2.1 | 2.0 | 2.1 | 2.1 |
| Irrigation at CRI and Flowering stages ($T_2$) | 1.6 | 1.4 | 1.5 | 1.8 | 2.4 | 2.1 |
| Irrigation at 0.25 PSI ($T_3$) | 1.6 | 1.8 | 1.7 | 1.3 | 1.6 | 1.5 |
| Irrigation at 0.50 PSI ($T_4$) | 1.9 | 2.0 | 1.9 | 2.0 | 2.3 | 2.2 |
| Irrigation at 0.75 PSI ($T_5$) | 0.9 | 1.3 | 1.1 | 1.1 | 1.5 | 1.3 |
| Irrigation at 25% depletion of FC ($T_6$) | 1.7 | 2.0 | 1.9 | 1.3 | 2.1 | 1.7 |
| Irrigation at 30% depletion of FC ($T_7$) | 1.9 | 2.0 | 2.0 | 1.6 | 2.1 | 1.9 |
| Irrigation at 75% depletion of FC ($T_8$) | 0.5 | 1.1 | 0.8 | 0.5 | 1.2 | 0.8 |
| Rainfed ($T_9$) | 0.4 | 1.0 | 0.7 | 0.4 | 1.1 | 0.8 |

## *II DISCUSSIONS*

The experimental findings obtained from this investigation, along with the significant results, are critically analysed and interpreted with reference to existing literature, supporting evidence, and relevant scientific explanations.

### *4.7 Crop phenology*

The standardization of irrigation scheduling based on canopy temperature and soil moisture regimes significantly influenced the phenological development of wheat (*Triticum aestivum* L.). The maximum number of days to reach various phenological stages was consistently recorded under the recommended irrigation treatment ($T_1$), whereas the minimum duration was observed under the rainfed condition ($T_9$) during both cropping seasons (2022–23 and 2023–24). This trend may be ascribed to the irrigation applied at the crown root initiation (CRI) stage in $T_1$, in conjunction with reduced ambient temperatures during the crop's developmental phase.

The comparatively lower minimum air temperatures observed during the 2022–23 and 2023–24 seasons—approximately 3°C and 4°C lower than in 2021–22—likely contributed to a deceleration in crop growth, particularly affecting the duration to reach the maximum tillering stage, irrespective of irrigation treatment. These findings are consistent with the observations of Hundal & Kaur (2007), who reported delayed progression through phenological stages in wheat under reduced temperature conditions. Similarly, Bisht *et al.,* (2019) noted that different irrigation levels did not significantly influence the time required to reach the CRI and tillering stages. Several studies have indicated that increased irrigation frequency tends to prolong the interval from sowing to heading and maturity (Ibrahim *et al.,* 2010; Mer & Amma, 2014). In the present study, $T_9$ (rainfed) treatment resulted in the shortest duration to reach various developmental stages, suggesting that water stress conditions may induce an adaptive response in plants to expedite their life cycle completion. This aligns with the findings of Ihsan *et al.,* (2016) and Seleiman & Abdel-Aal (2018), who also reported shortened phenological durations under moisture stress, allowing the crop to complete its life cycle in adverse conditions. Furthermore, Singh *et al.* (2013) documented that under optimal moisture regimes, wheat exhibited extended phenological durations, likely due to improved physiological activity and prolonged vegetative and reproductive growth phases. Conversely, moisture deficits during either vegetative or reproductive stages accelerated phenophase transitions. The data presented in Table 4.1 indicate that anthesis duration was significantly affected by the irrigation treatments. Irrigation at the booting stage was specifically applied to $T_1$ (recommended irrigation), $T_6$ (irrigation at 25% depletion of FC), and $T_7$ (irrigation at 30% depletion of FC), while the remaining treatments excluded irrigation during CRI and tillering stages, potentially leading to water stress at booting and hastening the onset of anthesis.

A similar trend was observed for the milking stage, with $T_1$ (recommended irrigation) showing prolonged duration, while $T_9$ (rainfed) reached the stage in a significantly shorter time. The reduced time to milking under water-limited conditions can be attributed to stress-induced acceleration of physiological processes. These observations are supported by previous reports indicating that increased irrigation leads to extended crop duration and reproductive phases (Dhaka *et al.,* 2006; Ngwako & Mashiqa, 2013; Kumar *et al.,* 2018; Bisht *et al.,* 2019). Additionally, the time required to attain the dough stage declined progressively from $T_1$ (recommended irrigation) to $T_9$ (rainfed), correlating with increasing water stress. Water deficit during maximum tillering and flowering stages contributed to a reduction in the duration to reach the dough stage compared to the fully irrigated treatment. Cooler air temperatures during the crop's early growth phase may have delayed physiological development and maturity, accounting for the extended crop duration observed in the 2023–24 season. Kumar *et al.* (2018) also reported that increased irrigation frequency delayed heading, anthesis, and maturity. In contrast, water stress appeared to promote early physiological maturity by shortening the crop’s life cycle, an adaptive strategy of the plant under suboptimal moisture conditions. This hastened progression through developmental stages is often associated with reduced grain yield, as also reported by Islam *et al.* (2018).

### *4.8 Crop growth*

Irrigation scheduling methods exerted a significant influence on the growth and development of wheat during the 2022–23 and 2023–24 cropping seasons. Growth parameters such as plant height, tiller count, dry matter accumulation, and LAI were markedly higher in 2023–24, primarily due to more favourable climatic conditions that supported optimal wheat growth and development. Plant height was significantly influenced by the irrigation scheduling methods, particularly at later growth stages (60 DAS to harvest), although the variation was not significant at 30 DAS, as also reported by Singh *et al.* (2018). Progressive increases in plant height with greater irrigation frequency may be attributed to enhanced moisture availability in recommended irrigation ($T_1$), which supports key physiological processes such as cell division and elongation, ultimately leading to improved stem elongation and plant growth. These results are consistent with the findings of Verma *et al.* (2017a) and Singh *et al.* (2020), as well as earlier studies by Ali *et al.* (2007), Shirazi *et al.* (2014), Pawar & Dingre (2014), Wairagade *et al.* (2020), Pallekonda *et al.* (2018), Rummana *et al.* (2018), and Abhineet *et al.* (2019), all of which reported a decline in wheat plant height under water stress conditions.

