



Micrometeorology of wheat (*Triticum aestivum*) under different paddy residue management and sowing environments

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ABSTRACT

Selection of optimal sowing dates with favourable environmental conditions is a key strategy for adaptation under climate change. To assess this, a field experiment was conducted during the winter (*rabi*) seasons of 2022–23 and 2023–24 at Punjab Agricultural University, Ludhiana, Punjab to investigate the effects of sowing environments and paddy residue management (PRM) practices on wheat (*Triticum aestivum* L.) canopy microclimate and productivity. Wheat variety 'PBW-725' was sown on three dates, viz. 22nd November (D1), 28th November (D2), and 6th December (D3) under three residue management treatments: mulching (M1), incorporation (M2), and residue removal (M3). Canopy temperature (CT), canopy relative humidity (CRH), and intercepted photosynthetically active radiation (PAR) were recorded at crown root initiation, jointing, anthesis, and physiological maturity stages. Timely sowing (D1) and residue mulching (M1) created a more favourable canopy microclimate by moderating CT, maintaining higher CRH, and enhancing PAR interception. Intercepted PAR increased from early growth stages to anthesis, with D1 recording the highest values, while delayed sowing (D3) consistently reduced radiation interception. Mulching improved canopy humidity and PAR interception compared with residue removal. Grain yield declined significantly with delayed sowing, decreasing from 49.7 q/ha in D1 to 42.8 q/ha in D3. Among residue management practices, mulching produced the highest grain yield (48.7 q/ha) followed by incorporation (46.6 q/ha) and residue removal (43.9 q/ha). Correlation analysis revealed that higher PAR and lower CT during anthesis and physiological maturity were strongly associated with improved yield and yield-attributing characters. The results indicated that timely sowing combined with paddy residue mulching enhances wheat productivity by improving canopy microclimatic conditions under the semi-arid conditions of Punjab.

Keywords: Canopy temperature, Crop micrometeorology, Dates of sowing, Photosynthetically active radiation

Agriculture is profoundly influenced by climatic conditions. In recent years, increased variability and more frequent extreme weather events have increased agricultural susceptibility to climate-related risks (Kingra and Kaur 2017). Rising temperatures and more intense temperature extremes are expected to adversely affect crop productivity. Since *rabi* season crops thrive in comparatively cooler climates, they are particularly vulnerable to yield losses. Given that higher temperatures are likely to diminish crop yields, developing effective adaptation strategies is essential to mitigate these negative effects. Fortunately, simple adjustments in crop management can optimise the microclimate for better growth and yield without imposing substantial financial costs (Debangshi 2021, Singh *et al.* 2021). A key strategy for maximising yields under climate change is aligning crop phenology with favourable

environmental conditions by selecting optimal sowing dates to avoid stress periods (Singh *et al.* 2016). The state of Punjab has experienced significant climatic variability over the past decades (Kingra *et al.* 2017), resulting in decreased wheat (*Triticum aestivum* L.) productivity. This underscores the urgent need to address climate change impacts on wheat production to safeguard food security and preserve natural resources in the region.

Paddy straw management offers a viable solution for enhancing soil moisture retention and mitigating environmental stress. Punjab generates approximately 20 mt of rice straw annually, much of which is burned in open fields causing agricultural, social and environmental losses in the tune of thousands of crores (Ranguwal and Kaur 2022). When used as mulch, crop residues protect the soil by reducing evaporation, minimising runoff, and improving water infiltration (Dhaliwal *et al.* 2019).

Given these challenges, this study was designed to investigate the microclimate of wheat under different sowing dates and residue management (mulching vs. incorporation)

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to identify sustainable strategies for reducing climatic risks in semi-arid agroclimates. This would ultimately be achieved by more yields with the same inputs. The relation of micrometeorology with yield and yield attributing characteristics can also enhance our understanding towards a climate resilient future.

