Wheat response to different dates of sowing and foliar application of plant bioregulators under poplar (Populus deltoides Bartr.) plantation

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Article

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Wheat response to different dates of sowing and foliar application of plant bioregulators under poplar (*Populus deltoides* Bartr.) plantation

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Abstract

The present investigation entitled "Wheat response to different dates of sowing and foliar application of plant bioregulators under poplar (Populus deltoides Bartr.) plantation" was conducted at Punjab Agricultural University, Ludhiana, during *rabi* seasons of 2022-23 and 2023-24. The study comprised two experiments laid out in split-plot design with three replications under poplar (8 m × 2.5 m spacing). Experiment I evaluated three sowing dates (25th October, 10th November and 25th November) in main plots and five foliar applications of plant bioregulators (control, potassium silicate @ 2.3%, sodium nitroprusside @ 0.5%, potassium nitrate @ 2% and zinc sulphate @ 0.5%) in sub-plots. Results revealed that wheat sown on 25th October and 10th November exhibited superior growth, physiological performance and yield attributes, as it synchronized crop development with the leafless phase of poplar and helped in escaping terminal heat stress. Among foliar treatments, significantly higher grain yield was recorded with application of potassium nitrate @ 2% (49.0 and 45.7 q/ha) which was statistically at par with zinc sulphate @ 0.5% (47.3 and 43.7 q/ha) and higher than control during 2022-23 and 2023-24, respectively.

Keywords: Heat stress, Plant bioregulators, Date of sowing, Wheat, Poplar

Introduction

Agroforestry is a site-specific and sustainable land use system that integrates economically important tree species with agricultural crops in such a manner that both components efficiently utilize spatial and temporal resources. This system simultaneously addresses the production needs of farmers while providing environmental, ecological and socio-economic benefits to society. Among the various agroforestry systems prevalent in North India, poplar-based agroforestry systems are considered economically viable, sustainable and widely adopted by farmers.

Poplar (*Populus deltoides* Bartr. ex Marsh.) is a fast growing tree species with a short rotation period of 5-7 years, a narrow crown, straight bole and multi-utility wood uses. It is commonly grown either along field boundaries or as block plantations and intercropped with annual or perennial crops throughout the region. Poplar is winter deciduous in nature; therefore, almost all *rabi* crops viz. wheat, mustard, barley, oats, potato, etc. can be successfully grown throughout its rotation period as the trees offer relatively less competition for light and nutrients (Gill *et al* 2009). Among *rabi* crops, wheat is the most suitable and widely cultivated crop under poplar plantations and constitutes one of the important agroforestry systems of North India.

Under the changing climatic scenario, rising temperature or heat stress has emerged as one of the most serious concerns adversely affecting agricultural productivity, particularly that of wheat. Wheat is more susceptible to high temperature stress during the reproductive stage than during the vegetative stage (Farooq *et al* 2011). Terminal heat stress in wheat occurs due to an increase in mean temperature beyond 31°C during the grain filling stage, leading to forced maturity and yield reduction. According to the Intergovernmental Panel on Climate Change (IPCC 2014), temperature in the Indian region is projected to increase by 0.7-2.0°C by the 2030s, with relatively higher increases in North India and during the *rabi* season (November-March). Several studies (Anjum *et al* 2008, Hasanuzzaman *et al* 2013 and Mustafa *et al* 2021) have documented the adverse impact of rising temperature on wheat productivity. Singh *et al* (2011) reported that a 1°C increase in mean temperature during March-April reduces the crop duration by seven days and grain yield by approximately 400 kg/ha. Similarly, an analysis for the Indo-Gangetic plains indicated that each 1°C rise in temperature could result in a loss of about 4-5 Mt of wheat production (Aggarwal 2008).

The negative effects of high temperature stress on wheat productivity can be mitigated through various agronomic interventions, among which modification in sowing time is considered one of the most effective strategies. Early sowing of wheat, from the last week of October to the first week of November, helps avoid overlap between wheat germination and poplar leaf shedding. Gill *et al* (2009) reported that sowing wheat during the first fortnight of November under four to six year old poplar plantations resulted in significantly higher grain yield compared to late sowing. Wheat sown at the optimum time is exposed to a greater accumulation of growing degree days, facilitating improved biomass production and translocation from source to sink. In contrast, delayed sowing shortens the reproductive phase, resulting in smaller grains and reduced grain weight (Ram *et al* 2017). Shahzad *et al* (2007) and Yusuf *et al* (2019) reported that wheat sown on 5th November exhibited superior growth and yield attributes compared to delayed sowing. Delay in sowing by 20 and 40 days beyond the normal sowing period (first fortnight of November) resulted in a reduction in grain yield at the rate of 23 kg/ha/day and 30 kg/ha/day, respectively (Kaur and Pannu 2008). This reduction in yield is mainly attributed to the shortened growth duration caused by increasing temperatures, which adversely affects yield attributing characters.

In addition to sowing time, plant bioregulators (PBRs) play a significant role in alleviating heat stress in crops (Ilyas *et al* 2017). Exogenous application of PBRs, including both organic and inorganic compounds, enhances the ability of plants to adapt to abiotic stresses either individually or synergistically (Srivastava *et al* 2016). These bioregulators also facilitate improved absorption and utilization of nutrients. Plant bioregulators such as sodium nitroprusside, potassium nitrate (KNO_3), silicon (Si) compounds and thiourea have been reported to reduce heat stress and enhance crop productivity without compromising grain quality. Exogenous application of sodium nitroprusside has been reported to improve net photosynthetic rate and reduce yield losses in wheat under heat stress conditions (Bavita *et al* 2012). Potassium, an essential component of potassium nitrate, plays a crucial regulatory role in enzyme activation, osmotic regulation and photosynthesis, thereby enhancing crop growth and productivity (Demidchik *et al* 2014). Silicon compounds have shown to have a variety of beneficial effects on crops viz. accelerating enzymatic activity, inhibition of reactive oxygen species (ROS) accumulation and osmotic adjustment. Additionally, it enhances photosynthesis and helps in maintaining the permeability of cell membranes (Kim *et al* 2017). Besides these bioregulators, foliar application of zinc has also been found effective in mitigating drought and heat stress while improving wheat productivity (Hafeez *et al* 2013 and Ma *et al* 2017).

Therefore, the adoption of appropriate agronomic management practices, including timely sowing and foliar application of plant bioregulators, plays a pivotal role in mitigating the negative effects of high temperature stress and in sustaining wheat productivity. However, information on the combined effect of sowing dates and plant bioregulators on wheat under poplar plantations is limited, particularly under the agro-climatic conditions of Punjab. In view of the above, the present investigation entitled "Wheat response to different dates of sowing and foliar application of plant bioregulators under poplar (Populus deltoides Bartr.) plantation" was undertaken during *rabi* 2022-23 and 2023-24 to evaluate the role of plant bioregulators in alleviating heat stress in wheat sown at different dates under a poplar-based agroforestry system.

