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Article

Defining and validating limits of meteorological parameters for high yield of wheat in Punjab, India

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Abstract: Wheat is a rabi season crop and is highly susceptible to abrupt increases/decreases in weather parameters. So, a study was conducted to compute the critical limits of temperature, relative humidity, and rainfall by analyzing meteorological and crop data (1999–00 to 2018–19) for six locations (Ballowal Saunkhari, Ludhiana, Patiala, Amritsar, Bathinda, and Faridkot) in Punjab. Amongst the 20 years, high, medium, and low yield years for each location were identified, and then meteorological data for crop growth stages, i.e., sowing-emergence (43–47 Standard Meteorological Week (SMW)), vegetative (48–02 SMW), anthesis (03–06 SMW), grain filling (07–11 SMW), and physiological maturity (12–15 SMW), were tabulated. The week-wise deviations of maximum/minimum temperature, maximum/minimum relative humidity, and rainfall from normal data of those 20 years under study were computed to derive their critical limits. Then these stage-wise critical limits were validated using the actual yields achieved during crop years 2019–20, 2020–21, and 2021–22. During a good crop year 2019–20, the upper and lower limits of the ranges accounted for high yields obtained at 03 locations and medium yields at the remaining 03 locations. During the crop year 2020–21, when the medium yield was obtained at all six locations, the major reason was the deviation of temperature above the upper range during the later grain-filling stage. On the other hand, during 2021–22, when low yield was reported at 03 locations and medium yield at remaining 03 locations, in addition to temperature deviations, heavy rainfall during SMW 1 and 2 (late vegetative stage) and hot and dry weather during SMW 10 and 11 (late grain development stage) were the major reasons. Hence it may be concluded that to get higher wheat productivity during vegetative growth, flowering, and grain filling, the maximum/minimum temperature ranges should be 16–22/4–9 ℃, 21–28/7–13 ℃ and 25–32/11–16 ℃, respectively; the maximum/minimum relative humidity ranges should be 85%–99%/39%–77%, 80%–92%/32%–66% and 75%–86%/31%–59%, respectively.

Keywords: wheat; optimum limits; temperature; relative humidity; yield; Punjab

1. Introduction

Wheat (*Triticum aestivum* L.) is an important crop from the food security perspective and is the second main source of the world's food energy and nutrition. During 2020–21, in India, wheat production of 109.5 MT was achieved from 31.1 Mha of cultivated area with a productivity of 3521 kg/ha [1]. While in Punjab state during 2020–21, wheat was cultivated over 35.30 lakh hectares of area with total production and productivity of 171.85 lakh tonnes and 48.68 q/ha, respectively [2].

Every crop thrives best under an optimum combination of weather factors. Sandhu et al. [3] reported that the optimum maximum temperatures during vegetative, anthesis, and grain-filling stages in central Punjab of India are 15–25, 18–24, and 23–34 ℃, respectively, and the temperature outside these ranges can diminish wheat

productivity. Hakim et al. [4] have concluded that temperatures below 10 ℃ and above 25 ℃ alter the phenology, growth, and development and, as a result, decrease the yield of wheat cultivars. Heat stress during the vegetative phase in November planted wheat hastened its growth rate, caused earlier jointing, and decreased its tillering period [5,6]. Studies [7,8] revealed that with an increase in temperature above normal, the phenological development of wheat crops is advanced. Sandhu et al. [3] reported that temperatures higher than 36 ℃ during the physiological maturity stage resulted in early maturity and reductions in yield.

With the increase in temperature by 1 ℃, wheat yield gets reduced by 10% under Punjab conditions [7,9]. Rao et al. [10] revealed that Indian wheat yields are becoming more sensitive to minimum temperature, particularly during the post-anthesis period. Exposure to a continual minimum temperature exceeding 12 ℃ for 6 days and terminal heat stress with a maximum temperature exceeding 34 ℃ for 7 days during the post-anthesis period are the other thermal limitations in attaining high productivity. Kumar et al. [11] found a critical decrease in soil microbial activity because of heat stress.