MATERIALS AND METHODS

Study location and climatic conditions: A two-year field experiment (2022–23 and 2023–24) was conducted at the research farm of the Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University (PAU), Ludhiana (30°40'N, 74°44'E; at an elevation of 247 m amsl), Punjab. The site lies in Punjab's central plain zone, experiences a semi-arid climate with an average annual rainfall of 768 mm. Winters are marked by frosty nights and chilly winds, with temperatures occasionally dropping to 0°C, while summers bring dust storms and extreme heat, with temperatures reaching up to 47°C. The experimental soil type was sandy loam. Weather data were taken from the records of PAU's Agro-meteorological Observatory.

Experimental design: The study evaluated three sowing dates: November 22nd (D1), November 28th (D2), and December 6th (D3), combined with two paddy residue treatments, i.e. mulching @3 q/ha (M1) and incorporation (M2), alongside a no-residue control (M3). A uniform row spacing of 22.5 cm was maintained across all treatments. The experiment followed a factorial split-plot design with four replications, totalling 36 plots (each 4 m × 4 m, with 19 wheat rows/plot). Fertilisers were applied as per PAU recommendations: 125 kg N/ha and 60 kg P₂O₅/ha. Half the nitrogen and all phosphorus were applied as a basal dose, with the remaining nitrogen split equally after the first and second irrigations.

Data were analysed using ANOVA with treatment effects compared at a 5% significance level (CD values) via SPSS. Visualisation was performed in R and MS Excel. Canopy microclimate parameters were compared with nearby meteorological data, and yield correlations were assessed using Pearson's coefficient.

Observations recorded: The study examined the effects of residue management and sowing dates on wheat's micrometeorological parameters [canopy temperature at 2:30 PM, relative humidity at bottom and top of the canopy at 2:30 PM and intercepted Photosynthetically Active Radiation (PAR%) at 12:30 PM] across key growth stages: crown root initiation (CRI), jointing, anthesis, and physiological maturity. At harvest, yield attributes (effective tillers/m, plant height, grains/earhead, earhead height, test weight, grain yield, and biological yield) were measured.

RESULTS AND DISCUSSION

Canopy temperature: The difference between canopy temperature and air temperature were calculated for each treatment. In the first year, early sowing (D1) exhibited the lowest canopy temperature difference at the CRI

stage (-2.04°C), suggesting a favourable microclimate for early crop establishment. As sowing was delayed, this difference progressively increased, with D3 recording a positive value (+1.25°C), implying increased canopy stress or warmer conditions. During the jointing stage, canopy temperature was substantially higher than air temperature in all dates, especially for D3 (5.70°C), indicating vigorous transpiration and possibly higher biomass. Temperature differences during anthesis remained close to neutral across all dates, suggesting stable canopy functioning (Fig. 1). At physiological maturity, D1 again recorded a high difference (3.52°C), potentially due to early senescence. The same was also observed by Singh *et al.* (2016). Singh *et al.* (2021) found similar results where early sowing was found to save the crop from late-stage heat stress.

In second year, the trend differed notably. At CRI, D2 and D3 had positive temperature differences, suggesting delayed sowing did not significantly stress the canopy early on. However, D1 showed a high positive difference at anthesis (1.29°C) and a negative difference at maturity (-2.51°C), pointing toward terminal stress or accelerated maturity. D2 showed the highest temperature difference at jointing (6.80°C), consistent with strong physiological activity.

Across residue management methods, mulching (M1) consistently produced more favourable canopy-air temperature profiles (Fig. 1). In first year, it moderated early-stage canopy temperatures and reduced heat load during anthesis and maturity. Incorporation (M2) offered intermediate benefits while conventional cultivation (M3) often resulted in higher canopy temperatures, particularly during maturity (1.90°C), possibly exacerbating stress. In the second year, mulch again led to more stable and moderate temperature differences, particularly at the late stages, reinforcing its role in conserving soil moisture and enhancing microclimate. Conventional methods, though slightly better during CRI, had elevated canopy temperatures at anthesis and maturity. Similar results as to lower temperatures in mulched crop were observed by Dhaliwal *et al.* (2019) in wheat and recently by Wu *et al.* (2025) in soyabean.

These patterns suggest that timely sowing with mulch application optimises canopy temperature regulation, supporting crop growth and potentially improving yield stability, especially under variable climatic conditions.

