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Hydro-thermal regimes and their impact on relative weather disparities and grain yield of wheat in central Punjab

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सार – तापमान और आर्द्रता कारक, जिन्हें सापेक्ष तापमान असमानता (RTD) और सापेक्ष आर्द्रता असमानता (RHD) के रूप में जाना जाता है, फेनोलॉजी और फसल उपज के साथ-साथ विभिन्न बुवाई वातावरण और सिंचाई व्यवस्थाओं से काफी प्रभावित पाए गए। लुधियाना, पंजाब में RTD और RHD क्रमशः 47.71 से 64.65 और 34.68 से 63.07 के बीच थे। फील्ड प्रयोग 2021-22 और 2022-23 के रबी सीजन के दौरान लुधियाना (30.90 डिग्री एन, 75.85 डिग्री ई और एमएसएल से 247 मीटर ऊपर) में स्प्लिट प्लॉट डिजाइन में चार प्रतिकृति के साथ तीन बुवाई तिथियों (डी1 = 27 अक्टूबर, डी2 = 17 नवंबर, डी3 = 8 दिसंबर) और 3 सिंचाई व्यवस्थाओं (I1 = सीआरआई पर 4 सिंचाई, जोड़, 50% फूल, नरम आटा चरण, I2 = सीआरआई पर 3 सिंचाई, झंडा पत्ती उद्भव, नरम आटा चरण, I3 = जोड़, नरम आटा चरण पर 2 सिंचाई) के साथ किया गया था। 27 अक्टूबर को बोई गई फसल को शारीरिक परिपक्वता प्राप्त करने में अधिकतम दिन लगे, इसके बाद 17 नवंबर और 8 दिसंबर को बोई गई फसल उपज। वनस्पति अवस्था (सीआरआई, बूटिंग) और प्रजनन अवस्था (दूध देने) पर उच्च आरटीडी और परिपक्वता पर कम आरटीडी के साथ-साथ बूटिंग और दूध देने पर उच्च आरएचडी और सीआरआई और परिपक्वता पर कम होने के कारण 17 नवंबर को बोई गई गेहूं की उपज में अधिक उपज हुई। समय पर बोई गई फसल के संबंध में, 20 दिनों की देरी से बुवाई के परिणामस्वरूप उपज में 25.8% की कमी आई, जबकि 20 दिनों की अग्रिम बुवाई से उपज में 7.7% की कमी आई।

ABSTRACT. The temperature and humidity factors, known as Relative temperature disparity (RTD) and relative humidity disparity (RHD) along with phenology and crop yield were found to be significantly influenced by various sowing environments and irrigation regimes. RTD and RHD ranged between 47.71 to 64.65 and 34.68 to 63.07 respectively in Ludhiana, Punjab. The field experiment was conducted during the *rabi* season of 2021-22 and 2022-23 at Ludhiana (30.90° N, 75.85 °E and 247m above MSL) in split plot design with four replications with three dates of sowing ((D_1= 27 October, D_2= 17 November, D_3= 8 December) and 3 irrigation regimes (I_1= 4 irrigations at CRI, Jointing, 50% Flowering, Soft dough stages, I_2= 3 irrigations at CRI, Flag leaf emergence, soft dough stage, I_3= 2 irrigations at Jointing, Soft dough stage). The crop sown on 27 October took the maximum number of days to attain physiological maturity, followed by crop sown on 17 November and 8 December. Wheat sown on 17 November (4257.7 kg/ha) along with I_1 irrigation level (4114.7 kg/ha) recorded the maximum yield. Higher RTD at vegetative stages (CRI, booting) and reproductive stage (milking) and lower RTD at maturity as well as higher RHD at booting and milking and lower at CRI and maturity resulted in higher yield in wheat sown on 17 November. With respect to timely sown crop, delay in sowing by 20 days resulted in decrease in the yield by 25.8 % while, advancement in sowing by 20 days indicated a decrement in the yield by 7.7 %.

Key words – Wheat, Sowing dates, Irrigation regimes, Relative temperature disparity, Relative humidity disparity.

1. Introduction

India currently holds the position of being the second largest wheat producer in the world. Global wheat trade has surpassed all other crops and the demand for country's wheat in the international markets is on the rise. In the fiscal year 2022-23, India exported 4,693,264.09 metric tons of wheat worth Rs. 11,826.90 crores (APEDA, 2023). The cultivation of wheat in India has historically been centred around the northern regions of the country. Punjab and Haryana have stood out as the prime contributors to the total wheat production. In spite of covering only 1.54% of the total geographical area of the country, Punjab plays a significant role in contributing approximately 43% of the country's wheat production (Kingra *et al*., 2016). Conversely, in recent years, there has been a notable variability in wheat productivity. According to the statistics provided by the Directorate of Economics and Statistics Department of Agriculture and Framers Welfare, the wheat production data for Punjab in 2020 was reported to be 17,615.600 Ton th, reflecting a decline from the previous figure of 18,261.800 Ton th in 2019 (CEIC, 2023). Year to year fluctuations in weather conditions pose a great threat to the growth, development and yield of crops significantly (Cheng *et al*., 2009; Singh *et al*., 2016).