During the grain filling period, the maximum temperature of 25.6 ℃ and minimum temperature of 10.8 ℃ resulted in the highest yield of wheat [12]. Mahajan et al. [13] reported that the monthly maximum/minimum temperatures and sunshine duration during wheat season, i.e., during December, January, February, and March, in the range of 20–23/5–9 ℃ and 5–8 h, 17–20/3–8 ℃ and 4–6 h, 19–25/5–11 ℃ and 5–8 h, and 25–30/10–15 ℃ and 8–9 h, respectively, are optimum for high yield of wheat. Singh et al. [12] revealed that during January (crop season 2003–04), maximum temperature is negatively correlated and rainfall is positively correlated to wheat yield, while during February, maximum and minimum temperature are positively correlated and rainfall is negatively correlated to wheat yield. However, during March, minimum temperature is positively correlated and rainfall is negatively correlated to wheat yield in the south-west region of Punjab.

Wheat is a major rabi season crop cultivated in Punjab State, but its productivity is highly vulnerable to fluctuations in temperature and untimely heavy rainfall [14]. So, the current study was conducted to evaluate the critical ranges of temperature, relative humidity, and rainfall for obtaining a high yield of wheat in Punjab. The novelty of the present study was that these ranges were validated using the district-level wheat grain yield data during the last three years.

2. Materials and methods

2.1. Description of the study region

The Punjab state of India is located between 29°30′ N to 32°32′ N latitude, 73°55′ E to 76°50′ E longitude, and at an elevation of 180 to 300 m above sea level (a.m.s.l.). The agricultural production in the region is favored by a subtropical climate, fertile soils (loamy to sandy loam), and easy availability of underground and canal water. Rice, followed by wheat, is the predominant cropping system practiced on nearly 85% of the agricultural land area in the state. The productivity levels of both crops are very high as the farmers are cultivating the crops with the optimized “Package of Practices” as recommended by the Punjab Agricultural University in the state.

2.2. Data sets used for the study

Wheat is a major winter-season crop sown from the last week of October (early sown) to mid-December (late sown), with normally recommended sowing from 1st week up to 3rd week of November. The data for the phenology of wheat were collected from field experiments conducted under the "All India Co-ordinated Research Project on Agrometeorology" in the Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana. The stages of wheat were categorized into sowing-emergence (43–47 Standard Meteorological Week (SMW)), vegetative (48–02 SMW), anthesis (03–06 SMW), grain filling (07–11 SMW), and physiological maturity (12–15 SMW) by taking into consideration the early, normal, and late sowing conditions for wheat in the state.

The daily weather data i.e., maximum and minimum temperature, maximum and minimum relative humidity and rainfall (as per availability of data records) for six major wheat growing districts (**Figure 1**) falling in the northeastern sub-mountainous region (Ballowal Saunkhri: 30°07′ N 76°23′ E 355 a.m.s.l), central irrigated plains (Ludhiana: 30°56′ N 75°48′ E 247 a.m.s.l., Patiala: 30°20′ N, 76°28′ E 251 a.m.s.l. and Amritsar: 31°37′N, 74°53′E 231 a.m.s.l.) and southwestern plains (Bathinda: 30°12′ N, 74°57′ E 211 a.m.s.l. and Faridkot: 30°40′ N, 74°45′ E 204 a.m.s.l.) of Punjab from 1999–2000 upto 2021–22 were collected from meteorological observatories to compute the weekly and crop stage wise normal. The historical data on the yield of wheat for the six districts were collected from Statistical Abstracts, Punjab, from 199–2000 up to 2021–22. The wheat yield during these 23 years was categorized into high, medium, and low yields (**Table 1**).