Canopy relative humidity: At jointing stage in the first year, relative humidity (RH) at the bottom of the canopy was consistently higher than at the top across all treatments, indicating accumulation of moisture due to restricted air movement and possible transpiration effects. The same was observed by Sattar *et al.* (2003). The highest bottom RH was observed in M1 (57.4%) while the lowest top RH was in D2 (47.5%). Actual ambient RH was highest in D1 (70.7%), indicating more humid weather conditions during early sowing. D3 had the lowest ambient RH (56.8%), suggesting drier atmospheric conditions for the late-sown crop (Fig. 2). All residue management treatments recorded a similar actual RH (64.5%), though the bottom RH was

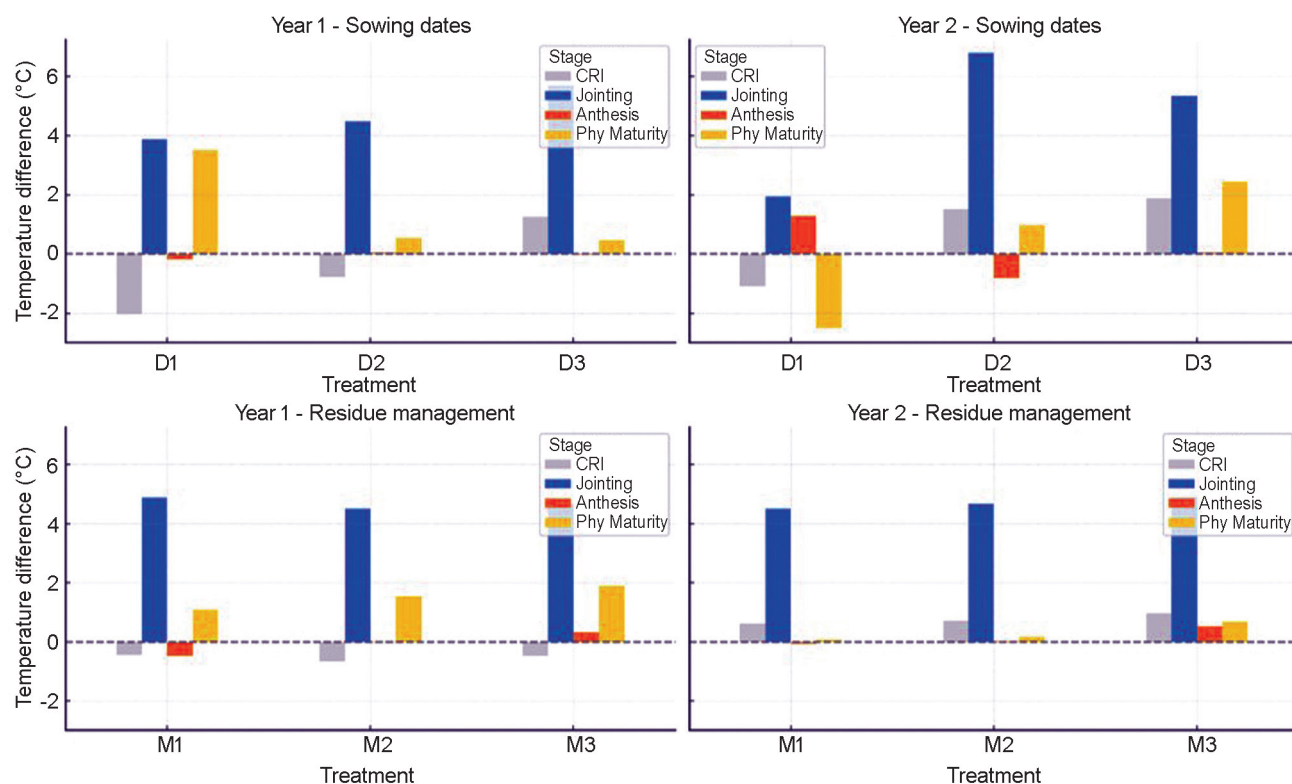


Fig. 1 Difference between canopy and air temperature (°C) at major growth stages for different treatments. CRI, Crown root initiation. Treatment details are given under Materials and Methods.

slightly higher in M1, suggesting better microclimatic retention due to mulching.