Consistent soil moisture as shown in figure 4.11 in the $T_1$ (recommended irrigation) likely promoted enhanced tiller production by facilitating metabolic activity and nutrient uptake (Kumar *et al.,* 2020; Baque *et al.,* 2006). Verma *et al.* (2018) observed a significantly greater number of effective tillers under optimal moisture regimes, highlighting the role of irrigation in improving nutrient mobilization and utilization. Prolonged greenness due to sustained chlorophyll content further enhanced photosynthetic efficiency, improving carbon assimilation and boosting ear-bearing tiller numbers (Chaplot & Sumeriyan, 2013), corroborating the findings of Nayak *et al.* (2015) and Bikrmaditya *et al.* (2011). Intermittent irrigation and extended intervals between water applications may have induced moisture stress, adversely affecting tiller density as observed in $T_9$ (rainfed). Variability in rainfall and missed irrigations could have exacerbated these effects, leading to more pronounced differences in tiller count among treatments at maturity. These observations are supported by previous research

(Khan *et al.,* 2007; Asif *et al.,* 2010; Meena *et al.,* 2015; Aslam *et al.,* 2015; Kumar *et al.,* 2016; Yousaf *et al.,* 2014), which collectively reported reduced tiller numbers under persistent water stress. Similar reductions in tiller density under moisture deficit conditions were noted by Patel *et al.* (2019), Ul-Allah *et al.* (2018), and Rady *et al.* (2021). LAI followed a trend of increasing up to 90 DAS before declining, consistent with the findings of Kumar *et al.* (2018). Adequate irrigation throughout the growing season contributed to higher LAI values (Fig. 4.11), enhancing the plant's ability to intercept and utilize incoming solar radiation (Fig. 4.14 and Fig. 4.16). These observations align with the findings of Kumar *et al.* (2012) and Asif *et al.* (2010). In contrast, under rainfed conditions ($T_9$), the observed reduction in soil moisture (Fig. 4.11) likely limited cellular elongation and expansion, resulting in decreased leaf growth and LAI. This outcome is consistent with the results of Zhang *et al.* (2016) and Dar (2017a), who documented a decline in LAI under moisture stress. Meena *et al.* (2015) also confirmed that increasing water deficit leads to a reduction in LAI.

Enhanced soil moisture availability in $T_1$ (recommended irrigation) treatments contributed to greater plant height, tiller count, and LAI, which collectively increased the crop's dry matter accumulation and was observed to be scientifically at par with $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC). The positive effect of irrigation on dry matter accumulation can be ascribed to improved nutrient availability and uptake under higher moisture regimes (Liu *et al.,* 2018; Si *et al.,* 2020; Regar *et al.,* 2005; Singh & Yadav, 2006). Saren *et al.* (2004) and Kumar *et al.* (2012) also observed comparable increases in dry matter accumulation with higher irrigation levels. Moreover, well-scheduled irrigation has been shown to enhance post-anthesis dry matter accumulation and its contribution to grain yield (Liu & Ouyang, 2012; Zhang *et al.,* 2008). Conversely, limited soil moisture under rainfed conditions ($T_9$) hindered cellular elongation, triggered stomatal closure, increased leaf temperature, and reduced photosynthetic efficiency, thereby constraining biomass production. These physiological constraints led to lower dry matter accumulation in $T_9$, consistent with the findings of Asif *et al.* (2010), Ram *et al.* (2013), Kumar *et al.* (2021), and Dar (2017a). The results underscore the critical role of adequate and timely irrigation in maintaining optimal growth and productivity in wheat.

### *4.9 Physiological parameters*

During 2022-23 and 2023-24, a significant effect of irrigation scheduling was observed during 60, 90 and 120 DAS. The highest Relative water content (RWC) was observed under treatment $T_1$ (recommended irrigation) and was observed to be scientifically at par with $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC). The lowest value was observed under rainfed conditions ($T_9$). As observed from the data recorded it was observed that the highest RWC during the reproductive phase of the growth period is due to active growth of the plant, which focuses on leaf and stem development. Thus, adequate water supply as observed from Fig 4.11 ensures cells are fully turgid, supporting rapid cell division and expansion as observed in recommended irrigation treatments ($T_1$). As indicated by Chaves *et al.,* (2003) the plants with higher RWC during the vegetative phase exhibit better resilience to subsequent stress conditions. A moderate decrease in RWC was observed during the reproductive stage especially during anthesis and early grain-filling stages as they are sensitive to water stress. A reduction in RWC during this stage can result in decreased grain set and lower yield due to impaired fertilization and early grain development (Saini & Westgate, 1999). This RWC may be associated with disparity in the plant's capability to absorb larger amounts of water from the soil and/or its efficiency in regulating water loss through the stomata. Additionally, it may be due to disparity in the wheat crop's ability to amass solutes and adapt osmotically to prolong tissue turgor, which is crucial for sustaining essential physiological processes (Schonfeld *et al.,* 1988; Siddique *et al.,* 2000). Moving towards the maturity phase, RWC generally declines as plants reduce their water uptake, and leaves begin to senesce, leading to limiting the overall water content of the plant. A sharp decline in RWC at maturity was observed as the plant relocates from leaves and stems to grains. Wajid *et al.,* (2011) observed that plants experiencing water stress displayed reduced leaf expansion, compromised photosynthetic systems, early onset of leaf senescence, oxidation of chloroplast lipids, and structural modifications in pigments and proteins. Previous studies by Keyvan, (2010) and El-Hendawy *et al.,* (2019) have also reported a decline in leaf RWC under water stress conditions.

Crop Growth Rate (CGR), Relative Growth Rate (RGR), Absolute Growth Rate (AGR), and Net Assimilation Rate (NAR) were recorded at their highest under $T_1$ (recommended irrigation) and were statistically at par with $T_6$ (irrigation at 25% depletion of FC) and $T_7$ (irrigation at 30% depletion of FC) across both cropping seasons. These trends were consistent during the crop growth intervals of 30–60, 60–90, and 90–120 DAS, while the lowest values for all growth indices were observed under rainfed conditions ($T_9$). The enhanced growth rates in $T_1$, $T_6$, and $T_7$ treatments can be attributed to the relatively higher LAI, which supported improved dry matter accumulation and reduced leaf senescence and stem mortality. This ultimately resulted in a higher number of effective tillers and better canopy longevity, as previously reported by Nakamura *et al.* (2003). Verma *et al.* (2018) also noted that increased dry matter production, coupled with elevated photosynthetic efficiency per unit area, contributed significantly to improvements in CGR, RGR, AGR, and NAR. Furthermore, similar observations were reported by Vishuddha *et al.* (2014) and Kumar *et al.* (2015), who demonstrated that higher irrigation frequencies positively influenced phenological growth parameters. Frequent irrigation supports a higher LAI, which in turn enhances dry matter accumulation per unit leaf area per unit time by minimizing tiller mortality and delaying leaf senescence (McDonald *et al.,* 1984; Patil *et al.,* 2014), thereby contributing to an increase in NAR. Conversely, a delay in irrigation or water deficit during critical growth stages leads to a significant reduction in NAR due to compromised physiological activity and photosynthetic efficiency. This, in turn, adversely affects other growth indices and total dry matter accumulation, as highlighted by Ghanbari-Malidarreh (2010).

The concept of Stress degree days (SDD) is highly valuable for quantifying yield variability attributable to heat and water stress conditions. The cumulative SDD data reveal significant differences among treatments in their ability to maintain favourable canopy temperatures relative to ambient air temperature. Negative cumulative SDD values observed in $T_3$ (irrigation at 0.25 PSI) and $T_4$ (irrigation at 0.50 PSI) across all growth stages suggest efficient transportational cooling and low levels of physiological stress (Idso et al., 1981; Jackson et al., 1981). In contrast, $T_5$ (irrigation at 0.75 PSI) consistently recorded positive cumulative SDDs during tillering–jointing, booting, heading–flowering and grain filling, suggesting that canopy temperatures frequently exceeded air temperatures, a sign of stomatal closure and impaired transpiration under stress (Blum, 1996; Farooq et al., 2011). This stress can severely limit assimilate availability for reproductive development, potentially reducing grain number and yield (Reynolds et al., 1994; Fischer et al., 1998). Similar results were reported by Sakshi et al. (2025), who found that in treatments with IW/CPE ratio of 2.0 and 1.5, more frequent irrigation contributed to maintaining higher soil moisture levels and a favourable crop microclimate. This, in turn, reduced the temperature differential between the canopy and air temperature. Monitoring SDD provides a valuable tool for identifying periods of stress and guiding timely agronomic interventions.