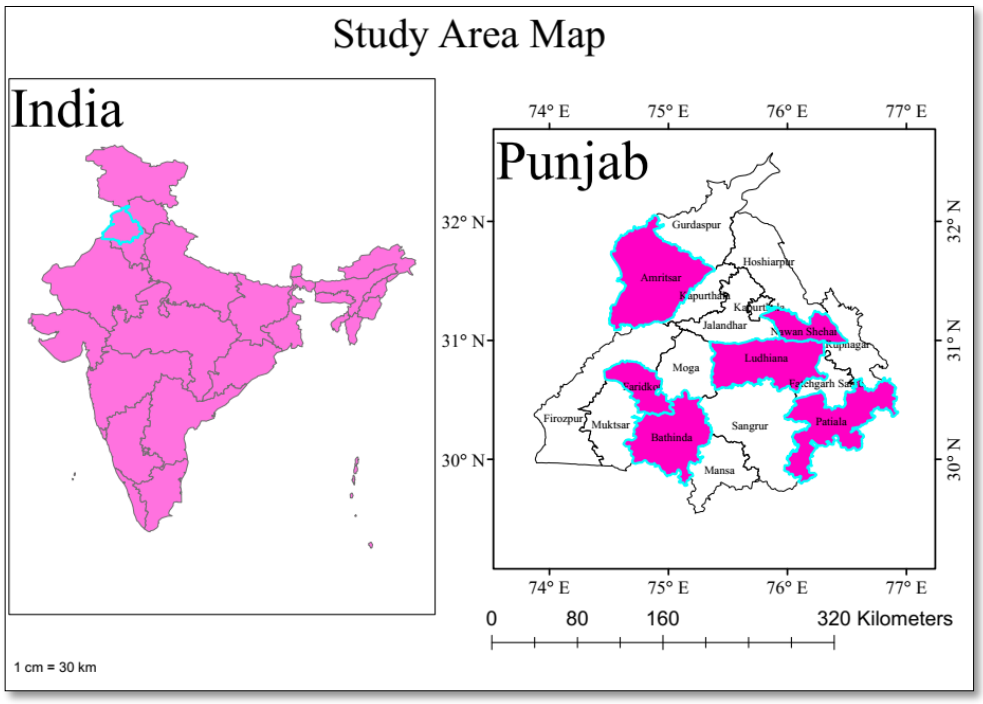


Figure 1. Map of the state with six districts under study.

Table 1. Location-wise yield (kg/ha) of wheat crop from 1999–00 to 2021–22.

Location	High yield year	Medium yield year	Low yield year
Ballowal Saunkhri	Yield > 5000 kg/ha	Yield 4000–5000 kg/ha	Yield < 4000 kg/ha
	2011–12,2017–18 and 2018–19, 2019–20	1999–00,2000–01,2001–02,2003–04,2004–05,2005–06,2006–07, 2007–08,2009–10, 2010–11,2012–13,2013–14,2015–16, 2016–17 and 2020–21	2002–03, 2008–09, 2014–15 and 2021–22
Ludhiana	Yield > 5100 kg/ha	Yield 4500–5100 kg/ha	Yield < 4500 kg/ha
	2000–01, 2011–12, 2013–14, 2017–18, 2018–19	1999–00, 2001–02, 2003–04, 2004–05, 2005–06, 2006–07, 2007–08, 2009–10, 2010–11, 2012–13, 2015–16, 2016–17, 2019–20, 2020–21 and 2021–22	2002–03, 2008–09 and 2014–15
Amritsar	Yield > 4850 kg/ha	Yield 4200–4850 kg/ha	Yield < 4200 kg/ha
	1999–00, 2011–12, 2013–14, 2016–17, 2017–18	2000–01, 2001–02, 2002–03, 2003–04, 2004–05, 2005–06, 2007–08, 2010–11, 2012–13, 2015–16, 2018–19, 2019–20, 2020–21 and 2021–22	2006–07, 2008–09, 2009–10, and 2014–15
Patiala	Yield > 5000 kg/ha	Yield 4500–5000 kg/ha	Yield < 4500 kg/ha
	2011–12,2016–17,2017–18 and 2018–19	1999–00, 2000–01, 2001–02, 2004–05, 2006–07, 2007–08, 2008–09,2009–10, 2010–11, 2012–13, 2013–14, 2015–16, 2019–20 and 2020–21	2002–03,2003–04,2005–06, 2014–15 and 2021–22
Bathinda	Yield > 5000 kg/ha	Yield 4000–5000 kg/ha	Yield < 4000 kg/ha
	2011–12, 2016–17, 2017–18, 2018–19 and 2019–20	1999–00, 2000–01, 2002–03, 2004–05, 2006–07, 2007–08, 2008–09, 2009–10, 2010–11, 2012–13, 2013–14, 2014–15, 2015–16, 2020–21 and 2021–22	2001–02, 2003–04, 2005–06
Faridkot	Yield > 5100 kg/ha	Yield 4200–5100 kg/ha	Yield < 4200 kg/ha
	2011–12, 2013–14, 2016–17, 2017–18, 2018–19 and 2019–20	1999–00, 2000–01, 2001–02, 2002–03, 2004–05, 2007–08, 2008–09, 2010–11, 2012–13, 2014–15, 2015–16, 2020–21 and 2021–22	2003–04, 2005–06, 2006–07, 2009–10