In the second year, there was a general increase in top and bottom RH values compared to Year 1 (Fig. 2). D3 recorded the highest top (50.1%) and bottom (57.6%) RH, aligning with its earlier findings of more favourable canopy temperatures. Actual RH was highest in D1 (68.1%) and lowest in D3 (60%). Among residue management methods, M1 again recorded the highest bottom RH (58.6%), reinforcing the microclimate-improving effect of mulch. All three residue treatments recorded similar actual RH (63.7%).

During the anthesis stage, top and bottom canopy RH remained in the 47–56% range across treatments. D3 exhibited a unique pattern, with a relatively higher top RH (50.7%) but lower bottom RH (47.8%), indicating vertical RH inversion that may reflect altered airflow or reduced transpiration (Fig. 2). All treatments recorded similar actual RH (~41.6%), indicating stable atmospheric humidity during this period. M1 showed a favourable top-to-bottom gradient (50.7% to 54.3%), which may have helped maintain better leaf water status.

In the second year, RH values at anthesis were generally higher than in the first year. D3 again had the highest top RH (52.1%) and a balanced bottom RH (49.2%), which paired with a significantly higher actual RH (48.7%), suggests a more humid environment is favourable for reproductive development. These results run contrary to Singh *et al.* (2021) mainly due to season specific weather conditions. M1 and M2 treatments exhibited similar RH profiles (top

~52%, bottom ~55–57%), and actual RH of 43.5%, higher than M3 which had lower bottom RH.

The vertical RH profile revealed a clear pattern where bottom canopy RH exceeds top canopy RH, supporting the idea of moisture retention within the canopy. Mulch consistently enhanced bottom RH, particularly at jointing, suggesting improved microclimate and potential for better stress resilience. These results are similar to Kumar *et al.* (2017), although due to different mechanisms, there was optimum moisture with irrigation, here it is better preservation of moisture by paddy residue mulching. Optimum sowing time and paddy straw mulch has been found to improve agroclimatic indices in other *rabi* crop as well (Singh and Singh 2026). The higher actual RH observed during early sowing (D1) may benefit vegetative growth but could vary in reproductive stages depending on the year. Late sowing (D3), especially in second season, aligned with more favourable RH conditions at anthesis, which may offset stress effects seen in other parameters.

Intercepted photosynthetically active radiation: The intercepted PAR% varied significantly across different growth stages during both the years, influenced by sowing dates and residue management practices. Timely sown wheat (D1) consistently exhibited the highest intercepted PAR%, while D3 led to lower radiation interception, particularly during later growth stages (Fig. 3).

At CRI, intercepted PAR% was relatively low across all treatments, ranging between 5–10%. As the crop progressed to jointing, intercepted PAR% increased to