As a winter crop, wheat is well suited to cooler conditions, making it more susceptible to temperature disparities, which can adversely impact the growth of the crop. The daily optimal average temperature range for ideal wheat growth is typically between 20°C to 25°C (Gahlot *et al*., 2020). If the temperature rises to 35 °C during the grain development stage, it might lead to heat stress (Deryng *et al*., 2014). According to Farooq *et al*. (2011) high temperatures are detrimental to wheat yield, particularly during flowering and grain filling stages. Extensive research has been conducted in recent decades to examine the effect of rising temperatures and heat stress on the wheat crop. According to Rao *et al*. (2015), wheat crop has more sensitivity towards minimum temperature, particularly during the post anthesis period. Increased minimum temperatures cause hike in respiration losses, thus, showing its negative effect on crop productivity (Singh *et al*., 2016). Continuous exposure to minimum temperatures of 12 °C for almost a week along with terminal heat stress during the post anthesis period, represent additional thermal limitations on the productivity (Hundal, 2007). Kingra (2016) also mentioned in her study that for each 1°C rise in temperature, there was a corresponding 10% decrease in wheat yield. So it is evident from various studies that the diurnal temperature fluctuations can have a significant impact on both the growth of wheat and its yield.

The majority of the studies have predominantly focused on weather variables like temperature, while overlooking the impact of other climate variables such as humidity etc. Humidity along with temperature can play a major role in deciding disease susceptibility, photosynthesis, grain development and its quality and can further mitigate heat stress (Zhang *et al*., 2017). Humidity disparities within the crop growing season can hinder the translocation of photosynthates to the sink (Pathak *et al*., 2019). Inconsistent humidity during grain development stages may result in poor grain formation and hence affect yield. High humidity during the harvesting period may increase the risk of high grain moisture affecting its grain quality. On the other hand, adequate humidity can help mitigate the impact of heat stress on wheat plants by preventing excessive transpiration (El Chami and Daccache, 2015). Temperature and humidity act as supporting elements in determining crop yield by impacting both heat and vapour fluxes (Shimoda *et al*. 2022). Thus, for better understanding of yield under climatic stress, it becomes crucial to investigate the impact of both humidity and temperature disparities on the wheat crop. In previous research, certain studies have incorporated a temperature variation factor called "relative temperature disparity" (RTD) to investigate its impact on the yield of wheat crop (Vexkull, 1967; Subrahmaniyan *et al*., 2004, Pal *et al*., 2013). The present study tried to incorporate a similar humidity variation factor called "relative humidity disparity" (RHD) to investigate its effect on wheat yield in combination with temperature disparity under different sowing environments and irrigation regimes. Altering sowing dates and saving up on irrigations would help mitigate the detrimental impacts of environmental stress.

Early sowing, due to the presence of high temperatures leads to the development of weak plants with inadequate root systems, whereas late planting undergoes low temperatures, resulting in poor tillering and stunted crop growth (Kingra, 2016). Moisture stress equally affects phenology and the metabolism of the crop. Stages like tillering or heading, booting, anthesis and milking have been reported to be highly susceptible to moisture availability (Sun *et al*., 2006). Given the weather disparities, an experiment was conducted to examine RTD, RHD and crop yield across diverse hydro-thermal conditions in central Punjab.

2. Materials and methods

The field experiment was conducted during the *rabi* season of 2021-22 and 2022-23 at the research farm of Department of Climate Change and Agricultural Meteorology, situated at Punjab Agricultural University (PAU), Ludhiana (30.90° N, 75.85 °E and 247m above

MSL), Punjab to investigate the disparities of temperature and humidity during the growth period of wheat (PBW 550) under three sowing environments (D_1= 27 October, D_2= 17 November, D_3= 8 December) and 3 irrigation regimes (I_1= 4 irrigations at CRI, Jointing, 50% Flowering, Soft dough stages, I_2= 3 irrigations at CRI, Flag leaf emergence, soft dough stage, I_3= 2 irrigations at Jointing, Soft dough stage). The study area is under semi-arid climate and receives an average annual rainfall of about 649 mm. For computing RTD and RHD, maximum and minimum temperature, morning and evening relative humidity were recorded from the agrometeorological observatory of PAU. Computations were made using the following formulae (Vexkull, 1967; Subrahmaniyan *et al.*, 2004);

$$RTD = \frac{T_{max} - T_{min}}{\text{Average } T_{max}} \times 100$$

$$RHD = \frac{RH_{max} - RH_{min}}{\text{Average } RH_{max}} \times 100$$

where,

T_{max} : Maximum temperature (°C)

T_{min} : Minimum temperature (°C)