2.3. Computation of crop growth stage-wise "critical limits" of the meteorological parameters

The stage-wise actual ranges of meteorological parameters for wheat crops at six different districts/locations were computed from the meteorological data from 1999–2000 up to 2021–22. Then the deviations of weekly meteorological parameters for wheat crops were computed for high, medium, and low yield years from the weekly normal. Later, the "critical limits" of various meteorological parameters were calculated by comparing the ranges of respective parameters observed during the high yield years during the calibration period, i.e., 1999–2000 up to 2018–19 (20 years) for each district/location. Finally, by computing the mean and standard deviation for each stage-wise meteorological parameter, their respective lower and upper ranges for sowing emergence (43–47 Standard Meteorological Week (SMW)), vegetative (48–02 SMW), anthesis (03–06 SMW), grain filling (07–11 SMW), and physiological maturity (12–15 SMW) were derived for obtaining a high yield of wheat in Punjab state.

2.4. Validation of the critical limits

The actual yield of wheat for the six districts/locations obtained during three crop years, i.e., 2019–20, 2020–21, and 2021–22, was evaluated within the lower and upper limits of maximum (Tmax) and minimum (Tmin) temperature, maximum (RHmax) and minimum (RHmin) relative humidity and rainfall (RF).

3. Results and discussion

3.1. The weekly average range of meteorological parameters during the wheat crop season

The daily meteorological data were analyzed and cloned into their weekly averages, which were then categorized into wheat crop growth stages for six locations (**Tables 2** and **3**). The perusal of the data revealed that during sowing-emergence, vegetative, anthesis, grain filling, and physiological maturity stages, the weekly maximum/minimum temperature ranged between 25.8 to 31.8/9.2 to 18.4 ℃, 16.0 to 25.6/3.3 to 10.5 ℃, 17.0 to 21.8/3.8 to 9.5 ℃, 21.3 to 28.1/8.2 to 15.7 ℃ and 28.7 to 36.1/12.9 to 21.7 ℃, respectively. Similarly, the weekly maximum/minimum relative humidity ranged between 58%–96%/24%–66% in the state. The average weekly rainfall during the wheat season was~10–15 mm during anthesis and start grain filling stages.

Table 2. Weekly average maximum and minimum temperature (℃) during the wheat growing season during the past two decades (1999–00 to 2018–19) in Punjab.