MATERIALS AND METHODS

Experimental site and design

The experiment was conducted at the research area of the Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana, Punjab for two consecutive years of 2022-23 and 2023-24 during the *rabi* season. Experimental site in Ludhiana is situated at 30^o 55' N latitude and 75^o 46' E longitude (247 m above mean sea level) and falls under the central agro-climatic zone of Punjab. The climate of the region is characterized by hot and dry summers (April-June), a hot and humid monsoon season (July-September), cold winters (November-January) and relatively mild conditions during February, March and October. The soil is loamy sand with pH of 7.2, electrical conductivity (0.21 dS/m), organic carbon (0.55 %) and available N, P and K of 278.1, 20.3 and 178.2 kg/ha. The experiment was laid out in a split plot design with three replications. Three dates of sowing (D1-25th October, D2-10th November and D3-25th November) were kept in the main-plots and four foliar applications (F1-Potassium silicate @ 2.3%, F2- Sodium nitroprusside @ 0.5%, F3- Potassium nitrate @ 2% and F4- Zinc sulphate @ 0.5%) with one as F0-control were assigned in the sub-plots. This resulted in 15 treatment combinations. The gross plot size was 5.4 m × 1.9 m in both the years.

The foliar spray was applied at the boot stage on 25th January 2023 and 19th February 2024 and at the anthesis stage on 26th January 2023 and 20th February 2024 in all the treatments except control using 400 l/ha water with a manually operated knapsack sprayer. All foliar spray treatments were applied during the evening under calm, clear conditions, as warm and humid environments enhance tissue permeability and improve spray absorption.

Tree and crop management

The tree lines of poplar variety L-48 were planted at spacing of 8 m × 2.5 m oriented in north to south direction in order to minimize shading effect on agricultural crop. In experimental area, there were 4 lines of poplar and each poplar line had 33 trees of 2 and 3 years age during 2022-23 and 2023-24 year, respectively. The experimental field was prepared by using disc harrow twice followed by rotavator after the pre-sown irrigation. The wheat variety PBW 725 was used in line sowing at 22.5 cm spacing (24 lines/plot) using seed rate of 125 kg/ha. As per recommendation basal dose of nitrogen (25 kg/ha) and phosphorus (62 kg/ha) in the form of DAP (18% N and 46% P) at the rate of 135 kg/ha was applied to wheat crop. Remaining nitrogen (162 kg/ha) was applied in two splits (during first and second irrigation). Post-sown irrigations were applied according to crop need as outlined in the Package of Practices for *rabi* crops by Punjab Agricultural University.

Data collection

Meteorological parameters

The mean weekly temperatures and relative humidity data were recorded through data logger installed at experimental site. Rainfall data were recorded from the meteorological observatory at PAU, Ludhiana.

Fig. 1 Weekly mean meteorological data during *rabi* 2022-23

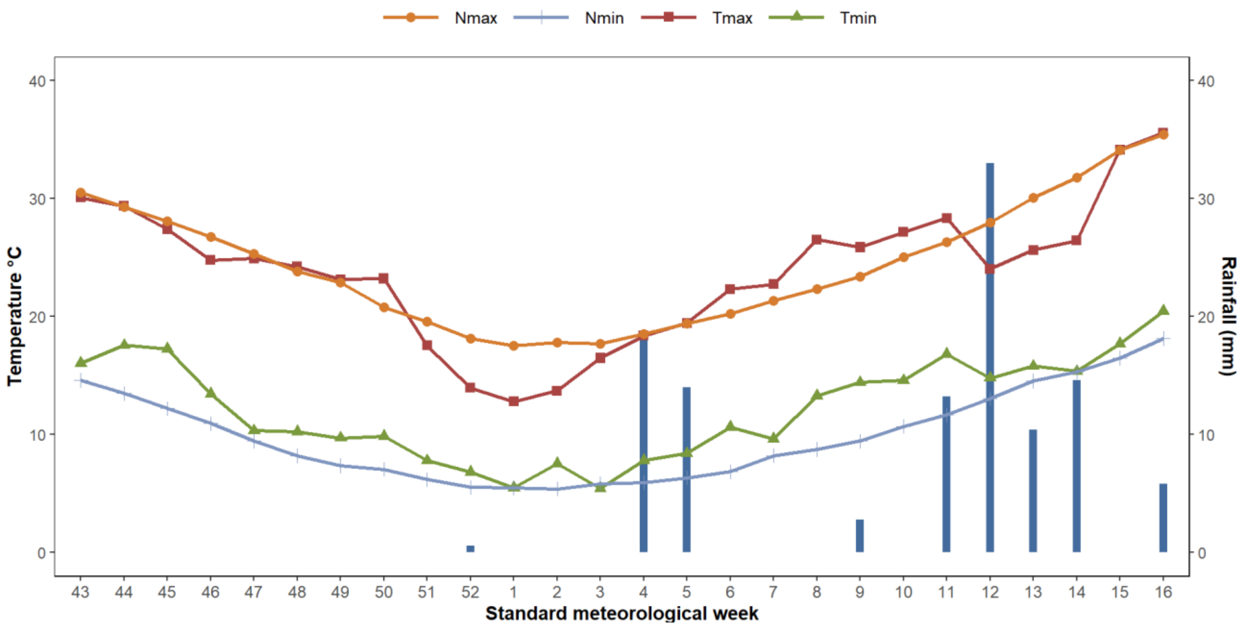
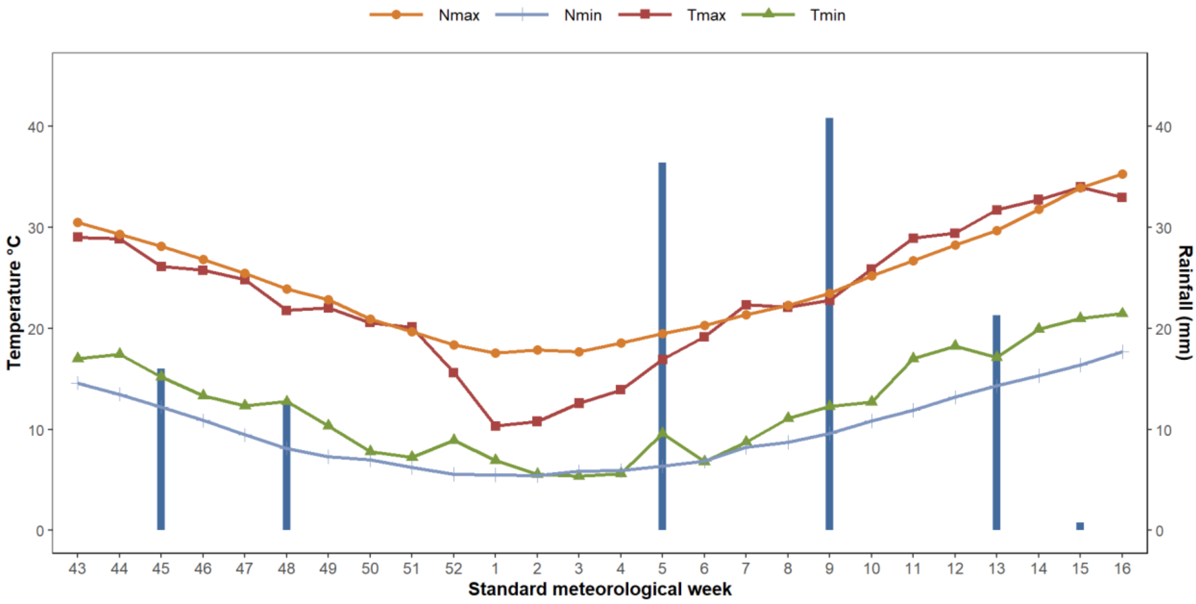