### *4.10 Yield attributes*

Irrigation scheduling methods had a significant influence on wheat yield attributes—including spike length, number of grains per spike, and 1000-grain weight—during the 2022–23 and 2023–24 cropping seasons, as well as in the pooled analysis across both years. The highest values for all yield parameters were recorded under the recommended irrigation treatment ($T_1$), followed by $T_7$ and $T_4$, while the lowest values were observed under rainfed conditions ($T_9$) across both seasons. The reduced spike length in $T_9$ may be attributed to limited or absent rainfall during the cropping period, leading to pronounced moisture stress. Such stress conditions impose physiological constraints that hinder plant development, resulting in diminished yield components. Moisture deficiency restricts cell expansion and nutrient translocation, thereby reducing spike elongation. Similar findings were reported by Sagar *et al.* (2017), who noted that longer spikes were indicative of improved vegetative growth under conditions of adequate and consistent water supply.

The superior performance of treatment $T_1$ (recommended irrigation) can be ascribed to optimal soil moisture conditions maintained throughout the crop's growth cycle, particularly during the reproductive phase as observed from Fig 4.11. These conditions likely facilitated efficient assimilate translocation from source to sink, improving plant nourishment and enhancing yield components such as the number of grains per spike (Verma *et al.,* 2017). This observation is further corroborated by Razaq *et al.* (2019), who found that fully irrigated plots produced a significantly higher number of grains per spike compared to those receiving 60% deficit irrigation. Nayak *et al.* (2015) also reported that increased irrigation levels, regulated via IW/CPE ratios, significantly enhanced yield-attributing traits in wheat. The reduction in spike length and grain number in $T_9$ under water-stressed conditions aligns with the findings of Khan *et al.* (2007), Dar (2017a), and Bathre *et al.* (2019), who associated such decreases with suboptimal water availability.

The elevated soil and plant water content in $T_1$ (recommended irrigation) during critical stages of development may have promoted efficient nutrient translocation and grain filling, contributing to a higher 1000-grain weight (Verma *et al.,* 2017). In contrast, under water-deficit conditions, reduced leaf water potential and relative water content lead to stomatal closure, limiting $CO_2$ assimilation and thereby reducing net photosynthetic rate (Zhao *et al.,* 2020). This physiological response ultimately impacts assimilate production and allocation to the developing grains. The observed decrease in 1000-grain weight under rainfed treatment ($T_9$) could be attributed to inadequate moisture availability during the grain filling stage, leading to the formation of shrivelled grains. Karim *et al.* (2000) similarly reported that moisture stress during grain filling significantly reduced grain weight. Liu *et al*. (2021) also demonstrated that water deficits during the grain filling period adversely affect grain size, filling rate, and duration, ultimately resulting in decreased 1000-grain weight and overall yield. These results are consistent with earlier studies by Khan *et al.* (2007), Meena *et al*. (2015), Dar (2017a), and Bathre *et al.* (2019).

### *4.11 Yield*

The effect of irrigation scheduling methods on grain yield, straw yield, and biological yield of wheat was found to be statistically significant across both the 2022–23 cropping season and the pooled data analysis. In contrast, the harvest index exhibited a significant response to irrigation scheduling in the 2022–23 season and in the pooled data; however, this effect was not statistically significant during the 2023–24 cropping season. Grain, straw, and biological yield were found to be highest under the recommended irrigation treatment ($T_1$) during the 2023–24 cropping season, with statistically comparable results also observed under $T_7$ (irrigation at 25% of FC) and $T_4$ (irrigation at 0.50 PSI). In contrast, the lowest values for these yield components were consistently recorded under rainfed conditions ($T_9$) across both growing seasons. Pooled data analysis further confirmed that the maximum yields were achieved with $T_1$, while $T_9$ produced the minimum yields. The superior grain yield observed in $T_1$ may be attributed to the maintenance of optimal soil moisture levels throughout the crop's growth cycle, which likely enhanced nutrient uptake and photosynthetic efficiency. Conversely, the reduction in grain yield under $T_9$ could be due to moisture stress during critical growth stages, which resulted in increased photorespiration and a subsequent decline in net photosynthesis (Kaur *et al.,* 2018). The reduced availability of soil moisture under $T_9$ may have impeded root water uptake, leading to various physiological limitations such as premature leaf senescence, impaired photosynthetic machinery, reduced carbon assimilation, inhibited nutrient translocation, and disrupted grain filling and maturation processes (Asch *et al.,* 2005; Farooq *et al.,* 2009). These findings are in agreement with Ram *et al.* (2013), who noted that well-irrigated conditions facilitated better nutrient and water absorption, resulting in enhanced wheat growth. Similar trends have also been reported by Huang *et al.* (2005a), Mubeen *et al.* (2013), Awasthy *et al.* (2014), and Singh *et al.* (2016). Moreover, Kang *et al.* (2002) observed that reducing irrigation by approximately 20% during early vegetative stages can still produce grain yields comparable to, or greater than, those achieved with full irrigation.

The increased straw yield observed under $T_1$ can be attributed to the sufficient soil moisture (Fig. 4.11), which facilitated greater plant height, enhanced LAI, and promoted increased dry matter accumulation. Improved nutrient availability under these moisture-rich conditions also contributed to higher straw biomass (Liu *et al.,* 2018; Si *et al.,* 2020). Wairagade *et al.* (2020) also demonstrated that applying three irrigations significantly improved wheat straw yield compared to lower irrigation levels. Interestingly, $T_4$ (irrigation at 0.50 PSI) also showed promising results, possibly due to optimized moisture availability during the grain-filling period. In contrast, treatment $T_9$, characterized by limited irrigation, exhibited reductions in plant height, tiller production, and biomass accumulation, primarily due to reduced photosynthetic activity under moisture stress (Asif *et al.,* 2010; Ram *et al.,* 2013; Dar, 2017a). Similar reductions in straw and biological yields under water-deficit conditions have been reported by Kumar *et al.* (2016), Suryavanshi & Buttar (2018), and Meena *et al.* (2019).

The highest harvest index (HI) was also recorded under $T_1$, whereas the lowest HI occurred in the rainfed treatment ($T_9$). The diminished grain yield under $T_9$ may be attributed to imbalanced assimilate partitioning, with a greater proportion allocated to vegetative biomass rather than to grains. In contrast, the higher HI observed under $T_1$ may be due to more efficient remobilization of stored assimilates from vegetative tissues to the grains during the reproductive phase (Meena *et al.,* 2019). These findings align with those of Meena *et al.* (2015) and Bathre *et al.* (2019), who reported that well-watered treatments resulted in improved harvest index values. Lathwal & Thakral (1999) further noted that elevated HI is often negatively correlated with straw yield. Therefore, inadequate irrigation scheduling may disrupt biomass allocation, ultimately resulting in a reduced harvest index.