RH_{max} : Morning relative humidity

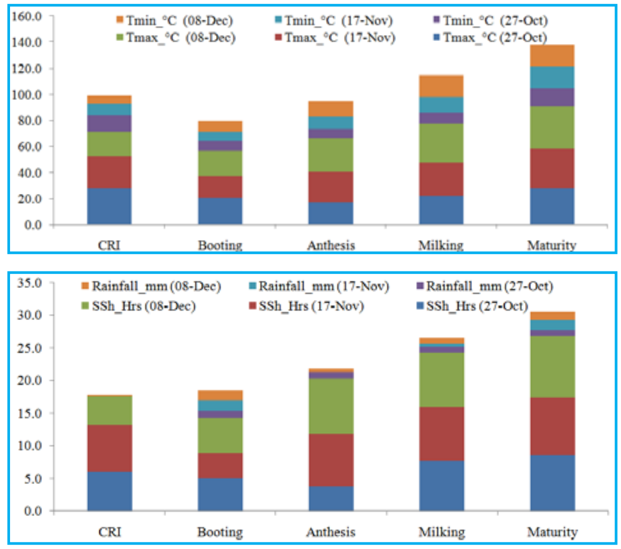
RH_{min} : Evening relative humidity

RTD and RHD were computed at different phenological stages, *viz.*, crown root initiation (CRI), booting (B), anthesis (A), milking (M) and physiological maturity (PM). The experimental data of two years (2021-22 and 2022-23) was pooled and was analyzed using ANOVA technique for a split plot design using R software.

3. Results and discussion

3.1. *Weather conditions at different phenophases of wheat*

The weather conditions [maximum temperature (°C), minimum temperature (°C), sunshine hour (Hrs) and rainfall (mm)] for wheat sown on 27 October, 17 November and 8 December showed distinct variations across different phenological stages (Fig. 1). During the Crown Root Initiation (CRI) stage, temperatures decreased progressively with later sowing dates, with T_{max} ranging from 27.69°C (27 October) to 18.70°C (8 December) and T_{min} from 12.73°C to 6.61°C. Sunshine



Figs. 1(a&b). Average meteorological conditions (maximum temperature, minimum temperature, sunshine hour and rainfall) prevailing at various phenophases

hours were highest for the 17 November sown wheat (7.24Hrs) and lowest for the 8 December sown wheat (4.57Hrs), with negligible rainfall across all sowing dates. At the booting stage, temperatures remained cooler for the 17 November sown wheat, while rainfall peaked for this date (1.61 mm), suggesting beneficial moisture conditions. During anthesis, the 8 December sown wheat experienced the highest T_{max} (25.88°C) and T_{min} (12.44°C), with significant sunshine hours (8.48Hrs) but minimal rainfall. For the milking stage, temperatures and sunshine hours were highest for the 8 December sown wheat, with moderate rainfall (0.87 mm). Finally, at maturity, the late sown wheat (8 December) faced the highest T_{max} (32.61°C) and T_{min} (16.75°C) with the most sunshine hours (9.49Hrs) and substantial rainfall (1.32 mm), indicating a need for careful management to avoid adverse effects from high temperature and moisture during critical grain development stages.

3.2. *Phenophases of wheat*

The results revealed that the number of days taken to attain various phenophases was significantly affected by sowing environments and irrigation regimes. The impact of sowing dates was found to be statistically significant at all the phenophases, whereas the significance of irrigation regimes was observed during CRI, milking stages and maturity. The study indicated that as sowing was delayed, the duration required to attain physiological maturity decreased. Progressive delay in sowing correlates with rising temperatures, resulting into higher accumulation of heat units, hence reduced crop growing period (Sattar

TABLE 1

The number of days taken to attain various phenophases under different sowing environments and irrigation regimes

Treatments	CRI	Booting	Anthesis	Milking	Maturity
Sowing dates					
D_1(27 October)	27 ± 0.49 [b]	75 ± 4.15[c]	97 ± 5.47[a]	114 ± 2.27[a]	153 ± 0.75 [a]
D_2 (17 November)	26 ± 1.30 [c]	81 ± 3.63[a]	97 ± 1.51[a]	113 ± 1.24[b]	139 ± 0.52 [b]
D_3 (8 December)	36 ± 1.08 [a]	78 ± 0.45[b]	92 ± 1.31[b]	104 ± 1.30 [c]	127 ± 0.00 [c]
F value	0.001 (S)	0.001 (S)	0.001 (S)	0.001 (S)	0.001 (S)
Irrigation regimes					
I_1 (CRI, JTNG, 50%ATH, SD)	30 ± 4.70[b]	78 ± 4.29 [a]	95 ± 3.88[a]	110 ± 4.81 [b]	140 ± 11.34 [ab]
I_2 (CRI, FL, SD)	30 ± 4.74[b]	78 ± 4.31 [a]	95 ± 4.22[a]	109 ± 5.52 [b]	139 ± 10.90 [b]
I_3 (JTNG, SD)	31 ± 4.52[a]	78 ± 4.37 [a]	96 ± 3.82[a]	111 ± 4.79 [a]	140 ± 11.45 [a]
F value	0.001 (S)	0.97 (NS)	0.290 (NS)	0.001 (S)	0.040 (S)