Growth stage	Week Number (#)	Ballowal Saunkhri		Ludhiana		Amritsar		Patiala		Bathinda		Faridkot	
		Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
Sowing Emergence	43	30.7	14.4	30.7	15.5	30.5	14.9	31.4	15.9	31.8	17.8	30.5	18.4
	44	29.9	13.4	29.5	14.7	29.7	13.6	30.4	14.9	30.8	16.7	29.5	16.9
	45	28.7	12.2	28.1	13.1	28.2	11.7	29.4	13.4	29.3	14.6	28.1	15.5
	46	27.3	10.9	26.6	11.6	27.0	9.8	28.2	12.1	27.8	13.3	26.7	13.6
	47	26.3	9.2	25.9	9.9	25.8	8.3	27.0	10.4	26.8	12.1	26.3	11.9
Vegetative	48	25.3	8.4	24.2	8.8	24.4	6.8	25.6	9.5	25.5	10.8	24.8	10.5
	49	24.5	7.5	23.3	7.9	23.5	5.7	24.3	8.6	24.1	10.0	23.7	10.2
	50	22.3	7.2	20.6	7.9	21.2	5.4	22.0	8.6	21.7	8.5	20.9	8.7
	51	21.6	6.2	19.6	6.7	19.8	4.4	20.8	7.5	20.5	8.1	20.0	7.7
	52	20.1	4.8	18.1	5.3	18.5	3.3	19.2	6.0	19.0	6.4	19.3	6.6
	01	18.2	5.2	16.0	6.2	16.0	3.7	16.9	6.3	16.3	5.2	16.2	6.8
	02	18.3	4.8	17.2	7.0	16.7	3.5	18.0	6.1	17.4	4.6	16.5	6.0
Anthesis	03	18.5	5.4	17.0	7.9	17.0	4.1	18.4	6.9	17.1	5.7	16.9	8.2
	04	19.8	5.5	18.3	7.4	18.1	3.8	19.1	6.8	18.8	5.9	17.9	8.4
	05	21.4	6.4	20.0	7.9	20.0	4.9	21.1	7.5	20.4	6.3	19.5	8.9
	06	21.8	7.6	20.2	8.0	20.4	5.9	21.5	8.2	20.5	7.0	19.6	9.5
Grain filling	07	23.0	8.6	21.5	8.7	21.6	7.2	22.6	9.5	21.9	8.2	21.3	10.7
	08	24.5	9.8	23.0	9.6	22.7	7.8	24.3	10.8	23.4	9.3	22.9	11.9
	09	25.5	10.2	24.1	10.1	23.7	8.4	25.3	12.0	24.7	10.0	23.7	12.8
	10	27.0	11.1	25.6	11.5	25.3	9.5	26.9	12.2	26.3	10.7	25.0	14.0
	11	28.1	12.2	27.3	12.5	26.7	10.8	27.8	13.5	27.9	12.0	26.7	15.7
Physiological Maturity	12	30.1	14.2	29.4	13.8	28.7	12.9	30.4	15.4	30.0	13.9	28.5	17.6
	13	31.6	15.1	31.3	14.6	30.6	14.2	32.0	16.5	31.9	15.1	30.6	19.2
	14	33.4	16.0	33.1	15.5	32.2	14.8	34.0	17.5	33.6	16.3	32.8	20.3
	15	35.1	17.2	35.4	16.8	34.5	16.4	35.9	18.9	36.1	17.7	35.3	21.7

Table 3. Weekly average Maximum (RHmax) and minimum (RHmin) relative humidity (%) and rainfall (RF, mm) during the wheat growing season during the past two decades (1999–00 to 2018–19) in Punjab.