### ***4.12 Irrigation Parameters***

Among the different irrigation scheduling methods evaluated, total water requirement (TWR) was found to be highest under treatment $T_6$ (irrigation at 25% depletion of field capacity) during the 2022–23 growing season, followed by $T_3$ (irrigation at 0.25 PSI). In contrast, during the 2023–24 season, the overall volume of irrigation water applied was lower than the previous year, with the highest TWR recorded under the recommended irrigation treatment ($T_1$), followed by $T_7$ (irrigation at 30% depletion of FC). Pooled data across both years revealed that the maximum TWR was consistently observed under $T_6$ (irrigation at 25% depletion of FC), followed by $T_3$ (irrigation at 0.25 PSI). The variation in water application levels across treatments can be attributed to differences in irrigation frequency and scheduling strategies. Treatments receiving more frequent irrigation, such as $T_6$ and $T_3$, maintained higher moisture levels in the upper soil profile for extended durations, thereby increasing surface evaporation losses. In contrast, treatments with less frequent irrigation demonstrated lower evaporation due to reduced soil surface wetting (Rajanna *et al.,* 2017).

During the year 2022-23, the maximum CWR was recorded when irrigation was applied at 25% depletion of FC ($T_6$) followed by treatment $T_3$. Whereas in the year 2023-24, the highest CWR was estimated when irrigation was applied at 0.25 PSI ($T_3$), it was followed by recommended irrigation schedule, irrigation at 30% depletion of FC ($T_7$) and irrigation at 25% FC ($T_6$). In both years, the minimum crop water requirement was recorded under the rainfed treatment ($T_9$). The fluctuations in the water demand of the crop can be ascribed to variations in both precipitation and temperature, which exert a notable influence on the crop's water needs. During the initial year of the study, the peak temperature exceeded that recorded in the subsequent year. A modification in the growing period is accompanied by a slight shift due to alterations in the timing of rainfall occurrences. Notably, rainfall was absent during the reproductive phase in the first year (Fig. 3.1), leading to a rise in temperature and subsequently impacting the crop's water requirement across the two years. Research conducted by Lobell *et al.,* (2011) emphasizes that the variability in climate from one year to another plays a significant role in driving alterations in the water usage of crops throughout different seasons. This is also reported by Tellioglu & Konandreas, (2017) climatic variables including evapotranspiration rates and irregular rainfall patterns, as well as soil fertility and inherent soil characteristics, which exert a considerable influence on the water requirements of crops (CWR). The varying amounts of irrigation water applied at different irrigation levels caused the difference in water utilization. When compared to treatments with lower irrigation frequency, the higher crop water requirement can be attributed to the increased irrigation frequency because the surface layers under these treatments remained wet for longer periods, which created conditions for a high rate of evaporation (Rajanna *et al.,* 2018).

The lower irrigation treatments led to increased IWUE values. During the year 2022-23, the highest IWUE was calculated for the treatment where irrigation was applied at 0.50 PSI ($T_4$) which was followed by the recommended irrigation regime ($T_1$). In 2023-24, the highest IWUE was observed where irrigation was applied during the CRI and flowering growth stages ($T_2$). During the pooled analysis, the highest IWUE was observed under treatment $T_2$ (irrigation applied at CRI and flowering stage). A IWUE was observed at 0.50 PSI irrigation regime ($T_4$). The minimum value of IWUE was under rainfed ($T_9$) treatment. The treatment with irrigation applied at CRI and flowering ($T_2$) achieved the highest IWUE, as it used less irrigation water compared to the other treatments. Furthermore, recommended irrigation and irrigation applied at 0.50 PSI, where IWUE was found to be significantly higher than other regimes. These results are consistent with the fact that other yield-contributing traits were not proportionately affected by the volume of irrigation water applied. Previous research also indicates that IWUE improves as irrigation scarcity increases, meaning that water limitations lead to higher IWUE values. Brahma *et al.,* (2007) documented that the IWUE in treatments subjected to singular irrigation events during the crown root initiation (CRI) phase was significantly elevated, primarily attributable to the judicious utilization of water resources, thereby suggesting the effectiveness of water management practices at reduced irrigation frequencies. These results were also corroborated by Chen *et al.,* (2014), Wang *et al.,* (2016), and Xu *et al.,* (2016). Meena *et al.,* (2015) also found that frequent irrigation fosters faster plant growth, greater biomass, and improved yield characteristics, which in turn results in maximum grain yield and ultimately enhances water use efficiency.

The peak irrigation water productivity recorded during the year 2022-23 was noted under treatment $T_4$ (irrigation at 0.50 PSI), followed closely by treatment $T_1$ (recommended irrigation). The minimum value occurred under treatment $T_8$, where irrigation was administered at 75% depletion of field capacity (FC). Nevertheless, in the subsequent year 2023-24, the highest water productivity was realized under treatment $T_2$ (irrigation at CRI and flowering), with $T_4$ (0.50 PSI) and treatment $T_1$ (recommended irrigation) following. In the pooled analysis, the highest water productivity was recorded in $T_2$, succeeded by $T_4$. Conversely, the least productivity was noted for $T_8$. Additionally, Kumaresan *et al*., (2013) also found that irrigation water productivity increased with decreasing water use. The elevated irrigation water productivity observed in $T_2$ can be ascribed to the precipitation recorded during the year 2023-24 in comparison to $T_4$, which has consequently diminished the volume of water necessary for irrigation, thereby enhancing the overall irrigation water productivity. Kang *et al.,* (2002) identified that wheat plants exposed to a diminution of irrigation water by approximately 20% during the formative vegetative stages produce grain yields that are comparable to or surpass those of wheat that was provided with full irrigation. This anomaly can be associated with strategic management of water deficit at a critical time, which effectively reduces transpiration rates without significantly impairing photosynthetic efficiency, thereby ultimately enhancing water productivity. Fang *et al.,* (2018) further indicated that the judicious allocation of irrigation volume can facilitate the optimal utilization of both light and thermal resources. According to Jalota *et al.,* (2006), water productivity can be increased by reducing the number of irrigations applied. Ali & Talukder, (2008) discovered that there was a decline in productivity with the escalation of irrigation volume. This phenomenon may be attributed to the suboptimal utilization of water resources and the ineffective translocation of assimilates to the grain as the water supply increases. Furthermore, it is noteworthy that elevated irrigation water productivities (IWP) were correlated with diminished yield levels, which were also associated with reduced quantities of irrigation water.

During 2022-23, the minimal water required to produce 1 kg of wheat was under treatment $T_4$ (irrigation at 0.50 PSI). Conversely, treatment $T_8$ demonstrated the highest water consumption. In the subsequent agricultural year of 2023-24, the treatment that required the least volume of water was $T_2$ per kg of wheat, succeeded by $T_4$ and $T_6$. The greatest water requirements were noted under treatment $T_8$. The reduced irrigation water requirement for producing 1 kg of wheat grain, along with the improved water productivity observed in the $T_2$ (irrigation at CRI and flowering stage) treatment during the 2023-24 growing season, compared to the $T_4$ treatment, can be attributed to the rainfall during the flowering stage as shown in fig. 3.3. This rainfall event significantly minimized the need for supplemental irrigation. This highlights the variability in irrigation needs influenced by rainfall, particularly related to climate change. The rainfall during the flowering stage in 2023-24 led to considerable reductions in supplemental irrigation, resulting in notable improvements in metrics such as irrigation water savings, IWUE, irrigation water productivity, and the water requisite to produce 1 kg of wheat grain.