(CRI: crown root initiation, JTNG: jointing, 50%ATH: 50% anthesis, SD: soft dough, FL: flag leaf)

Lowercase letters (a, b, c) in the same column show results that are significantly different

S: Significant at F value <0.05, NS: Non significant at F value >0.05 (LSD test)

TABLE 2

Relative temperature disparity at various phenophases under different sowing environments and irrigation regimes

Treatments	CRI	Booting	Anthesis	Milking	Maturity
Sowing dates					
D_1(27 October)	54.21 ± 0.08 [c]	61.78 ± 2.00 [a]	56.36 ± 10.06 [ab]	59.23 ± 2.73 [a]	49.68 ± 0.75 [a]
D_2 (17 November)	64.65 ± 0.30 [a]	56.23 ± 0.43 [b]	60.29 ± 1.24 [a]	52.16 ± 0.33 [b]	45.44 ± 0.20 [c]
D_3 (8 December)	58.85 ± 0.37 [b]	56.99 ± 0.22 [b]	52.83 ± 0.23 [b]	43.79 ± 1.00 [c]	48.13 ± 0.32 [b]
F value	0.001 (S)	0.001 (S)	0.010 (S)	0.001 (S)	0.001 (S)
Irrigation regimes					
I_1 (CRI, JTNG, 50%ATH, SD)	59.35 ± 4.53 [a]	58.41 ± 2.83 [a]	56.62 ± 6.72 [a]	51.63 ± 6.96 [a]	47.75 ± 1.95 [a]
I_2 (CRI, FL, SD)	59.32 ± 4.58 [a]	58.41 ± 2.84 [a]	56.61 ± 6.73 [a]	52.15 ± 6.36 [a]	47.71 ± 1.88 [a]
I_3 (JTNG, SD)	59.04 ± 4.29 [b]	58.18 ± 2.80 [a]	56.26 ± 6.52 [a]	51.41 ± 7.05 [a]	47.80 ± 1.85 [a]
F value	0.001 (S)	0.86 (NS)	0.98 (NS)	0.56 (NS)	0.87 (NS)

(CRI: crown root initiation, JTNG: jointing, 50%ATH: 50% anthesis, SD: soft dough, FL: flag leaf)

Lowercase letters (a, b, c) in the same column show results that are significantly different

S: Significant at F value <0.05, NS: Non significant at F value >0.05 (LSD test)

et al., 2023). In delayed sowing, reduced growth period and advanced maturity was observed by Ram *et al*. (2017), Brar *et al*. (2022). Wheat sown on 27 October took 27 days to attain CRI, 75 days for booting, 97 days for anthesis and 114 and 153 for milking and maturity respectively, while crop sown on 17 November took 26 days for CRI, 81 days for booting, 97 days for anthesis, 113 days for milking and 139 days for maturity. With respect to 27 October sown crop, 8 December sown crop took 9 and 3 days more to attain CRI and booting respectively whereas, 5, 10 and 26 days less to attain anthesis, milking and maturity respectively. With respect

TABLE 3

Relative humidity disparity at various phenophases under different sowing environments and irrigation regimes

Treatments	CRI	Booting	Anthesis	Milking	Maturity
Sowing dates	61.03 ± 0.14 [a]	45.14 ± 2.98 [a]	33.23 ± 6.25 [b]	47.56 ± 4.70[b]	51.83 ± 1.05 [c]
D_1(27 October)	46.91 ± 0.86 [b]	34.68 ± 0.97 [c]	52.08 ± 2.17[a]	50.07 ± 0.69[a]	54.05 ± 0.72 [b]
D_2 (17 November)	43.51 ± 0.24 [c]	42.18 ± 0.35 [b]	52.12 ± 0.36[a]	50.11 ± 0.88[a]	63.07 ± 0.88 [a]
D_3 (8 December)	0.001 (S)	0.001 (S)	0.001 (S)	0.040 (S)	0.001 (S)
F value					
Irrigation regimes	50.58 ± 7.94 [a]	40.76 ± 4.80 [a]	46.02 ± 10.23[a]	48.86 ± 2.96[a]	56.18 ± 5.14 [b]
I_1 (CRI, JTNG, 50%ATH, SD)	50.56 ± 7.90 [a]	40.80 ± 4.82 [a]	46.04 ± 10.31[a]	49.43 ± 3.18[a]	55.91 ± 4.70 [b]
I_2 (CRI, FL, SD)	49.95 ± 8.31 [b]	40.44 ± 5.19 [a]	45.38 ± 9.56 [a]	49.45 ± 2.98[a]	56.86 ± 5.53 [a]
I_3 (JTNG, SD)	0.001 (S)	0.88 (NS)	0.86 (NS)	0.82 (NS)	0.001 (S)
F value					

(CRI: crown root initiation, JTNG: jointing, 50%ATH: 50% anthesis, SD: soft dough, FL: flag leaf)