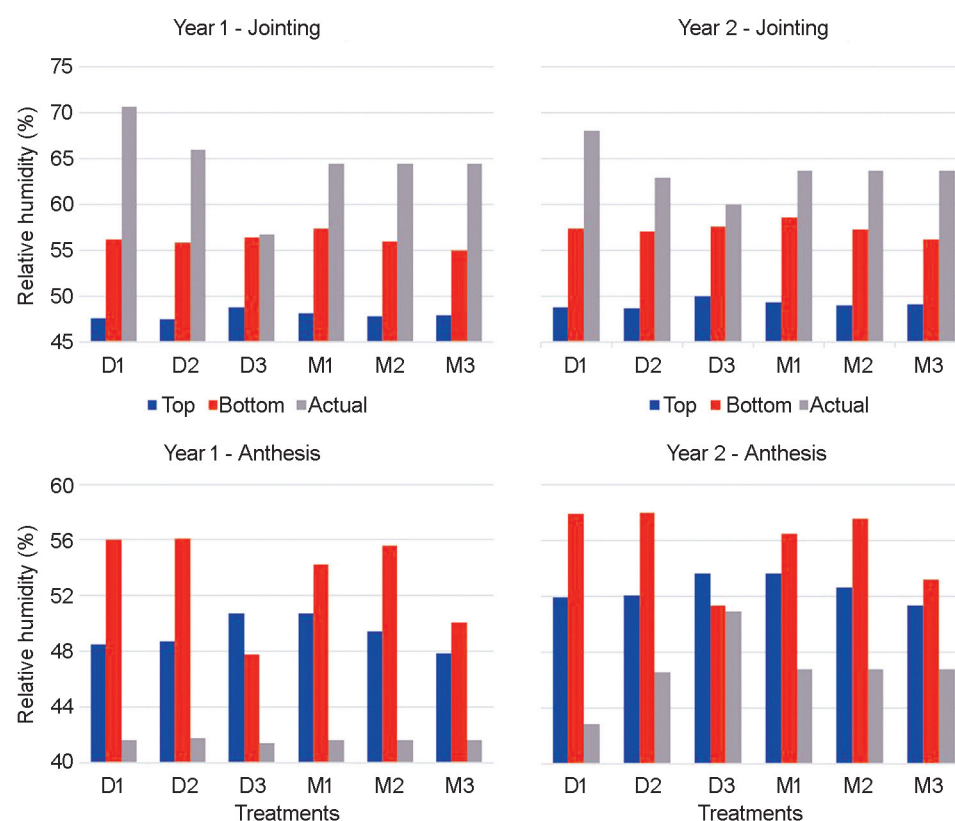


Fig. 2 Difference between canopy and air relative humidity (%) at jointing and anthesis stages of wheat.

Treatment details are given under Materials and Methods.

approximately 65–70% in D1 whereas D2 and D3 showed slightly lower values of around 63–68%. The differences became more evident at anthesis, where D1 recorded the highest intercepted PAR% (79–81%) while D2 and D3 showed slightly lower values, ranging between 75–79%. At physiological maturity, intercepted PAR% declined across all treatments, with D1 maintaining the highest values whereas D2 and D3 exhibited a noticeable decrease (Fig. 3).

Residue management also played a critical role in intercepted PAR%, particularly during jointing, anthesis, and maturity stages. Among the treatments, M1 resulted in the highest intercepted PAR% across all growth stages, with values of 70–73% at jointing, 80–82% at anthesis and 70–72% at physiological maturity. Residue incorporation (M2) followed closely with intercepted PAR% values of 68–72% at jointing, 78–81% at anthesis, and 68–71% at physiological maturity. The M3 consistently recorded lowest intercepted PAR%, highlighting the reduced canopy coverage and lower radiation utilisation efficiency in the absence of residue retention.

Overall, the results indicated that timely sowing optimised light interception across all growth stages, whereas delayed sowing significantly reduced intercepted PAR%, particularly at critical reproductive stages. Delayed sowing resulted in decreased crop growth and health resulting in a reduced plant canopy and lower intercepted PAR% (Singh *et al.* 2021, Singh and Singh 2026). Additionally,

residue mulching improved light interception efficiency, ensuring better canopy development and higher radiation utilisation. Similar results were obtained by Saikia *et al.* (2014) and Dhaliwal *et al.* (2019). Conversely, the combination of delayed sowing and conventional tillage resulted in the lowest intercepted PAR% (63–67% at maturity), reflecting poor canopy structure and reduced radiation use efficiency. These findings highlight the importance of timely sowing and residue retention in maximising intercepted PAR% and improving wheat productivity under varying sowing and residue management conditions.

Yield and yield attributing traits: The data revealed significant effects of sowing time and residue management practices on wheat yield and its contributing attributes (Table 1). Among the three

sowing dates, D1 consistently outperformed D2 and D3. Effective tillers/m² were highest under D1 (82.46)