Water saving (%) has been calculated when compared to treatment $T_1$ for both the years i.e., 2022-23 and 2023-24. During the first year, the maximum water saving was observed under PSI-based treatment $T_5$ (irrigation at 0.75 PSI) followed by $T_4$ (irrigation at 0.50 PSI). Among the soil moisture depletion-based treatments, the maximum water saving was achieved in $T_8$ (irrigation at 75% depletion of FC). However, during the subsequent year, the highest water saving was observed under treatment $T_2$ (irrigation at CRI and flowering stages) followed by PSI-based irrigation scheduling methods i.e., $T_5$ and $T_4$. Among the soil moisture depletion methods, the maximum water saving was observed under $T_8$. Similarly, in pooled analysis, the water saving observed under $T_2$ representing the most significant level of savings observed. This can be attributed due to when crops experience inadequate irrigation, their root systems extend deeper into the soil profile in pursuit of soil moisture, leading to substantial water saving without compromising crop productivity, while simultaneously enhancing water productivity (WP) and augmenting net farm income (Chai *et al.,*2016; Evett *et al.,* 2009; Kato *et al.,* 2006). Also, Hassan *et al.,* (2000) examined the effects of deficit irrigation methods on wheat production and water conservation. Their findings, based on a one-year study, revealed that a two-stage deficit irrigation approach applied during the yield formation and ripening phases resulted in the best yield while reducing irrigation water usage by 34% compared to conventional four-frequency watering practices.

### *4.13 Soil moisture stress relationship with plant water status based on remote sensing techniques*

In FCC, various spectral bands are allocated to the red, green, and blue colour channels to accentuate specific characteristics, such as vegetation and water bodies. The vegetation present in the designated area during that temporal interval is observed to exhibit a hue of red. In contrast, the remainder of the area is characterized by shades of blue and cyan, which serve to denote regions of buildup as well as fallow land or those locales wherein the germination of crops has not yet occurred. From December through February, the augmentation of bright red hues signifies an enhancement in vegetation coverage when juxtaposed with November, attributable to the elevated reflectance of the near infrared (NIR) band. Nevertheless, in March, the subdued red colouration denotes that the agricultural vegetation is reaching its maturation phase, resulting in a marginal reduction in the reflectance of the NIR band. Nonetheless, in January, the hue tends to exhibit a lighter shade of red, a phenomenon that can be ascribed to a diminished reflectance of the near-infrared (NIR) band; this occurrence may be linked to the lower ambient temperatures prevalent during this time frame, which consequently attenuated the metabolic processes of the plant, resulting in a decline in chlorophyll concentration and, hence, a reduction in NIR reflectance. In April, the diminishing proportion of red colouration suggests that the harvesting of the crops has transpired, as evidenced by the illustration presenting cyan or yellow tones.

Lillesand *et al.,* (2015) similarly noted that temperature is a significant determinant in the modulation of plant growth and can induce variations in false colour composites (FCC), particularly under cooler climatic conditions. As we progress from February to March, when the temperature tends to become optimum for plant growth, the vegetation appears to be in bright red. The softer crimson hue of April suggests that the foliage is getting closer to maturity. Jensen (2007), noted similar fluctuation, with healthy vegetation (high NIR reflectance) usually seeming to be deeper red tones. Furthermore, seasonal temperature variations have an impact on vegetation growth, as noted by Campbell & Wynne (2011), and this fluctuation can be seen in FCC imagery.

NDVI in November the was still very low, near land level, and the wheat had just been seeded. Wheat leaf growth over time resulted in a progressive increase in the NDVI value, which has a greater value than other ground feature kinds and displays the opposite tendency to other ground cover types (Wang *et al.,* 2023). A similar pattern in NDVI was observed in the study area (Fig. 4.16). Changes are detected in vegetation cover indicating that wheat and other *rabi* crops reach the vegetative development stage by December, at which point the NDVI values begin to increase. Plants that are developing leaves absorb more red light for photosynthesis and reflect more near-infrared light (NIR), which causes the NDVI levels to steadily rise. These ranges indicate the peak values of the NDVI during February and March, which can be attributed to the wheat crop reaching the peak of vegetative growth and developing a dense canopy that reflects a significant amount of NIR radiation due to its robust, actively photosynthetic leaves. April, which shows a decline in NDVI values as crops approach senescence and their chlorophyll content decreases. In mature crops, lower NIR reflectance and reduced red light absorption result in lower NDVI values. Vermote *et al.,* (2016) confirmed these findings by observing that NDVI values for wheat-dominant regions in Northern India increased steadily from December through February, peaked in March, and then began to decline in April. During the second year, the second year's lower minimum temperatures (Fig. 3.1 and 3.2) in comparison to the first year may have contributed to the decline in the NDVI in January by slowing down the rate of photosynthesis and producing less chlorophyll.

Reduced photosynthesis and chlorophyll result in decreased NIR reflectance and possibly higher red reflectance, which lowers NDVI values because normalized difference vegetation index is based on the difference between red and near-infrared (NIR) reflectance. Further, the decrease in the NDVI values reflects the plant’s reduced but ongoing growth. Further, decreased NDVI values were observed by Zhang *et al.,* (2003) due to lower temperatures which leads to reduced vegetation health and chlorophyll content. Similar trends were observed for NDVI for the study area for the year 2023-24 (Fig. 4.16). The spectral curve of wheat provides valuable information about the plant’s health, water content, and growth stage for the Phagwara region along with the study area as shown in Fig. 4.18 to 4.21.

Huang *et al.,* (2022) also observed that during January the value of NDVI decreases because of low temperatures during the wintering period and after that, it increases. Also, the lowest numerical values are observed in soils with minimal vegetation, likely due to elevated soil reflectance, which results in diminished values within the near-infrared (NIR) spectrum and increased values in the red spectrum; consequently, NDVI values are low. Vegetation remains green and exhibits high NDVI values due to the ample availability of water in the soil. Conversely, when the availability of soil moisture is reduced, because of various environmental factors (such as stress induced by water scarcity), the verdant vegetation is prone to decline, leading to a reduction in NDVI values (Bhandari *et al.,* 2012).

Plant health and stress can be assessed using reflectance indices, which measure the extent of light reflected from vegetation at definitive wavelengths. The physiological processes associated with plant water status, such as chlorophyll fluorescence, stomatal conductance, leaf water potential, and water content, are closely associated with plant stress (Safdar *et al.,* 2023). Numerous scholars have documented the utilization of NDVI in the surveillance of vegetation (Yang *et al.,* 2010; Lan *et al.,* 2009), assessment of crop coverage, observation of drought (Yamaguchi *et al.,* 2010; Kim *et al.,* 2008), and examination of agricultural drought at both the domestic level (Zhang *et al.,* 2009; Demirel *et al.,* 2009) and worldwide scale (Smith *et al.,* 2015). Therefore, the NDVI values are inclined to decline with the increase in water stress due to the reduced presence of green biomass, consequently limiting the capacity of satellite sensors to detect such vegetation.