Fig. 2 Weekly mean meteorological data during *rabi* 2023-24



Growth parameters

Plant height (cm) was measured from the ground level to the base of the spike on five randomly selected plants/plot at harvest stage of crop. Plant samples were taken (at harvest) from 0.5 metre row length from two sites in each plot of treatment. Samples were first dried in shade and then kept in oven (60^{o} C temp) till the constant weight was achieved. Dry weight of the samples was measured and converted to g/m^2.

Yield parameters

The data on ear bearing tillers was taken from 1 m row length at two sites in each treatment before harvest stage and converted it to no. of effective tillers/m^2. For spike length ten randomly selected spikes their length was recorded with scale later manually threshed and grains were counted to calculate grains/spike. Threshed grain samples were collected from each plot. Counted One thousand grains were weighed and the value was recorded as test weight (g). After threshing, grain yield from each net plot was recorded and converted to quintals/hectare.

Physiological parameters-

Chlorophyll content index (CCI) of flag leaf was measured using chlorophyll content meter (CCM-200 plus, Opti-sciences Inc., Hudson, USA). The physiological parameters viz., Intercellular CO_2 concentration, photosynthetic rate and stomatal conductance were recorded 10 days after foliar application with Infrared gas analyzer (LCi-SD ADC BioScientific Ltd., UK). The data was recorded from fully expanded flag leaf of five selected tagged plants under ambient CO_2 conditions (nearly 380 ppm) on clear sunny day between 1-3pm.

Statistical analysis

The statistical analysis of recorded data for various parameters was done according to split plot design using R statistical software. Least Significant Difference (LSD) test was used for the comparison of treatment means at a 5% probability level using package ("agricolae"). The clustered heatmap [packages ("GGally"), ("PerformanceAnalytics"), ("Hmisc"), ("ggcorrplot"), ("heatmaply"), ("plotly"), ("viridis")] and graphics [packages (dplyr), (ggplot2), (patchwork)] were constructed using R-studio (v4.3.3)

Results

Growth parameters

The results revealed that date of sowing significantly influenced plant height and dry matter accumulation in both years (Table 1). Maximum plant height was recorded under 25th October sowing (96.3 and 92.4 cm), which was statistically at par with 10th November (95.1 and 92.3 cm), while the minimum was observed under 25th November sowing (87.5 and 85.2 cm) during 2022-23 and 2023-24, respectively. Dry matter accumulation followed a similar trend, 10th November recorded the highest values (1066.4 and 1020.2 q/ha), which was statistically at par with 25th October but significantly higher than 25th November (974.9 and 930.7 q/ha).

Foliar application did not significantly influence plant height in either year, although higher values were observed with potassium nitrate @ 2% (94.7 and 92.0 cm). In contrast, dry matter accumulation was significantly influenced by foliar treatments, foliar application of potassium nitrate @ 2% recorded highest values (1082.8 and 1051.9 q/ha), followed by zinc sulphate @ 0.5% and potassium silicate @ 2.3%, which remained at par during both years. Control treatment recorded the lowest values. Results have revealed that foliar application of potassium nitrate @ 2%, zinc sulphate @ 0.5% and potassium silicate @ 2.3% increased dry matter accumulation by 12.7, 9.3 and 7.9% respectively as compared to control treatment during 2022-23. In year 2023-24, the percentage improvement in dry matter accumulation was 11.8, 8.5 and 6.3%.

The interaction effect between date of sowing and foliar application was found to be non-significant for plant height and dry matter accumulation in both years.

Table 1 Effect of different dates of sowing and application of plant bioregulators on plant height of wheat

Treatments	Plant height (cm)		Dry matter accumulation (q/ha)	
	2022-23	2023-24	2022-23	2023-24
Date of sowing				
D1	96.3 a	92.4 a	1036.9 ab	1053.9 a
D2	95.1 a	92.3 a	1066.4 a	1020.2 a
D3	87.5 b	85.2 b	974.9 b	930.7 b
P value	**0.0427**	**0.0214**	**0.0403**	**0.0138**
Foliar application				
F0	90.3 b	88.1 b	960.7 c	940.9 c
F1	93.0 ab	89.1 ab	1036.8 ab	1000.3 abc
F2	93.1 ab	89.9 ab	999.4 bc	985.1 bc
F3	94.7 a	92.0 a	1082.8 a	1051.9 a
F4	93.9 ab	90.7 ab	1050.5 ab	1029.8 ab
P value	0.2895	0.3097	**0.0013**	**0.0120**
Date of sowing * Foliar application	NS	NS	0.0734	0.0578

Physiological parameters

The perusal of data revealed that physiological parameters were significantly ($p \leq 0.01$) influenced by date of sowing during both years. Higher chlorophyll content index was recorded under 25th October (25.05 and 23.85) which was statistically at par with 10th November (24.21 and 22.82) and the lowest values were recorded under 25th November (22.35 and 20.88) during year 2022-23 and 2023-24, respectively. Net photosynthetic rate and stomatal conductance followed a comparable trend during 2022-23, where higher values were recorded under 25th October (15.13 µmol $CO_2/m^2/s$ and 0.62 mol $H_2O/m^2/s$) which was statistically at par with 10th November (14.59 µmol $CO_2/m^2/s$ and 0.60 mol $H_2O/m^2/s$) and both being significantly superior to 25th November (12.27 µmol $CO_2/m^2/s$ and 0.45 mol $H_2O/m^2/s$). However, during 2023-24, 25th October (16.01 µmol $CO_2/m^2/s$ and 0.57 mol $H_2O/m^2/s$) recorded significantly higher values than 10th November (14.385 µmol $CO_2/m^2/s$ and 0.45 mol $H_2O/m^2/s$) and 25th November (12.31 µmol $CO_2/m^2/s$ and 0.26 mol $H_2O/m^2/s$). In contrast, intercellular CO_2 concentration showed an inverse trend, 25th November recorded significantly higher values (362.93 and 359.40 µmol $CO_2/m^2/s$) compared to 25th October (343.13 and 331.40 µmol $CO_2/m^2/s$) and 10th November (337.93 and 339.33 µmol $CO_2/m^2/s$).