Growth stage	Week No. (#)	Ballowal Saunkhri			Ludhiana			Amritsar	Patiala	Bathinda			Faridkot
		RHmax	RHmin	RF	RHmax	RHmin	RF	RF	RF	RHmax	RHmin	RF	RF
Sowing-Emergence	43	82.0	44.2	2.2	89.7	37.7	1.20	0.7	0.2	81.1	33.7	2.1	0.10
	44	87.6	46.6	1.1	91.2	41.2	0.70	0.1	0.1	84.4	36.6	1.1	0.10
	45	85.0	45.1	0.6	90.8	38.4	0.29	3.8	0.9	86.4	38.6	1.2	1.06
	46	84.7	44.2	1.1	92.0	37.7	0.84	2.3	0.1	87.5	37.3	2.4	0.86
	47	86.8	43.3	0.3	91.8	37.0	0.69	0.1	0.8	87.6	33.7	6.8	0.74
Vegetative	48	87.0	42.3	0.3	93.5	39.4	1.81	1.5	3.0	87.6	35.2	3.2	0.44
	49	87.2	44.9	1.4	94.2	43.0	0.90	1.2	0.6	89.3	34.3	2.6	0.21
	50	90.4	51.5	7.8	94.6	52.8	6.90	5.6	6.4	91.2	44.1	1.7	2.26
	51	92.1	53.7	2.0	96.1	56.3	0.65	1.3	0.1	91.4	49.2	2.2	0.19
	52	92.8	54.9	3.9	96.4	58.2	1.79	1.6	1.1	92.6	51.3	4.8	0.38
	01	93.9	66.8	6.3	96.1	66.6	3.79	3.5	5.6	94.0	61.5	3.5	1.17
	02	93.9	59.1	4.9	95.7	61.2	3.35	3.8	2.2	92.0	52.2	1.0	1.17
Anthesis	03	93.9	60.2	9.5	95.7	65.5	6.66	7.2	4.6	92.2	57.9	2.4	3.66
	04	93.1	55.4	13.4	95.9	58.3	12.89	10.9	10.7	91.0	54.5	5.9	6.48
	05	89.0	52.6	6.0	95.6	55.4	5.08	9.3	5.9	90.9	51.7	3.0	5.25
	06	89.7	52.1	15.3	94.2	56.3	12.15	9.9	10.3	90.8	52.3	8.3	8.88
Grain filling	07	86.1	52.3	13.4	93.6	55.7	12.99	11.2	7.8	89.5	51.7	3.2	4.00
	08	85.6	49.3	5.9	93.6	54.2	5.66	13.0	4.4	88.7	50.8	4.9	7.45
	09	82.1	46.5	10.2	92.3	50.6	5.13	7.7	9.6	88.0	48.3	4.1	5.88
	10	78.6	44.4	5.8	90.7	47.3	5.43	5.3	6.5	87.7	45.4	2.4	2.87
	11	78.0	46.6	10.0	91.6	45.5	6.23	16.5	6.8	87.2	43.8	6.3	9.61
Physiological maturity	12	72.8	41.1	6.2	87.8	40.9	5.17	4.9	2.3	83.2	39.4	2.8	4.82
	13	70.6	39.3	3.5	85.3	36.4	2.16	2.4	3.7	80.1	35.1	2.1	1.89
	14	61.8	34.9	6.9	76.9	29.2	4.92	3.9	3.5	74.8	33.3	2.1	3.76
	15	58.4	30.5	2.8	68.4	24.3	3.57	3.0	4.1	68.7	28.0	1.8	2.40

3.2. Comparison of the range of normal and optimum meteorological parameters during wheat crop season

The normal weekly meteorological data for six locations was then compared with the respective weeks (43–15 SMW) data, and their deviations from normal were calculated for each category (high, medium, and low) of wheat yield over the 20 years. Thereafter, the range of optimum meteorological parameters for each stage of the wheat crop was derived from the actual data recorded during the high-yield years at each respective location (**Tables 4** and **5**). The perusal of the data revealed that at six locations during sowing-emergence, vegetative, anthesis, grain filling, and physiological maturity stages (**Tables 6–11),** the optimum weekly maximum/minimum temperature ranged between 21.7 to 33.4/8.0 to 21.4 ℃, 14.5 to 27.1/−0.7 to 13.4 ℃, 13.8 to 22.5/2.6 to 10.6 ℃, 19.2 to 31.2/3.4 to 14.9 ℃ and 23.3 to 33.4/8.1 to 17.3 ℃ respectively; optimum weekly maximum/minimum relative humidity ranged between 75% to 98%/29% to 68%, 78% to 100%/25% to 83%, 81%

to 100%/34% to 78%, 75% to 96%/28% to 73%, and 71% to 87%/27% to 67%, respectively; and maximum rainfall varied between 1 to 23, 6 to 46, 11 to 89, 9 to 52, and 14 to 60 mm, respectively.