LSWI values during the sowing and emergence period were observed to be higher (Huang *et al.,* 2022). LSWI readings are often greater in high moisture content vegetation and soil. This is because water rapidly absorbs light that is shortwave infrared (SWIR), decreasing SWIR reflectance while maintaining a comparably higher near-infrared (NIR) reflectance. Thus, the results revealed that high positive values of LSWI generally suggest the existence of water, observed in thriving vegetation or regions characterized by sufficient soil moisture. Reductions in LSWI measurements could suggest a rise in water stress within crops caused by inadequate precipitation, deficits in irrigation, or other variables influencing the availability of moisture in the soil. Similarly, Chandrasekar *et al.,* (2010) used LSWI to discern the increase or decrease in soil moisture as LSWI is recognized for its sensitivity to the overall quantity of liquid water present in both vegetation and the underlying soil environment. Dangwal *et al.,* (2016) identified water stress in wheat cultivation through the utilization of NIR and SWIR spectral bands obtained from multi-temporal Landsat imagery. The findings indicated that the LWSI, which is predicated on simple SWIR and NIR metrics, demonstrated considerable efficacy in quantifying water stress in wheat crops and exhibited a strong correlation with the empirically observed water stress parameters for wheat.

### *4.14 Economics*

The disparities observed in economic outcomes across various irrigation treatments can be predominantly ascribed to the efficacy of water management practices and the plant's physiological response to stress. The PSI-based treatment ($T_4$) exhibited markedly enhanced economic results relative to alternative irrigation methodologies, attributable to its meticulous alignment of irrigation practices with the actual water requirement of the plants, thereby mitigating resource wastage. The estimated benefit cost (B:C) ratio associated with $T_4$ signifies that the judicious utilization of water not only optimizes crop yield but also facilitates the irrigation of supplementary land by using amount as conserved water as compared to treatment $T_2$ subsequently augmenting overall revenue and enhancing economic returns. These outcomes are also corroborated by Ali *et al.,* (2007) and Yu *et al.,* (2020).

## *CHAPTER 5*

## *SUMMARY AND CONCLUSIONS*

Climate, crop varieties, and soil patterns are important aspects that influence our understanding of the amount of water needed in agriculture (Singh *et al.,* 2021; Sharma *et al.,* 2021). The principal irrigation resource in Punjab is canal water; yet the amount of irrigated land that may be distributed to farmers' fields depends on the size of those lands (Garg *et al.,* 2022; Changade *et al.,* 2023). Due to overuse and careless irrigation water management techniques, Punjab's groundwater reserves are being quickly depleted at a rate of 0.54 metres per year (Agarwal *et al.,* 2020). Traditional irrigation methods, which optimise crop productivity but do not guarantee water savings, rely on groundwater from farmers. Significant seepage loss, uneven distribution, and erratic supply are to blame for this. According to Garg *et al.,* (2022), these irrigation systems are therefore incompatible with sustainable agriculture practices. Therefore, it is critical to mitigate the trend of dropping groundwater levels by reducing the amount of water utilised for irrigation, all the while ensuring that agricultural productivity is not adversely affected. This suggests that, in addition to evaluating creative, accurate irrigation methods, irrigation schedule needs to be improved from ample to restricted irrigation.

To increase the WUE and prevent excess water application while maintaining crop productivity, irrigation scheduling can be optimised in terms of both amount and time based on soil moisture depletion at field capacity, canopy temperature, and diverse growth stages of wheat crop (Meena *et al.,* 2015). Considering the above-mentioned problems along with depleting groundwater table, the present study entitled "Standardization of irrigation scheduling based on canopy temperature and soil moisture regimes in wheat (*Triticum aestivum* L.)" was conducted at Lovely Professional University, Phagwara during the *rabi* season of 2022-23 and 2023-24. The field study was conducted in randomized block design consisting of nine treatments i.e., $T_1$- Recommended irrigation, $T_2$- irrigation at CRI and flowering stages, $T_3$- irrigation at 0.25 PSI, $T_4$- irrigation at 0.50 PSI, $T_5$- irrigation at 0.75 PSI, $T_6$- irrigation at 25% depletion of FC, $T_7$- irrigation at 30% depletion of FC, $T_8$- irrigation at 75%

depletion of FC and $T_9$- no irrigation/rainfed. The major findings have been outlined below:

- The recommended irrigation techniques led to an elongation of the wheat crop growth duration (from sowing to maturity) in comparison to alternative irrigation schedules during both seasons. In comparison to other irrigation scheduling strategies used in both years, the crop that received irrigation at 75% FC depletion ($T_8$) and the crop that received no irrigation ($T_9$) attained maturity earlier.
- The maximum plant height (104.1 cm and 107.7 cm) was reached in both years following the recommended irrigation practice. Nevertheless, these measurements were at par with those obtained under an irrigation regimen employing the soil moisture depletion method, specifically $T_7$ (101.2 cm and 104.6 cm) and $T_6$ (98.4 cm and 102.5 cm). Within the context of PSI-driven irrigation scheduling methods, the greatest plant height was recorded at an irrigation pressure of 0.25 PSI (94.3 cm), which was equivalent to the measurements of $T_4$ (irrigation at 0.50 PSI), namely 93.9 cm and 99.3 cm.
- Maximum accumulation of dry matter was attained when irrigation was applied in accordance with the prescribed recommendations ($T_1$) for the years 2022-23 (794.7 g $m^{-2}$) and 2023-24 (819.5 g $m^{-2}$). It was noted that irrigation at 30% depletion of field capacity (FC) demonstrated comparable results to $T_1$ in both years (782.0 and 810.3 g $m^{-2}$) and exhibited the highest dry matter accumulation among the various soil moisture depletion methods of irrigation scheduling. However, within the methods based on plant stress index (PSI), the highest dry matter accumulation for both years (769.4 and 802.1 g $m^{-2}$) was observed in the irrigation scheduling based on 0.25 PSI.
- Among the various irrigation treatments, a notably higher effective tiller density was observed under the recommended irrigation regime, specifically $T_1$ (396.4 and 416.5 $m^{-2}$), which demonstrated statistical similarity with $T_7$ and $T_6$. Treatments $T_3$ and $T_4$ exhibited similar results to each other. The treatment that did not receive any irrigation, relying solely on rainfall ($T_9$), showed a

significantly lower number of effective tillers (302.4 and 317.2 $m^{-2}$) respectively.

- During the 2022-23 period, the irrigation treatment denoted as $T_1$ exhibited notably greater Leaf Area Index (LAI) values at 60 (2.58), 90 (4.40), and 120 (4.12) days after sowing (DAS) in comparison to $T_9$. However, there was no significant difference observed between $T_1$ and $T_7$ or $T_6$. Similarly, in the following year, 2023-24, the LAI values under the recommended irrigation treatment showed a highly significant difference when compared to alternative irrigation strategies, with the lowest LAI values recorded in $T_9$ across various growth stages of the crop.
- The relative water content of wheat crop was found to be significantly influenced by irrigation treatments on 30-60, 60-90 and 90-120 DAS during both the years (2022-23 and 2023-24). Results for both the years revealed that the highest RWC was observed under the treatment where recommended irrigation ($T_1$) was applied at 30-60, 60-90 and 90-120 DAS. The lowest RWC value was observed in $T_9$ (rainfed).
- CGR during both the years was observed to be higher at 60-90 DAS which is the grand growth period. The highest CGR values for 30-60 (5.9-6.5 g $m^{-2}$ $day^{-1}$), 60-90 (17.2-19.5 g $m^{-2}$ $day^{-1}$) and 90-120 (10.4-13.6 g $m^{-2}$ $day^{-1}$) DAS were obtained under recommended irrigation ($T_1$).
- During both years the RGR was found to be significantly impacted by irrigation regimes. The highest RGR was observed under fully recommended irrigation ($T_1$) for both the years of the growing season i.e., 2022-23 and 2023-24.
- Irrigation regimes have significantly persuaded the net assimilation rate during the growing period of the crop. The highest NAR was observed with recommended irrigation ($T_1$) practice and was significantly higher when juxtaposed to other methods of irrigation scheduling during 30 to 60, 60 to 90 and 90 to 120 DAS.
- During the growth span from 30 to 120 DAS, AGR was found to be significantly affected by various irrigation scheduling methods. Maximum values of AGR during the whole period of growth for both the years were noted under fully recommended irrigation ($T_1$) scheduling method.