Foliar application significantly ($p \leq 0.01$) influenced all physiological parameters. Similar values of chlorophyll content index were recorded under all foliar application treatments which were significantly higher than control during both years. Significantly higher net photosynthetic rate and stomatal conductance were recorded under potassium nitrate @ 2%, followed by zinc sulphate @

0.5% and potassium silicate @ 2.3%, which remained statistically at par in most cases. But during 2023-24, higher stomatal conductance was recorded under potassium nitrate @ 2% which was statistically at par with potassium silicate @ 2.3% and significantly higher than zinc sulphate @ 0.5%, Sodium nitroprusside @ 0.5% and control. In contrast, intercellular CO_2 concentration was highest in the control treatment, while potassium nitrate @ 2% recorded the lowest values. The interaction effect between date of sowing and foliar application was non-significant for all physiological parameters.

Fig. 3 (a) Effect of different dates of sowing and application of plant bioregulators on physiological parameters of wheat during 2022-23

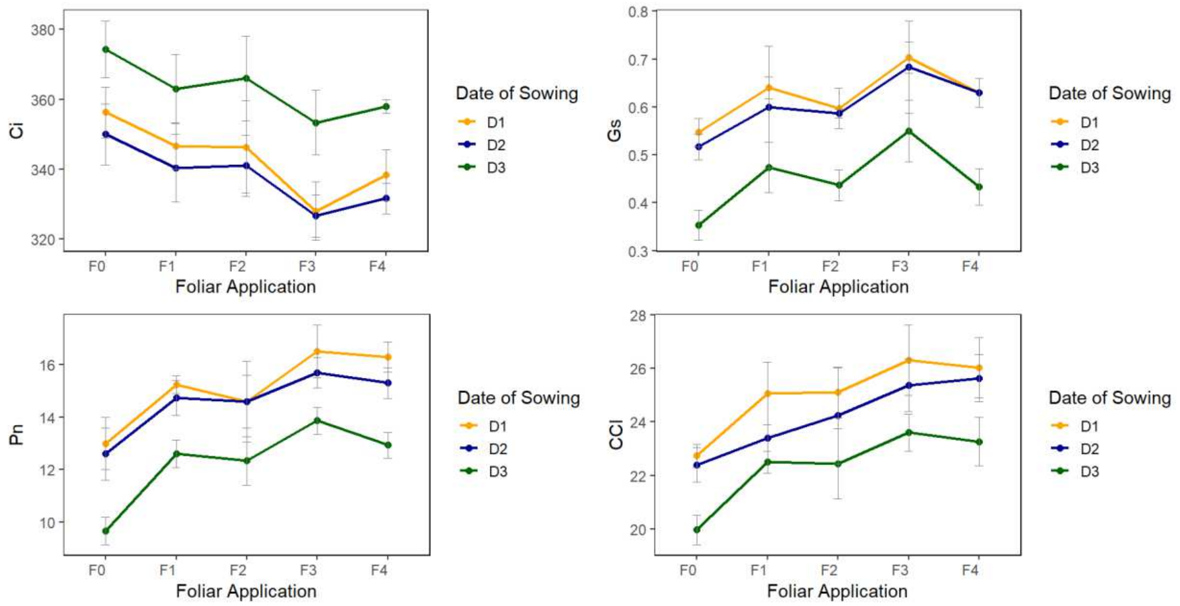
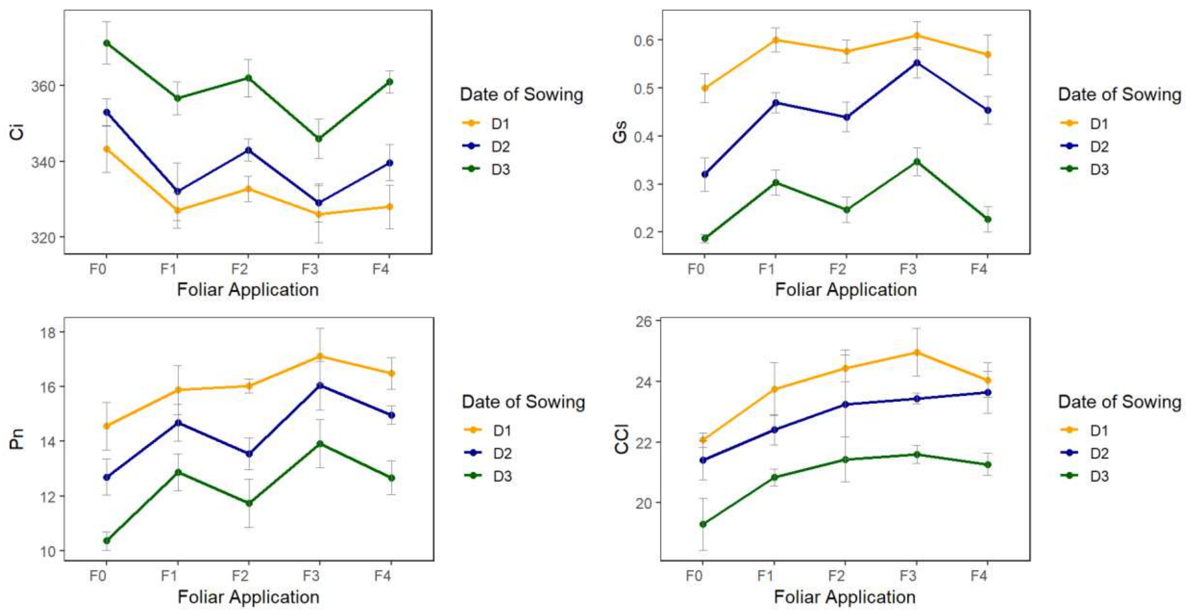


Fig. 3 (b) Effect of different dates of sowing and application of plant bioregulators on physiological parameters of wheat during 2023-24



Yield attributes

Date of sowing significantly influenced effective tillers, grains/spike and test weight, while spike length remained unaffected during both years. Higher effective tillers were recorded under 25th October (304.3 and 294.9 no./m^2) and 10th November sowing (315.9 and 299.8 no./m^2), which were statistically at par, whereas 25th November recorded significantly lower values (281.4 and 269.9 no./m^2). Spike length did not vary significantly among sowing dates. Higher number of grains/spike were recorded under 25th October (48.1 and 44.9) and remained statistically at par with 10th November, but were significantly higher than 25th November (41.0 and 36.1). Similarly, higher test weight was observed under 25th October (42.8 and 42.4 g) and 10th November sowing (41.4 and 41.6 g), which were at par with each other and significantly superior to 25th November (39.3 and 38.3 g).

Foliar application did not significantly influence effective tillers and spike length. However, grains/spike and test weight were significantly influenced. Potassium nitrate @ 2% recorded the highest grains/spike (47.6 and 45.6) and test weight (42.1 and 42.3 g), which was statistically at par with zinc sulphate @ 0.5% and potassium silicate @ 2.3% during both years. Lowest values were recorded in control treatment. The interaction effect between date of sowing and foliar application was non-significant for all parameters, except for grains/spike, where it showed a marginal effect.