Table 4. Stage-wise range of average meteorological parameters during the wheat growing season over the past two decades (1999–00 to 2018–19) in Punjab.

Crop Growth Stage		Temperature (℃)		Rainfall (mm)	Relative Humidity (%)	
		Maximum	Minimum		Maximum	Minimum
Ballowal Saunkhri						
Sowing emergence	Normal	26.3–30.7	9.2–14.4	0.3–2.2	82.0–87.6	43.3–46.6
	Optimum	24.5–28.7	8.2–15.2	0.0–9.6	85.0–96.1	39.8–68.4
Vegetative	Normal	18.3–25.3	4.8–8.4	0.3–7.8	87.0–93.9	42.3–66.8
	Optimum	17.4–20.9	2.9–11.0	0.0–34.4	84.0–98.0	43.5–81.7
Anthesis	Normal	18.5–21.8	5.4–7.6	6.0–15.3	89.0–93.9	52.1–60.2
	Optimum	15.1–22.5	4.5–6.9	0.0–89.8	84.2–98.4	43.9–78.3
Grain filling	Normal	23.0–28.1	8.6–12.2	5.8–13.4	78.0–86.1	44.4–52.3
	Optimum	20.4–29.7	6.8–13.4	0.0–52.0	82.5–90.0	37.9–73.1
Physiological Maturity	Normal	30.1–35.1	14.2–17.2	2.8–6.9	58.4–72.8	30.5–41.1
	Optimum	26.3–35.5	13.3–19.0	0.0–68.4	64.9–84.4	29.4–60.9
Ludhiana						
Sowing emergence	Normal	25.9–30.7	9.9–15.5	0.3–1.2	89.7–92.0	37.0–41.2
	Optimum	22.3–33.4	8.1–18.4	0.0–12.0	83.1–98.4	29.0–60.3
Vegetative	Normal	16.0–24.2	5.3–8.8	0.7–6.9	93.5–96.4	39.4–66.6
	Optimum	15.1–22.0	3.1–12.2	0.0–24.3	86.9–100	39.1–83.4
Anthesis	Normal	17.0–20.2	7.4–8.0	5.1–12.9	94.2–95.9	55.4–65.5
	Optimum	15.5–21.9	3.2–10.0	0.0–68.4	89.0–100	40.2–73.4
Grain filling	Normal	21.5–27.3	8.7–12.5	5.1–13.0	90.7–93.6	45.5–55.7
	Optimum	20.0–30.0	5.6–11.4	0.0–16.0	82.6–96.0	29.5–61.0
Physiological Maturity	Normal	29.4–35.4	13.8–16.8	2.2–5.2	68.4–87.8	24.3–40.9
	Optimum	28.8–35.2	10.7–21.7	0.0–32.6	74.2–77.4	31.4–43.5
Bathinda						
Sowing emergence	Normal	26.8–31.8	12.1–17.8	1.1–6.8	81.1–87.6	33.7–38.6
	Optimum	21.9–30.1	10.3–18.7	0.0–14.0	75.0–97.8	28.8–66.7
Vegetative	Normal	16.3–25.5	4.6–10.8	1.0–4.8	87.6–94.0	34.3–61.5
	Optimum	17.1–21.6	0.4–9.3	0.0–6.0	77.7–96.2	25.0–66.0
Anthesis	Normal	17.1–20.5	5.7–7.0	2.4–8.3	90.8–92.2	51.7–57.9
	Optimum	13.8–22.4	4.4–8.3	0.0–10.8	80.8–97.8	34.2–77.8
Grain filling	Normal	21.9–27.9	8.2–12.0	2.4–6.3	87.2–89.5	43.8–51.7
	Optimum	20.3–26.9	8.3–14.9	0.0–14.4	74.6–90.0	28.7–62.8
Physiological Maturity	Normal	30.0–36.1	13.9–17.7	1.8–2.8	68.7–83.2	28.0–39.4
	Optimum	31.7–35.4	15.1–19.8	0.0–15.3	68.2–79.7	26.1–50.0

Table 5. Stage wise range of average meteorological parameters during wheat growing season over past two decades (1999–00 to 2018–19) in Punjab.