- SDD values were more negative in 2023–24, indicating cooler canopy conditions and reduced thermal stress in $T_3$ and $T_4$. $T_5$ consistently exhibited positive SDD across critical stages, reflecting persistent heat stress.
- Among the various irrigation schedules, spike length (11.1 & 11.3 cm), number of grains per spike (50.0 & 50.8 cm), and the weight of 1000 grains (48.3 & 48.6 g) were documented under the recommended irrigation schedule. This schedule exhibited statistical equivalence with $T_7$, $T_6$, $T_4$, and $T_3$, but notably outperformed $T_9$ in both years.
- In both years, the maximum grain yield was obtained when recommended irrigation practices were followed i.e., 5.9 t $ha^{-1}$ and 6.1 t $ha^{-1}$. This treatment was noted to be significantly at par with $T_7$ i.e., irrigation at 30% depletion of FC (5.7 t $ha^{-1}$ and 5.9 t $ha^{-1}$) followed by $T_4$ i.e., irrigation at 0.50 PSI (5.5 t $ha^{-1}$ and 5.8 t $ha^{-1}$). When no irrigation was applied or when crop was only dependent on rainfall ($T_9$), minimum grain yield was observed during both years (2.4 t $ha^{-1}$ and 3.6 t $ha^{-1}$) due to moisture stress.
- A significant effect on straw yield was observed due to different irrigation scheduling methods during the rabi season of 2022-23 and 2023-24. The highest straw yield among different irrigation scheduling methods was attained when recommended irrigation ($T_1$) was applied to wheat i.e., 7.4 t $ha^{-1}$ and 7.8 t $ha^{-1}$. It was found to be statistically like $T_7$ (irrigation at 30% depletion of FC) and $T_4$ (irrigation at 0.50 PSI).
- Biological yield was significantly affected by various irrigation scheduling during the year 2022-23 and 2023-24. The significant higher biological yield of 13.3 t $ha^{-1}$ and 13.9 t $ha^{-1}$ was observed under recommended irrigation ($T_1$) and was significantly at par with $T_7$ (irrigation at 30% depletion of FC) and $T_4$ (irrigation at 0.50 PSI).
- Different irrigation regimes significantly influenced the HI in the year 2022-23, where the maximum of HI of 44.2% was achieved when recommended irrigation ($T_1$) was applied. It was followed by $T_4$ (44.0%) and $T_7$ (44.0%). They were found to be statistically at par with $T_1$. However, during the year 2023-24, no significant effect of irrigation scheduling was observed on HI.

- The volume of irrigation water applied to wheat under irrigation at 25% depletion of FC and at 0.25 PSI was 875.64 mm and 814 mm during 2022-23. However, during 2023-24, the amount of irrigation water applied under the 0.25 PSI was higher (778 mm) and was followed by irrigation at 30% depletion of FC (667 mm).
- Effective rainfall in 2022-23 was found to be 96 mm and was higher than that of 2023-24 (87 mm).
- Crops grown under irrigation at 25% depletion of FC were found to have the highest crop water requirement of 972 mm followed by 0.25 PSI (910 mm) in 2022-23. Whereas, in 2023-24 the crop water requirement was highest for crops grown under irrigation at 0.25 PSI (865 mm) and 30% depletion of FC (754 mm).
- Higher IWUE (0.085 t $ha^{-1}$ cm) was observed under irrigation at 0.50 PSI followed the recommended level of irrigation (0.083 t $ha^{-1}$ cm) in 2022-23. During 2023-24, the IWUE value of 0.206 t $ha^{-1}$ cm was recorded to be higher under irrigation applied at the CRI and flowering growth stage. It was followed by irrigation at 0.50 PSI with an IWUE of 0.100 t $ha^{-1}$ cm and recommended irrigation (0.090 t $ha^{-1}$ cm).
- The maximum irrigation water productivity documented in the year 2022-23 was observed under treatment $T_4$ (0.50 PSI) at a rate of 0.848 kg $m^{-3}$, with treatment $T_1$ (recommended irrigation) closely trailing at 0.832 kg $m^{-3}$. In the subsequent year, 2023-24, the highest water productivity was attained under treatment $T_2$ (2.056 kg $m^{-3}$), followed by treatment $T_4$ (0.996 kg $m^{-3}$) and treatment $T_1$ (0. 895 kg $m^{-3}$).
- The volume of water requisite for the cultivation of 1 kg of wheat grain was observed to be minimal under the experimental condition $T_4$ (1179 litres) during the rabi season of 2022-23, with condition $T_1$ closely trailing at 1202 litres. In the year 2023-24, the treatment that necessitated the minimal quantity of water was $T_2$ (486 litres) per kilogram of wheat, followed by $T_4$ (1003 litres) and $T_6$ (1112 litres).

- Water saving of 23 % was observed in $T_5$ (0.75 PSI) in the year 2022-23, but during the subsequent year the maximum water saving over $T_1$ was observed under treatment $T_2$ (69 %).
- NDVI values computed for the Phagwara block during the *rabi* season of 2022-23, spanning the months from November to April, exhibit a range from -0.303 to 0.795. Furthermore, NDVI values fluctuated between -0.369 to 0.822 over the same period from November to April in the subsequent year of 2023-24.
- The land surface water index exhibited a variation from -0.744 to 0.941 during the period from November to April in 2022-23, whereas, for the 2023-24 period, the index ranged from -0.556 to 0.874 within the same temporal frame of November to April.
- During the 2022–23 and 2023–24 growing seasons, the highest gross returns were obtained under the recommended irrigation treatment ($T_1$), amounting to `151,553 $ha^{-1}$ and `164,932 $ha^{-1}$, respectively. A similar trend was observed in net returns, with $T_1$ yielding the maximum net return of `101,264 $ha^{-1}$ in 2022–23 and `112,459 $ha^{-1}$ in 2023–24. Correspondingly, the highest benefit–cost (B:C) ratios of 2.0 and 2.1 were also recorded under $T_1$ in 2022–23 and 2023–24, respectively, indicating the superior economic performance of the recommended irrigation regime over other treatments.
- However, based on water saving maximum net returns (1,00,275 ` $ha^{-1}$) were observed under treatment $T_4$ in the year 2022-23 and in the year 2023-24, the maximum net returns of 1,21,094 ` $ha^{-1}$ were achieved under treatment $T_2$. Pooled analysis revealed the highest net returns (1,10,455 ` $ha^{-1}$) in treatment $T_4$. Furthermore, B:C ratio based on water saving the highest of 2.0 was achieved under the treatment $T_4$ for the year 2022-23. In the year 2023-24 the B:C ratio of 2.4 was achieved in $T_2$. Among the pooled analysis the maximum B:C ratio of 2.2 was achieved in 0.50 PSI treatment ($T_4$).
- **CONCLUSION**

❖ The recommended irrigation practice outperformed all other treatments in terms of crop growth and yield. Therefore, it is suitable for adoption as an irrigation scheduling strategy in regions with adequate water availability.