Table 2 Effect of different dates of sowing and application of plant bioregulators on effective tillers of wheat

Treatments	Effective tillers (no./m^2)		Spike length (cm)		Grains/spike (no.)		Test weight (g)	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Date of sowing								
D1	304.3 a	294.9 a	11.5 a	11.4 b	48.1 a	44.9 a	42.8 a	42.4 a
D2	315.9 a	299.8 a	11.6 a	11.6 a	46.5 a	42.7 a	41.4 a	41.6 a
D3	281.4 b	269.9 b	11.6 a	11.5 ab	41.0 b	36.1 b	39.3 b	38.3 b
P value	0.0277	0.0474	0.6541	0.0956	0.0133	0.0032	0.0204	0.0442
Foliar application								
F0	290.1 a	279.3 a	11.2 b	11.3 b	40.8 c	37.4 c	39.4 b	39.1 b
F1	300.0 a	291.3 a	11.5 ab	11.4 ab	47.0 ab	41.0 bc	41.6 a	40.5 ab
F2	298.2 a	288.2 a	11.7 ab	11.6 a	43.7 bc	40.3 bc	41.2 a	40.6 ab
F3	309.8 a	292.0 a	11.8 a	11.7 a	47.6 a	45.6 a	42.1 a	42.3 a
F4	304.4 a	290.2 a	11.7 ab	11.6 a	46.8 ab	41.9 ab	41.7 a	41.4 a
P value	0.8405	0.9749	0.2701	0.0826	0.0037	0.0060	0.0021	0.0466
Date of sowing * Foliar application	NS	NS	NS	NS	0.0795	NS	NS	NS

Fig. 4 Effect of different dates of sowing and application of plant bioregulators on grain yield of wheat

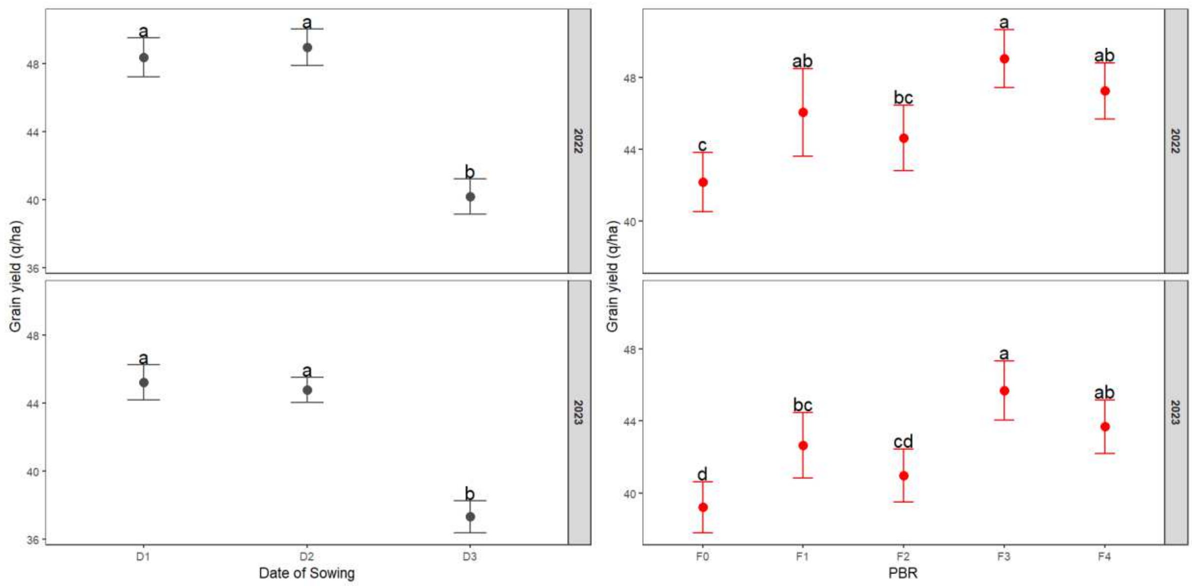
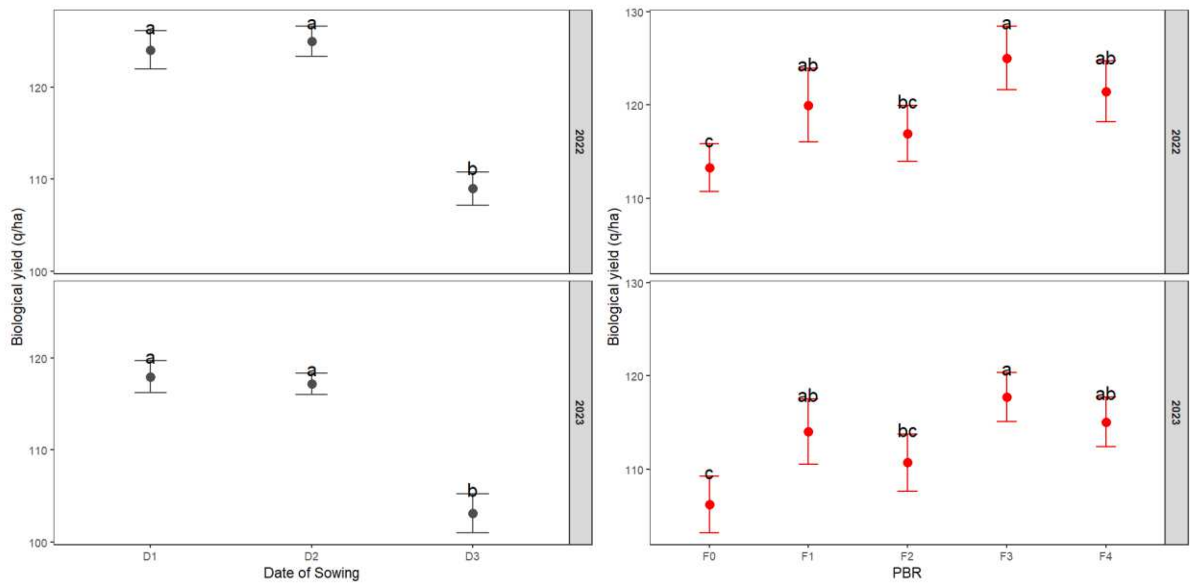
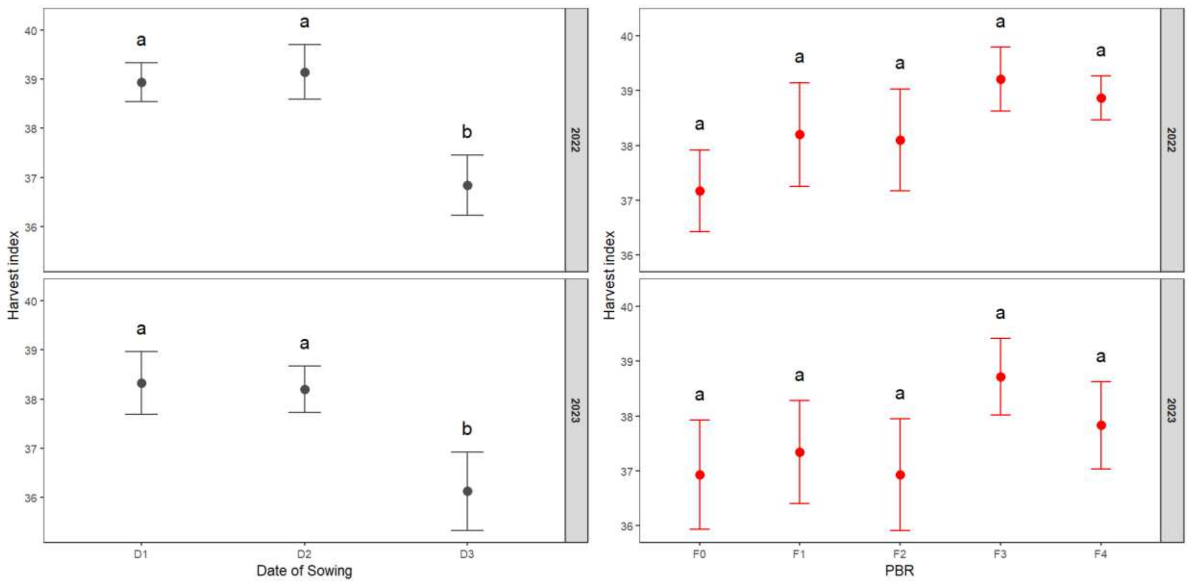