Lowercase letters (a, b, c) in the same column show results that are significantly different

S: Significant at F value <0.05, NS: Non significant at F value >0.05 (LSD test)

to 17 November sown crop, it took 3 days more to attain CRI and 3, 5, 9 and 12 days less to attain booting, anthesis, milking and maturity respectively. The maximum number of days to attain milking and maturity was recorded by 27 October sown crop. In general, crops sown till the second fortnight of November took fewer days to attain vegetative stages and more number of days to attain reproductive stages, whereas in the case of wheat sown in the first fortnight of December, took more number of days to attain vegetative stages, while less number of days to attain reproductive stages (Table 1). This is because the vegetative stages of the late sown crop encountered lower temperatures. Results also revealed that there was a delay in attainment of various phenophases with a decrease in irrigation frequency. This can be accounted to the insufficient moisture during vegetative growth, consequently impacting the growth rate. In contrast to this, the number of days taken by I_1 and I_2 irrigation levels to attain various phenological stages was statistically at par because 1_2 irrigation level was provided with supplementary irrigation during its vegetative stage, resulting in enhancement in the time taken to attain various phenophases as that of I_1 level (Zhang *et al*., 2018).

3.3. *Relative temperature disparity (RTD)*

The sowing environments showed significant impact on RTD at all the phenophases whereas irrigation regimes showed significant efficiency at CRI, which is one of the critical and sensitive stages of the crop. Among phenology, the highest RTD value of 61.78 ± 2.00 was recorded during the booting stage, while the lowest RTD occurred at maturity with the crop sown on 27 October. Meanwhile, for the crop sown on 17 November, the highest RTD was observed at the CRI stage (64.65 ± 0.30), with the lowest RTD at maturity. Conversely, in the case of the 8December sown wheat crop, highest RTD was found at the CRI stage (58.85 ± 0.37), while the lowest RTD was observed during the milking stage. Among the irrigation regimes, it was observed that RTD decreased progressively from the CRI stage to physiological maturity (Table 2). The vegetative stages experienced high differences in diurnal temperatures whereas, due to encountering higher temperatures during the reproductive stages, the crop experienced low diurnal temperature difference. The effect of irrigation levels on RTD was observed to be non-significant; hence, followed the trend according to the thermal variation. The high value of RTD refers to a situation wherein there is a higher mean maximum temperature and relatively lower mean minimum temperature (Pal *et al*., 2013; Subrahmaniyan *et al*., 2004). The diminishing of RTD at reproductive stages and maturity was attributed to the high temperature exposure at later stages of the crop (Ouda *et al*., 2005).

3.4. *Relative Humidity disparity (RHD)*

Like RTD, relative humidity disparity (RHD) is also one of the most important indexes which influences the phenology and yield of the crop. Results revealed that

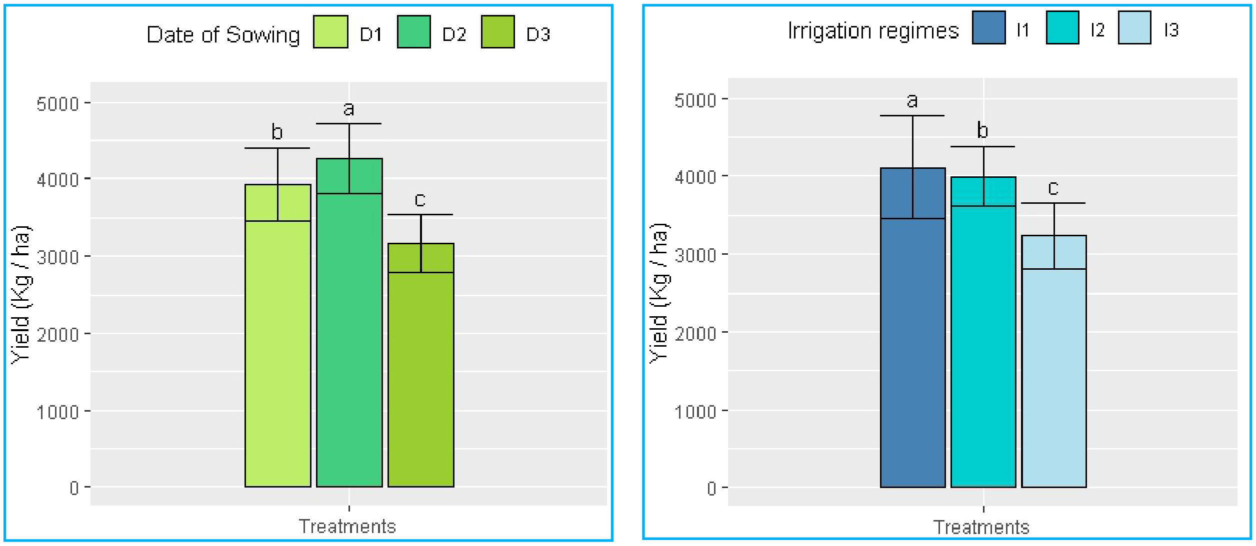


Fig. 2. Yield of wheat crop under different sowing environments and irrigation regimes