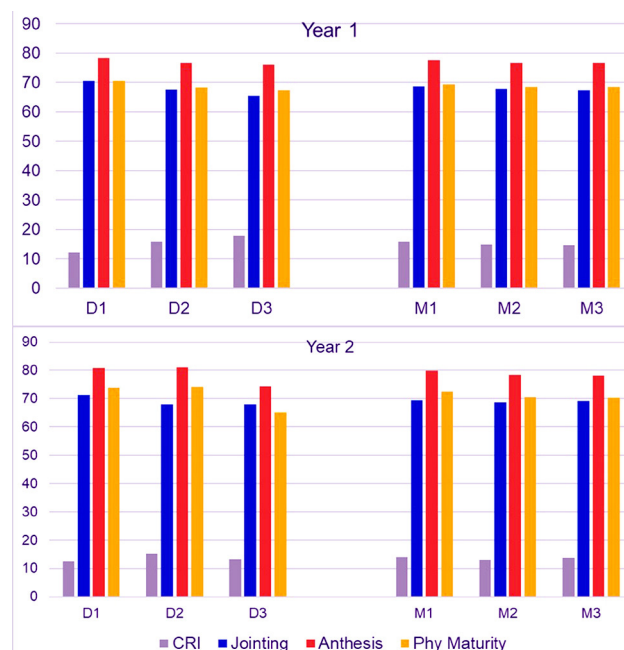


Fig. 3 Intercepted PAR (%) during major phenophases of wheat crop during experimental years.

CRI, Critical root initiation; PAR, Photosynthetically active radiation. Treatment details are given under Materials and Methods.

Table 1 Yield and yield attributes comparison of treatments during two years of study

Treatment	Effective tillers	Tiller height (cm)	Grains/earhead	Earhead height (cm)	Test weight (g)	Grain yield (q/ha)	Biological yield (q/ha)
D1	82.46	89.17	42.38	9.05	41.52	49.7	126
D2	81.88	87.00	40.83	8.75	38.93	46.7	116
D3	75.92	85.50	38.75	8.22	37.48	42.8	108
CD ($p < 0.05$)	ns	0.58	1.82	0.26	ns	5.10	6.43
SE(m)	2.05	0.16	0.52	0.07	1.01	1.45	1.82
M1	81.54	87.92	40.54	8.88	39.28	48.7	120
M2	79.17	87.04	40.42	8.63	39.45	46.6	116
M3	79.54	86.71	41.00	8.50	39.21	43.9	114
CD ($p < 0.05$)	ns	ns	ns	ns	ns	3.70	ns
SE(m)	1.34	0.88	0.90	0.13	0.73	1.24	1.84

ns, Non-significant. Treatment details are given under Materials and Methods.

followed closely by D2 (81.88) while the lowest value was recorded in D3 (75.92). Tiller height showed a significant decreasing trend from 89.17 cm in D1 to 85.5 cm in D3. The number of grains/earhead also declined from 42.38 in D1 to 38.75 in D3, with a critical difference (CD) of 1.823, indicating statistical significance. Earhead height and test weight also followed a decreasing trend. These differences translated into notable variations in grain yield, which was significantly higher under D1 (49.7 q/ha), followed by D2 (46.7 q/ha), and D3 (42.8 q/ha). The critical difference for grain yield was 5.10, confirming the statistical significance of the observed differences. A similar trend was evident in biological yield.

Among the residue management techniques, M1 resulted in the highest grain yield (48.7 q/ha), followed by M2 (46.6 q/ha) while the lowest yield was observed under M3 (43.9 q/ha). The critical difference for grain yield among residue management methods was 3.703, suggesting statistically significant differences. However, for other parameters such as effective tillers, tiller height, grains/earhead, and earhead height, the differences were statistically non-significant (Table 1).

In terms of biological yield, M1 again performed best (120 q/ha), with M2 and M3 following at 116 and 114 q/ha, respectively. While these differences were numerically clear, they were not statistically significant, indicating that although M1 may have agronomic benefits, variability may limit its consistency across environments. The rice straw retention in rice–wheat system improved productivity and quality of wheat grain (Gupta *et al.* 2022).

Thus, increase in yield attributes improved yield as a result of timely sowing and paddy residue mulching and incorporation. Similar studies have found similar results both in terms of date of sowing (Joshi *et al.* 2016, Mehta and Dhaliwal 2020, Singh *et al.* 2021, Singla and Sarlach 2023) and residue management (Ram *et al.* 2013, Ali *et al.* 2016, Dhaliwal *et al.* 2019, Sangwan and Deswal 2023).