Fig. 5 Effect of different dates of sowing and application of plant bioregulators on grain yield of wheat



In line with yield attributes, grain and biological yield were significantly influenced by date of sowing during both years. Significantly higher grain yield was recorded under 25th October (48.4 and 45.2 q/ha) and 10th November sowing (49.1 and 44.8 q/ha), which remained statistically at par, while the lowest grain yield was recorded under 25th November (40.2 and 37.3 q/ha). A similar trend was observed for biological yield, where 25th October (124.0 and 118.0 q/ha) and 10th November (125.0 and 117.2 q/ha) were statistically at par and significantly superior to 25th November (109.0 and 103.1 q/ha). Foliar application significantly influences both grain and biological yield. Potassium nitrate @ 2% recorded the highest grain yield (49.0 and 45.7 q/ha) and biological yield (125.0 and 117.7 q/ha), which was statistically at par with zinc sulphate @ 0.5% and potassium silicate @ 2.3%. The control treatment recorded the lowest values. The interaction between date of sowing and foliar application was non-significant for both parameters.

Fig. 6 Effect of different dates of sowing and application of plant bioregulators on harvest index of wheat



Correlation matrix-

The correlation matrix represents the correlation among different parameters of wheat sown under different sowing dates and foliar application of plant bioregulators (Figs. 7(a) and (b)). Plant growth attributes have shown a significant ($p \leq 0.01$) strong positive correlation with plant physiological and yield attributes. Plant height (0.90 and 0.86), grains/spike (0.80 and 0.87), test weight (0.92 and 0.93), grain yield (0.92 and 0.88) and biological yield (0.94 and 0.89) showed a strong positive correlation with stomatal conductance and net photosynthetic rate, respectively. In addition, Gs (0.95 and 0.91) showed a strong positive correlation with crop Pn and CCI. Among the physiological attributes, Ci showed a strong negative correlation with stomatal conductance (-0.94), net photosynthetic rate (-0.92), grain yield (-0.93) and biological yield (-0.94).

Fig. 7(a) Correlation matrix for the effect of different dates of sowing and application of plant bioregulators on growth, physiological, yield and yield attributes of wheat during 2022-23

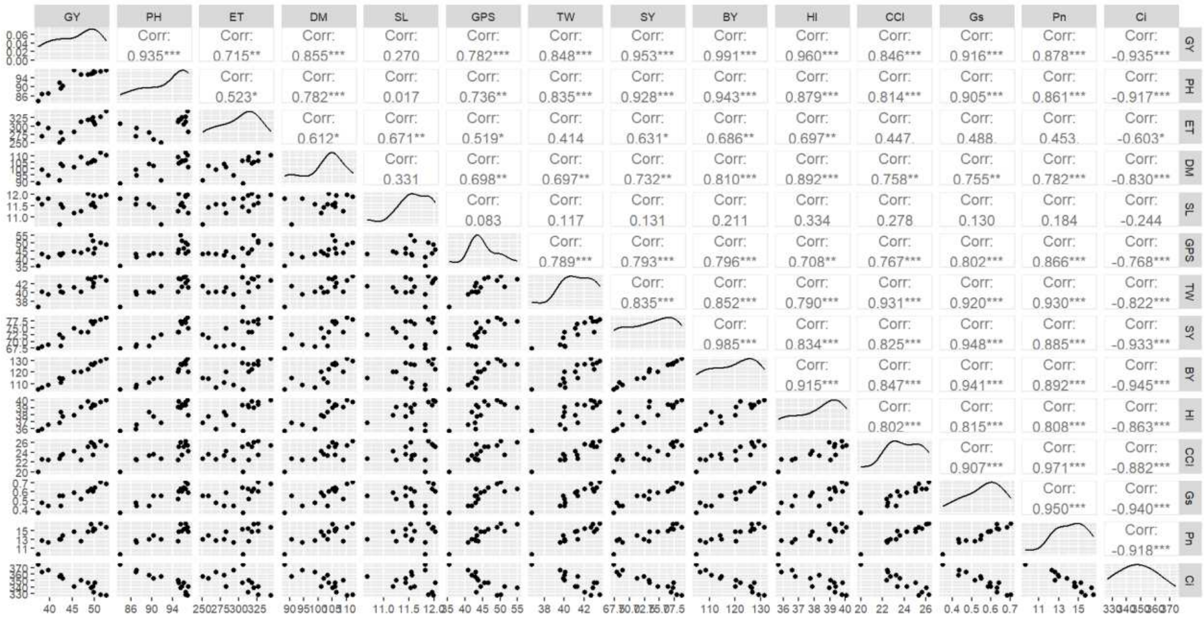
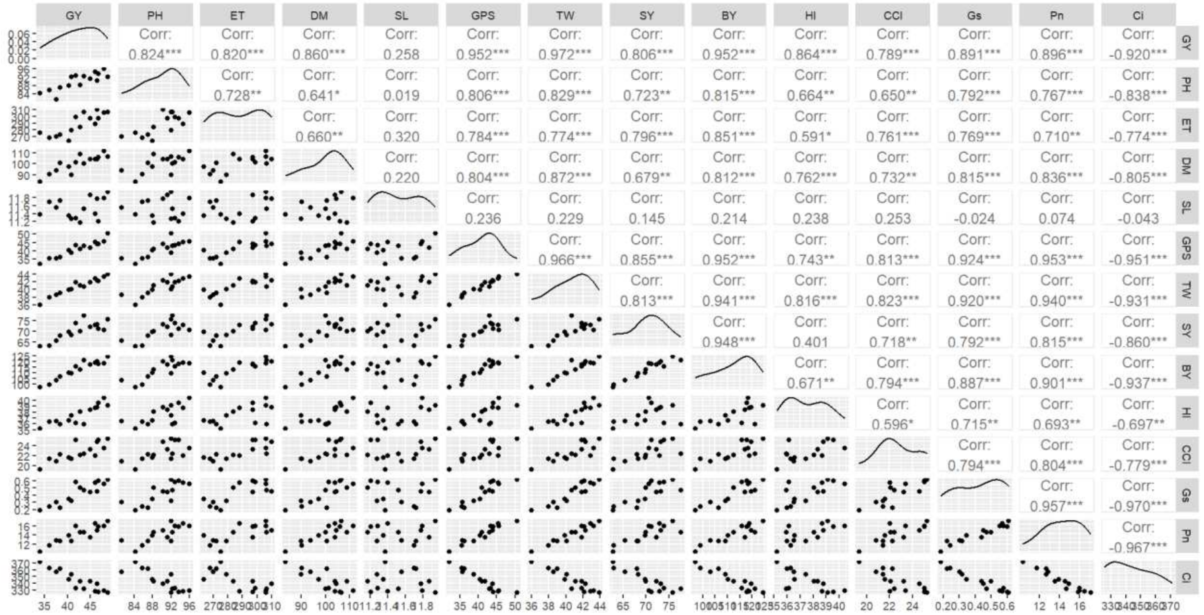