TABLE 4

ANOVA table for yield of wheat crop under different sowing environments and irrigation regimes

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Significance
Replication	3	3955	1318	0.454	0.717	
Date of Sowing (A)	2	7637921	3818961	1314.772	< 2e-16	S
Irrigation regimes (B)	2	5492926	2746463	945.538	< 2e-16	S
Interaction (AB)	4	670398	167599	57.7	5.79E-12	S
Residuals	24	69712	2905			

crops sown on different sowing dates showed significant impact on RHD at all the phenophases whereas, effect of irrigation regimes was significant at CRI stage and physiological maturity. Moreover, in respect to the crop sown on 27 October, the highest RHD was recorded during the CRI stage (61.03 ± 0.14), while the lowest RHD occurred during anthesis. Meanwhile, for the crop sown on 17 November and 8 December, the highest RHD was observed at physiological maturity, with the lowest RHD during booting stage. Among the irrigation regimes, RHD was observed to decrease from CRI to booting stage and then progressively increased till physiological maturity (Table 3). The absence of significant impact of irrigation levels on RHD during the booting, anthesis and milking stages suggests that humidity was the dominant factor influencing RHD during these periods. Initial stages are characterized by low temperature and high diurnal humidity, hence lower RHD. With the progression of the growth period, high temperatures and low diurnal humidity result in high RHD.

3.5. *Yield response to sowing time and irrigation regimes*

Sowing environments and irrigation regimes both had a significant impact on the yield of the wheat crop (Table 4). Timely sown crop (17 November) with an average seasonal temperature of 16.4 °C resulted in the highest yield of 4257.7 kg/ha. A delay in sowing by 20 days experienced an increase in average seasonal temperature (16.4 to 17 °C) which resulted in a decrease in yield by 25.8 %. Similarly, advancement in sowing by 20 days also indicated a decrement in the yield by 7.7 % due to increased average seasonal air temperature by 0.4 °C (Fig. 2). Hence, instead of delaying the sowing, crops may be sown early to avoid higher yield losses.

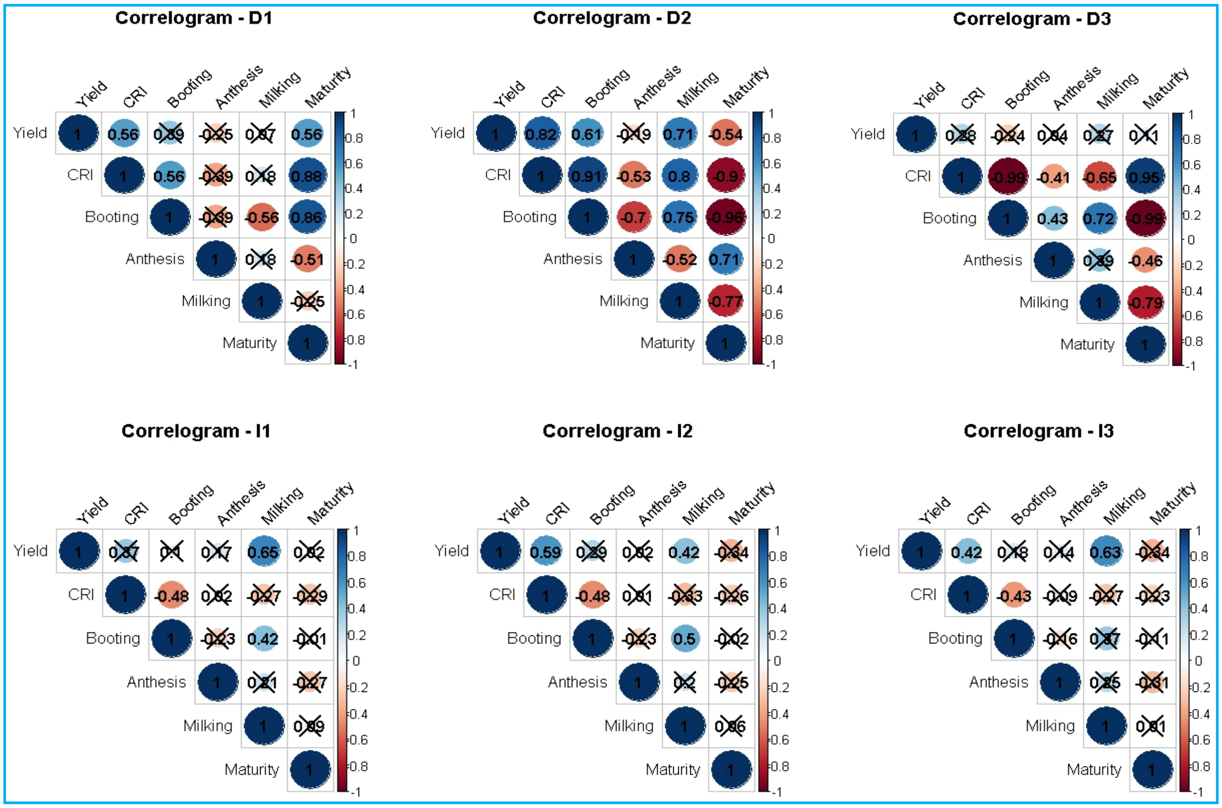


Fig. 3. Correlation heat map of RTD values and grain yield under different sowing environments (D_1, D_2, D_3), irrigation regimes (I_1, I_2, I_3)