- In the selected study area, irrigation at 0.50 PSI resulted in grain yield statistically comparable to the recommended irrigation practice, while increasing irrigation water use efficiency by 7% and reducing irrigation water requirement by 11%. Hence, irrigation at 0.50 PSI can be regarded as a scientifically viable strategy for irrigation scheduling, particularly under water-scarce conditions in Punjab.
- Maximum irrigation water use efficiency, irrigation water productivity along with minimum water required to produce 1 kg of wheat was achieved in 0.50 PSI irrigation treatment.
- Spectral indices such as the NDVI and LSWI can be instrumental in delineating the characteristics and dynamic patterns of surface vegetation and non-vegetative elements.
- The maximum net returns and B:C ratio based on yield was observed in treatment with recommended irrigation. However, net returns and B:C ratio-based water saving was achieved when wheat was irrigated with 0.50 PSI.

Consequently, the cultivation of wheat through the strategic scheduling of irrigation at 0.50 PSI has the potential to enhance the efficient utilization of accessible water resources within the study region as well as in other wheat-cultivating areas of Punjab that possess analogous agro-climatic conditions and agricultural management practices. Hence, the execution of these irrigation strategies could significantly facilitate sustainable wheat production while concurrently managing water resources effectively.

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# Appendix- I

## Weekly average of meteorological data during crop season 2022-23

| Standard Meteorological Week | Max temp (°C) | Min temp (°C) | Rain (mm) | RH (%) | Windspeed (km/hr) | Evaporation (mm) |
|---|---|---|---|---|---|---|
| 46 | 27.71 | 14.86 | 0.00 | 54.00 | 16.00 | 17.00 |
| 47 | 28.14 | 18.29 | 0.00 | 73.86 | 1.43 | 12.30 |
| 48 | 24.86 | 13.71 | 0.00 | 85.43 | 0.57 | 12.30 |
| 49 | 27.00 | 10.86 | 0.00 | 86.57 | 1.43 | 11.30 |
| 50 | 26.71 | 11.43 | 0.00 | 89.14 | 1.71 | 10.60 |
| 51 | 24.57 | 9.86 | 0.00 | 90.43 | 0.86 | 3.20 |
| 52 | 21.57 | 8.71 | 2.00 | 95.00 | 1.14 | 1.00 |
| 1 | 15.40 | 5.93 | 0.00 | 93.86 | 1.14 | 1.40 |
| 2 | 14.07 | 7.86 | 2.10 | 94.57 | 2.57 | 1.90 |
| 3 | 13.11 | 6.51 | 0.00 | 93.14 | 2.57 | 9.00 |
| 4 | 18.96 | 7.26 | 34.60 | 85.43 | 2.00 | 13.40 |
| 5 | 19.44 | 8.19 | 12.40 | 91.86 | 2.29 | 7.10 |
| 6 | 23.30 | 11.44 | 0.01 | 83.14 | 2.00 | 15.40 |
| 7 | 25.73 | 10.99 | 0.00 | 60.14 | 2.57 | 19.80 |
| 8 | 28.09 | 13.97 | 0.00 | 93.57 | 1.43 | 20.10 |
| 9 | 27.33 | 14.06 | 0.02 | 71.86 | 2.86 | 15.10 |
| 10 | 29.29 | 13.71 | 0.00 | 41.86 | 1.14 | 17.50 |
| 11 | 29.21 | 16.79 | 0.00 | 72.54 | 2.29 | 16.30 |
| 12 | 24.07 | 13.86 | 28.40 | 93.14 | 2.29 | 10.00 |
| 13 | 27.43 | 16.03 | 27.20 | 91.43 | 4.57 | 12.10 |
| 14 | 26.80 | 14.39 | 2.42 | 66.71 | 3.43 | 14.40 |
| 15 | 34.41 | 15.35 | 0.00 | 72.86 | 3.71 | 33.90 |
| 16 | 36.49 | 17.70 | 9.30 | 79.57 | 10.57 | 33.20 |

# Appendix- II

## Weekly average of meteorological data during crop season 2023-24

| Standard Meteorological Week | Max temp (°C) | Min temp (°C) | Rain (mm) | RH (%) | Windspeed (km/hr) | Evaporation (mm) |
|---|---|---|---|---|---|---|
| 46 | 27.11 | 10.03 | 0.00 | 49.90 | 5.04 | 13.20 |
| 47 | 26.19 | 9.89 | 0.40 | 46.93 | 4.78 | 13.40 |
| 48 | 23.52 | 11.17 | 6.80 | 59.72 | 4.53 | 7.50 |
| 49 | 23.55 | 7.97 | 0.00 | 52.46 | 4.63 | 9.40 |
| 50 | 22.02 | 4.46 | 0.00 | 53.07 | 3.75 | 9.00 |
| 51 | 21.23 | 4.33 | 0.00 | 55.66 | 4.22 | 8.20 |
| 52 | 18.94 | 7.20 | 0.40 | 69.87 | 2.70 | 4.80 |
| 1 | 12.46 | 7.07 | 0.20 | 84.86 | 2.97 | 3.60 |
| 2 | 11.61 | 6.48 | 0.00 | 79.00 | 2.87 | 4.40 |
| 3 | 13.29 | 5.36 | 0.00 | 78.29 | 2.98 | 5.20 |
| 4 | 13.00 | 5.71 | 0.00 | 76.57 | 4.78 | 6.60 |
| 5 | 18.57 | 8.29 | 8.80 | 71.14 | 5.56 | 6.50 |
| 6 | 18.75 | 4.64 | 0.60 | 59.87 | 5.01 | 12.80 |
| 7 | 23.69 | 4.95 | 0.00 | 49.39 | 4.47 | 13.10 |
| 8 | 22.51 | 7.96 | 1.10 | 52.39 | 9.88 | 22.00 |
| 9 | 23.30 | 8.59 | 64.00 | 51.01 | 8.54 | 16.00 |
| 10 | 21.80 | 6.25 | 0.00 | 53.42 | 6.89 | 10.60 |
| 11 | 25.69 | 9.68 | 0.00 | 56.99 | 6.58 | 18.50 |
| 12 | 29.24 | 11.92 | 0.00 | 48.96 | 6.84 | 20.60 |
| 13 | 31.06 | 16.20 | 14.00 | 50.01 | 5.97 | 14.10 |
| 14 | 31.42 | 13.83 | 0.00 | 38.07 | 7.57 | 22.20 |
| 15 | 34.66 | 14.61 | 0.00 | 31.17 | 6.12 | 35.80 |
| 16 | 33.90 | 17.56 | 8.20 | 37.37 | 8.64 | 32.80 |