Fig. 7 (b) Correlation matrix for the effect of different dates of sowing and application of plant bioregulators on growth, physiological, yield and yield attributes of wheat during 2023-24



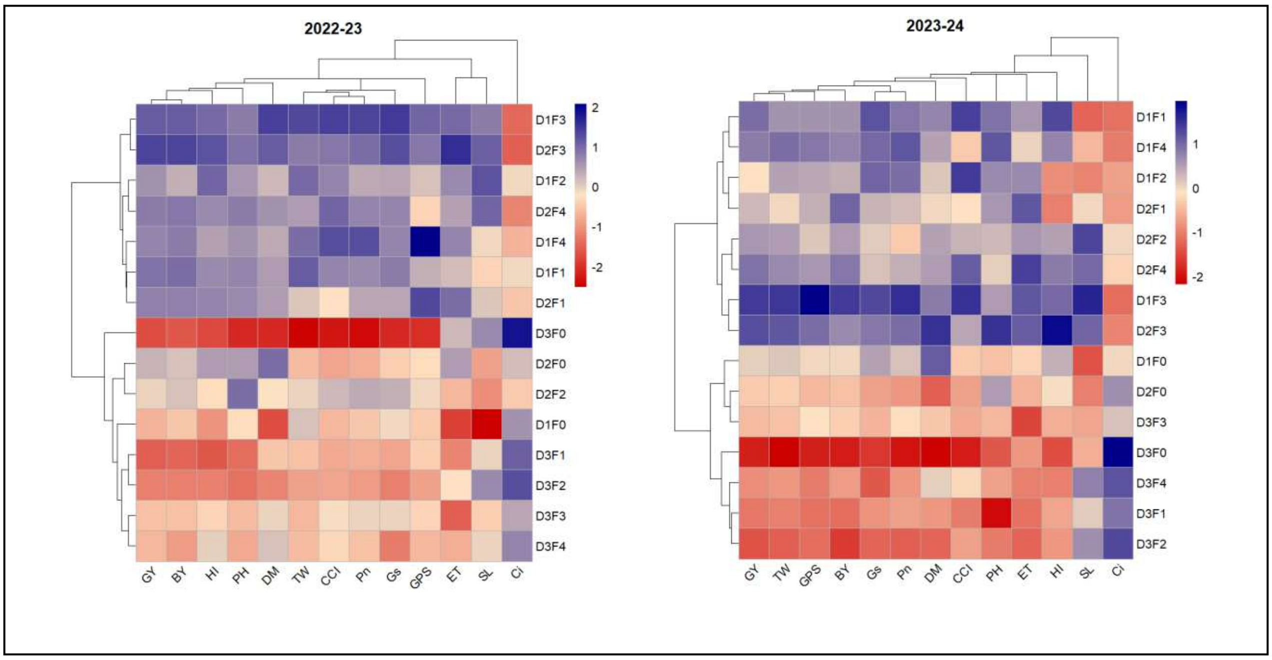
During 2023-24, plant growth attributes have shown a strong positive correlation with plant physiological and yield attributes (Figs. 7 (a) and (b)). Plant height (0.905 and 0.861), grains/spike (0.92 and 0.95), test weight (0.92 and 0.94), grain yield (0.89 and 0.90) and biological yield (0.89 and 0.90) showed a strong positive correlation with stomatal conductance and net photosynthetic rate, respectively. In addition, Gs (0.96 and 0.79) showed a strong positive correlation with crop Pn and CCI. Ci showed a strong negative correlation with stomatal conductance (-0.97), net photosynthetic rate (-0.97), grain yield (-0.92) and biological yield (-0.95).

Clustered heatmap

The agglomerative clustering of treatment combinations grouped the treatments into distinct clusters according to their overall performance. The treatment combinations associated with early and timely sowing dates (D1 and D2), particularly D1F3, D2F3, D1F4, D2F4, and D1F1, formed a major positive cluster characterized by higher values of grain yield (GY), biological yield (BY), straw yield (SY), Stomatal conductance (Gs), chlorophyll content index (CCI), photosynthetic rate (Pn) and test weight (TW). In contrast, the late sowing treatments grouped predominantly in a separate cluster. Treatments D3F0, D3F1, D3F2, D3F3, and D3F4 exhibited comparatively lower values for yield and physiological parameters, as reflected by the dominance of red and light red shades during both years.

The divisive clustering of parameters classified them into functionally related groups. Yield attributes including GY, BY, SY, TW and HI clustered closely with physiological parameters such as stomatal conductance, chlorophyll content index and photosynthetic rate, indicating strong positive associations among these variables. Similarly, other yield attributes such as effective tillers and spike length formed separate cluster, reflecting their weak relationship under varying sowing dates and foliar applications during both years.

Fig. 8 Hierarchal clustered analysis of the growth, physiological, yield and yield attributes of wheat under different dates of sowing and foliar application of plant bioregulators during 2022-23 and 2023-24



Discussion

In the present study, early sowing and foliar application of potassium nitrate at booting and anthesis stages resulted in higher wheat productivity under high thermal stress conditions. The observed variation in plant height and dry matter accumulation under different sowing dates indicated the strong influence of high temperature stress on crop growth and biomass production. Significantly higher plant height recorded under 25th October sowing which might be attributed to the availability of optimum temperature and photoperiodic conditions during vegetative stages, which favoured enhanced internode elongation, accumulation and translocation of assimilates [Jatana *et al* 2022]. In contrast, delayed sowing on 25th November exposed the crop to comparatively higher temperatures during late vegetative stages, resulting in shortened phenological duration, thereby restricting stem elongation and dry matter production under terminal heat stress conditions [Yajam and Madani 2013]. Although foliar application of plant bioregulators did not significantly influence plant height, it significantly affected dry matter accumulation at harvest. Higher dry matter accumulation under foliar application of potassium nitrate can be attributed to enhanced physiological efficiency and improved source-sink relationship within the plant system. Potassium plays an important role in gas exchange, enzyme activation and assimilate translocation, whereas nitrate contributes to synthesis of photosynthetic pigments. The combined effect may have enhanced photosynthetic activity and delayed senescence during post anthesis stages, thereby resulting in greater accumulation of dry matter [Tanin *et al* 2023 and Chaurasiya *et al* 2018].