These results were in accordance with Pal *et al.* (2012) where the 20 November sown wheat crop resulted in the highest yield with an average seasonal temperature of 16.3 °C while; 25 day delay in sowing caused a reduction in yield by 13 to 26.1 %. Hundal (2004) also observed that a 2°C increase in temperature resulted in a reduction in grain yield by 15-17 %. Similar findings of Kingra (2016) confirmed that with a 1 °C increase in temperature, there was a reduction in yield by 10% in Punjab conditions. Amongst irrigation regimes the highest grain yield was recorded at I_1 level, followed by I_2 and I_3 levels. A timely irrigated wheat crop utilizes optimum time to complete its growth period without undergoing any kind of moisture stress (Brar *et al*., 2022).

3.6. *Statistics between RTD, RHD, wheat phenology and yield under different treatments*

The stage wise RTD values were correlated under different sowing environments and irrigation regimes in which significant positive correlation was observed with CRI, milking and booting in the case of crop sown on 17November (Fig. 3). High RTD present during its vegetative stages (CRI, booting) and grain developing stage (milking) resulted in higher yield. The high RTD values present during these stages were observed to favour the grain yield (Subrahmaniyan *et al*., 2004). Moreover, negative correlation during maturity indicated that a decrease in RTD values during this phase would favour grain yield, because an increase in temperature from sowing to anthesis followed by decrease in temperature during ripening and maturity may facilitate effective translocation of photosynthates to the grains (Morachan *et al*., 1974).

Conversely, in the case of RHD, significant positive correlation was found with booting and milking while, significant negative correlation was found with CRI and physiological maturity for wheat sown on 17 November (Fig. 4). This implies that higher RHD at booting and milking and lower RHD at CRI and maturity would favour grain yield. This can be explained by the negative effects of high humidity combined with high temperatures during the early and late stages of crop development. Conversely, during the mid-stages, higher humidity would be beneficial for reproductive and grain development due to the presence of lower temperatures (Khan *et al*., 2020).Thus, in the case of the crop sown on 27 October, presence of a positive correlation at CRI, maturity and a negative correlation at anthesis was observed to be a