Correlation between micrometeorology and yield attributes: The correlation analysis between PAR, canopy temperature (CT), canopy relative humidity (CRH), and various yield-attributing traits in wheat showed critical insights into the environmental determinants of crop productivity (Fig. 4). A consistent pattern of significant positive relationships was observed between PAR and major yield components during key developmental stages. Specifically, PAR recorded at anthesis and physiological maturity stages exhibited the strongest positive correlations with effective tillers ($r = 0.942^{**}$), tiller height ($r = 0.845^{**}$), grains/earhead ($r = 0.868^{**}$), earhead length ($r = 0.906^{**}$), test weight ($r = 0.827^{**}$), grain yield ($r = 0.877^{**}$), and biological yield ($r = 0.877^{**}$) (Fig. 4). These findings suggest that adequate light availability during the reproductive and grain-filling phases is crucial for enhancing assimilate accumulation and final yield formation, similar to the results of Barua *et al.* (2021). In contrast, PAR at the CRI stage showed negative or non-significant associations with most yield traits, indicating that early-season light interception may play a limited role in determining final yield outcomes.

Canopy temperature displayed a uniformly strong negative correlation with all measured traits across all phenological stages. It was particularly detrimental, during anthesis and physiological maturity stages with correlations reaching $r = -0.967^{**}$ for test weight and $r = -0.977^{**}$ for biological yield. The consistently negative associations across stages especially CT at jointing ($r = -0.958^{**}$ with grains/earhead) and CT at CRI ($r = -0.903^{**}$ with grains/earhead) highlight the sensitivity of wheat to elevated canopy temperatures, which can impair photosynthetic efficiency, shorten grain filling duration, and ultimately reduce yield. These results align with previous studies (Kingra *et al.* 2010, Singh *et al.* 2021) emphasising the adverse impact of heat stress on wheat performance during reproductive stages.

Canopy relative humidity, in contrast, showed mixed effects depending on the stage of measurement. At the



Fig. 4 Correlation of micrometeorology parameters of wheat crop with yield and yield attributing traits.

Blue indicate positive while red indicate negative correlation, size of the circle represents the strength of the correlation. CRI, Crown rot initiation; CT, Canopy temperature; PAR, Photosynthetically active radiation; RH, Relative humidity.

jointing stage, CRH had no significant association with any trait, suggesting minimal physiological influence at this phase. However, CRH recorded at anthesis showed significant positive correlations with several traits including effective tillers, tiller height, grains/earhead, earhead length, and grain yield. These results underscore the beneficial effects of moderate canopy humidity during anthesis, potentially supporting enhanced pollen viability, fertilisation, and subsequent grain development.

The results demonstrate that optimal environmental conditions, particularly high PAR and low CT during anthesis and physiological maturity, are critical for maximising wheat yield. High canopy temperatures during these sensitive stages significantly hinder yield potential, while adequate canopy humidity can positively influence reproductive success (Singh and Singh 2026). These findings have practical implications for agronomic management and breeding strategies aimed at improving wheat resilience to climate variability, particularly in environments prone to terminal heat stress.

This study highlights the critical role of microclimatic conditions within the wheat canopy, shaped by sowing time and paddy residue management (PRM) practices in influencing crop performance and yield. Timely sowing combined with paddy residue mulching created the most favourable canopy microenvironment, marked by moderated canopy temperature, enhanced relative humidity, and improved interception of PAR%. These conditions supported better canopy development and stress resilience, particularly during key growth stages such as anthesis and physiological maturity. The vertical RH profile indicated improved moisture retention with mulching, especially at the bottom canopy layers, contributing to a favourable microclimate for growth and reproduction. Higher intercepted PAR% in timely sown and mulched plots further enhanced radiation use efficiency and canopy photosynthesis, directly influencing yield potential. Yield and yield-attributing

traits were significantly improved under D1 with PRM treatments, particularly M1 and M2, confirming the synergy between sowing time and residue management. Correlation analysis reinforced the importance of maintaining lower canopy temperature and higher PAR% during reproductive stages for yield maximisation. These insights are particularly relevant for wheat cultivation in climate-vulnerable regions, where terminal heat stress and moisture variability pose significant challenges. The findings underscore the need to integrate timely sowing and residue-based conservation practices into wheat management strategies to optimise microclimatic conditions, enhance productivity, and support climate-resilient agriculture.

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