Date of sowing significantly influenced chlorophyll content index, stomatal conductance and net photosynthetic rate during both years of study. Wheat sown on 25th October consistently maintained higher chlorophyll content index and photosynthetic activity, followed by 10th November sowing, whereas late sowing on 25th November recorded substantially lower values of these physiological parameters. The comparatively favourable thermal regime prevailing under early sowing during anthesis and grain filling may have contributed to sustained chlorophyll content index and stomatal functioning. Conversely, exposure of late-sown wheat to elevated temperatures during reproductive stages resulted in accelerated chlorophyll degradation, leading to impaired stomatal conductance and restricted CO_2 diffusion into leaf tissues and leaf senescence. Reduced CO_2 availability under heat stress conditions resulted in lowered net photosynthetic rate [Feng *et al* (2014), Prasad *et al* (2008), Rahman *et al* (2018) and Elbasyoni (2018)]. The decline in physiological activity under delayed sowing further indicates the adverse effect of terminal heat stress on photosynthetic machinery and overall crop productivity.

Foliar application of potassium nitrate at booting and anthesis stages significantly influenced stomatal conductance, chlorophyll content index and net photosynthetic rate of wheat during both seasons. Potassium nitrate helped to maintain higher stomatal conductance through improved osmotic regulation and leaf water relations, thereby sustaining guard cell turgidity under stress conditions. Enhanced stomatal conductance and transpiration may also have contributed to effective canopy cooling and reduced heat-induced oxidative damage to chloroplast structures and photosynthetic pigments. Chlorophyll, being the principal photosynthetic pigment involved in light energy absorption, is highly sensitive to thermal stress, which accelerates chlorophyll degradation through disruption of photosynthetic machinery, protein instability and increased chlorophyllase activity. Improved stomatal functioning under potassium nitrate application reduced stress severity within leaf tissues, thereby minimizing chlorophyll degradation during reproductive stages. In addition, nitrate availability has supported nitrogen metabolism and chlorophyll biosynthesis, resulting in sustained photosynthetic activity and greater CO_2 assimilation [Chowdhury *et al* (2020) and Zheng *et al* (2010)]. Among yield attributes, significantly higher number of effective tillers recorded under 10th November sowing during both years may be attributed to the favourable climatic conditions prevailing during the early vegetative stage, which promoted tiller initiation. In contrast, delayed sowing likely exposed the crop to comparatively less favourable thermal conditions during vegetative development, resulting in reduced tillering. The highest values of grains/spike and test weight were recorded under 25th October sowing which may be associated with the favourable temperature regime prevailing during anthesis and grain filling stages. At anthesis stage, crop sown on 25th October experienced maximum temperatures of 26.5 and 22.1 °C during 2022-23 and 2023-24, respectively, which remained comparatively favourable for reproductive development. Conversely, crop sown on 25th November was exposed to relatively higher maximum temperatures (28.3 and 28.9 °C), leading to heat stress during reproductive stages. In addition, timely sowing on 25th October provides a longer reproductive period for assimilate production and translocation towards developing grains. These conditions collectively contributed to improved grain formation and higher test weight [Gill *et al* (2016)]. Significantly lower grains/spike and test weight recorded under delayed sowing was attributed to terminal heat stress encountered during anthesis and grain filling stages. Exposure to elevated temperatures during reproductive development is known to accelerate senescence, impair photosynthetic activity, and reduce assimilate availability for grain filling, ultimately leading to poor grain development and reduced grain weight [Elbasyoni (2018), Fayed *et al* (2015), Mukherjee (2012), Prasad *et al* (2008) and Talukder *et al* (2014)].

Foliar application of potassium nitrate @ 2% at booting and anthesis stages improved yield attributes under high temperature conditions. The improvement may be linked to maintenance of chlorophyll content index, stomatal conductance and net photosynthetic rate in flag leaves during the post-anthesis period, which supported sustained efficient translocation of assimilates towards grains [Chowdhury *et al* 2020 and Singh *et al* 2021]. In contrast, lower values of grains/spike and test weight under the control treatment were due to the adverse effects of terminal heat stress on physiological activity and grain filling [Nouri et al (2011)].

Grain yield is determined by the combined contribution of yield components such as effective tillers, grains/spike and test weight, whereas biological yield represents the total biomass produced during the crop growth period. These parameters collectively reflect the efficiency of crop growth, assimilate production and partitioning under different environmental and management conditions.

Significantly higher grain yield, biological yield and harvest index were recorded under 25th October and 10th November sowing compared with 25th November sowing. This may be attributed to the comparatively favourable thermal conditions prevailing during vegetative and reproductive stages, which supported better crop growth and assimilate accumulation. In contrast, the crop sown on 25th November experienced relatively higher minimum temperature stress during anthesis, milking and dough stages, which adversely affected physiological activity and biomass production during both years. Exposure to elevated temperatures during reproductive development may have reduced chlorophyll content index, stomatal conductance and photosynthetic efficiency. The combined effect likely reduced assimilate availability for grain filling, resulting in lower grain and biological yield under delayed sowing conditions [Prabhjyot-Kaur and Hundal (2007) and Lobell (2005)].

Foliar application of potassium nitrate @ 2% recorded the highest grain and biological yields, whereas the lowest values were observed under the control treatment during both years. The higher efficacy of potassium nitrate was associated with enhanced tolerance to heat stress during reproductive stages. Potassium improved osmotic regulation, maintained cellular K^+ balance, chlorophyll integrity, sustained stomatal conductance and photosynthetic rate, thereby ensuring efficient photosynthate translocation from source to sink under stress conditions. In addition, foliar application at booting and anthesis supported efficient translocation of assimilates from source to sink, resulting in improved grain filling and greater biomass accumulation [Chowdhury *et al* (2020), Zheng *et al* (2010), Pal and Murthy (2013) and Ram *et al* (2012)].

Conclusion

The foliar application of potassium nitrate significantly improved wheat performance under both normal and late sown conditions. Early sowing enhanced growth, yield attributes and physiological traits, including stomatal conductance and net photosynthetic rate, compared with late sowing. Foliar application of potassium nitrate helped maintain wheat growth under high temperature stress by improving stomatal conductance and photosynthetic activity while reducing intercellular CO_2 concentration. Furthermore, the combination of early sowing and potassium nitrate application exhibited greater resilience to heat stress, resulting in improved crop performance under elevated temperature conditions.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author (Gurpreet Singh, [gurpreetsinghmatharoo993@gmail.com]) on reasonable request.

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Competing interests

The authors declare no competing interests.