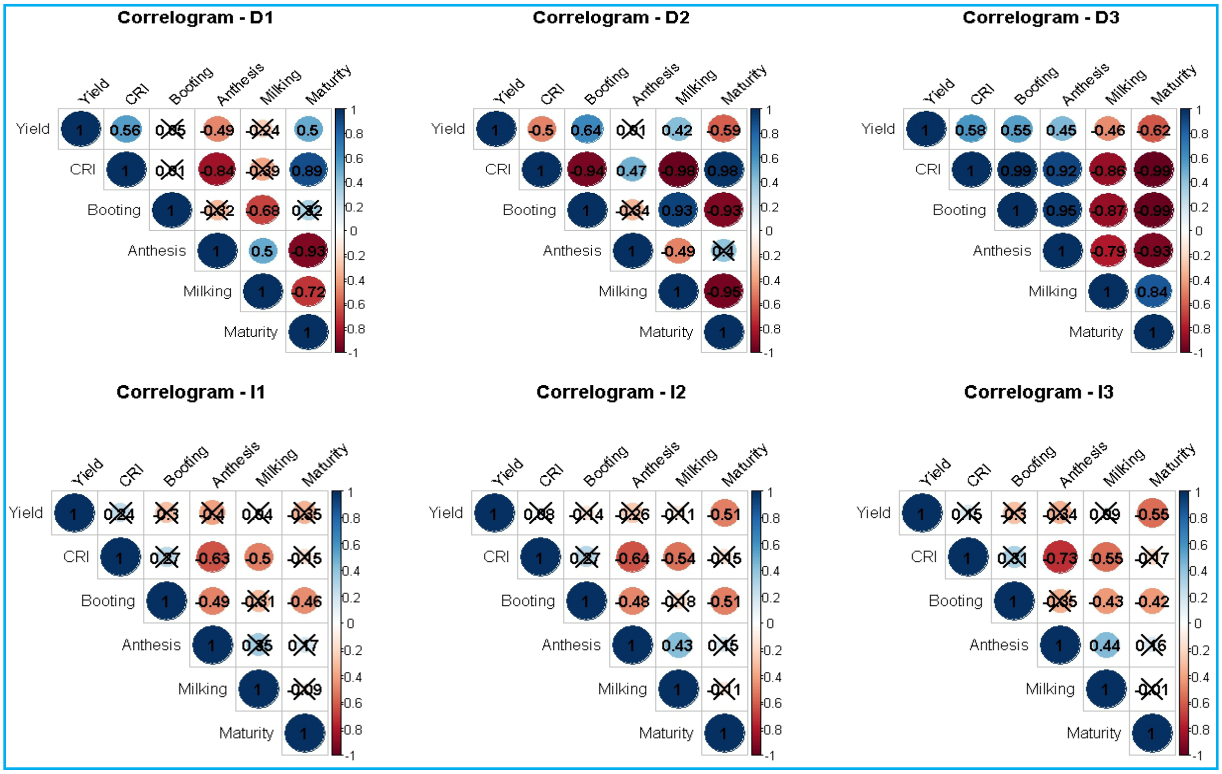


Fig. 4. Correlation heat map of RHD values and grain yield under different sowing environments (D_1, D_2, D_3), irrigation regimes (I_1, I_2, I_3)

possible factors resulting in decreased yield with respect to the 17 November sown crop. While, in the case of 8 December sown crop, results showed a positive correlation at CRI, booting and anthesis while negative correlation at the milking and maturity likely because the cooler and drier conditions of late sowing require adequate moisture to support vegetative and reproductive growth (Baloch *et al*., 2012). However, higher humidity during milking and maturity stages for this sowing date might negatively impact yield due to increased disease susceptibility and potential moisture stress during critical grain development phases (Barlow *et al*., 2015). The observed differences in grain yield responses to humidity at various growth stages for wheat sown on different dates can be attributed to the specific physiological needs and stress tolerance of the crop during its development. Mahajan *et al*., (2024) also reported that the humid weather from November to February is conducive to the optimal growth and development of the wheat crop.

In respect to irrigation regimes, I_1 level indicated significant positive correlation of RTD at milking stage only (Fig. 3). The grain filling period holds significant importance in achieving high yields as it is during this stage that the size and weight of kernels are determined (Barnard and Smith, 2012). Thus, high RTD at milking stage resulted in attaining higher yield at I_1 level. Moreover, significant positive correlation of RTD was found at CRI and milking stage, while, significant negative correlation of RHD at maturity with I_2 and I_3 irrigation levels (Fig. 3, Fig. 4). Though, presence of positive correlation at CRI in addition to milking stage would definitely prove beneficial in attaining better grain yield only when there is no antagonistic effect of negative correlation of RHD present at maturity. Summarizing, the study revealed that higher RTD at vegetative stages (CRI, booting) and reproductive stage (milking) and lower RTD at maturity as well as higher RHD at booting and milking and lower at CRI and maturity resulted in higher yield in different sowing environments. Similarly, in different irrigation regimes, higher RTD at CRI and milking and lower RHD at maturity would potentially favour improving wheat grain yield respectively.

4. Conclusion

This study critically evaluates the impact of differential hydro-thermal regimes on temperature and humidity disparities, as well as the phenology and wheat yield. The findings highlight significant differences in crop response to varied sowing environments and irrigation regimes. Crop sown until the second fortnight of November exhibited shorter duration to attain vegetative stages but longer duration to attain reproductive stages. In contrast, wheat sown in the first fortnight of December took more time to attain vegetative stages, while fewer days to attain reproductive stages. Furthermore, with the decrease in irrigation frequency, there was a delay in the attainment of various phenophases. With respect to timely sown crop, delay in sowing by 20 days resulted in decrease in the yield by 25.8 % while, advancement in sowing by 20 days indicated a decrement in the yield by 7.7 %. So, wheat sowing upto 17 November can be recommended for attaining higher yields. The results also revealed that the sowing environments showed a significant impact on RTD across all phenophases, while the irrigation regimes showed a significant impact on CRI, which is one of the critical and sensitive stages of the crop. Crop sown on 27 October and 17 November along with 8 December recorded maximum RTD at booting stage and CRI respectively. The effect of irrigation levels on RTD was observed to be non-significant, therefore, followed the trend according to the thermal variations during different phenophases. The crop sown on 27 October observed maximum RHD at CRI while, 17 November and 8 December sown crop recorded maximum RHD at physiological maturity. Irrigation regimes influenced RHD differently, with a decreasing trend from CRI to booting stage and a subsequent increase until physiological maturity. The key findings of the study suggest that higher RTD at vegetative stages (CRI, booting) and reproductive stage (milking) along with lower RTD at maturity, as well as higher RHD at booting and milking and lower at CRI and maturity can contribute to improved wheat yields under timely sowing. Moreover, under different irrigation regimes, higher RTD at CRI and milking along with lower RHD at maturity, have the potential to enhance wheat grain yields respectively. To further enhance our understanding of these complex dynamics, additional research employing various wheat cultivars and a broader range of management practices are essential. This will enable us to better understand how future weather disparities will impact wheat yields in the region, thereby reflecting strategies for sustainable crop production.

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