Crop Growth Stage		Temperature (°C)		Rainfall (mm)
		Maximum	Minimum	
Amritsar				
Sowing emergence	Normal	25.8–30.5	8.3–14.9	0.1–3.8
	Optimum	25.1–24.4	8.0–11.4	0.0–23.1
Vegetative	Normal	16.0–24.4	3.3–6.8	1.2–5.6
	Optimum	14.5–21.1	–0.7–9.2	0.0–32.8
Anthesis	Normal	17.0–20.4	3.8–5.9	7.2–10.9
	Optimum	18.2–19.8	2.6–8.8	0.0–51.0
Grain filling	Normal	21.6–26.7	7.2–10.8	5.3–16.5
	Optimum	22.7–25.7	3.4–9.6	0.0–36.9
Physiological Maturity	Normal	28.7–34.5	12.9–16.4	3.0–4.9
	Optimum	28.0–34.0	12.7–17.3	0.0–30.4
Patiala				
Sowing emergence	Normal	27.0–31.4	10.4–15.9	0.1–0.9
	Optimum	25.0–32.7	13.5–14.3	0.0–0.8
Vegetative	Normal	16.9–25.6	6.0–9.5	0.1–6.4
	Optimum	19.2–22.6	5.1–13.4	0.0–46.0
Anthesis	Normal	18.4–21.5	6.8–8.2	4.6–10.7
	Optimum	16.0–23.2	6.4–10.6	0.0–50.1
Grain filling	Normal	22.6–27.8	9.5–13.5	4.4–9.6
	Optimum	23.8–31.2	9.8–14.4	0.0–34.2
Physiological Maturity	Normal	30.4–35.9	15.4–18.9	2.3–4.1
	Optimum	33.2–35.7	17.4–19.8	0.0–20.4
Faridkot				
Sowing– emergence	Normal	26.3–30.5	11.9–18.4	0.1–1.1
	Optimum	21.7–33.1	8.9–21.4	0.0–11.0
Vegetative	Normal	16.2–24.8	6.0–10.5	0.2–2.3
	Optimum	17.2–27.1	4.7–10.2	0.0–10.0
Anthesis	Normal	16.9–19.6	8.2–9.5	3.7–8.9
	Optimum	14.4–22.0	4.1–9.8	0.0–12.0
Grain filling	Normal	21.3–26.7	10.7–15.7	2.9–9.6
	Optimum	19.2–25.0	9.4–13.4	0.0–9.3
Physiological Maturity	Normal	28.5–35.3	17.6–21.7	1.9–4.8
	Optimum	27.9–35.6	16.2–21.0	0.0–24.0

Table 6. Comparison of optimum meteorological parameters during the Sowing Emergence stage for the wheat crop at different locations in Punjab.

Stations	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RHmax (%)	RHmin (%)
Ballowal Saunkhari	24.5–28.7	8.2–15.2	0.0–9.6	85.0–96.1	39.8–68.4
Ludhiana	22.3–33.4	8.1–18.4	0.0–12.0	83.1–98.4	29.0–60.3
Amritsar	25.1–24.4	8.0–11.4	0.0–23.1	-	-
Patiala	25.0–32.7	13.5–14.3	0.0–0.8	-	-
Bathinda	21.9–30.1	10.3–18.7	0.0–14.0	75.0–97.8	28.8–66.7
Faridkot	21.7–33.1	8.9–21.4	0.0–11.0	-	-
Average	23.4–30.4	10.4–16.0	0.0–11.7	81.0–97.4	32.5–65.1

Table 7. Comparison of optimum meteorological parameters during the Vegetative stage for the wheat crop at different locations in Punjab.

Stations	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RHmax (%)	RHmin (%)
Ballowal Saunkhari	17.4–20.9	2.9–11.0	0.0–34.4	84.0–98.0	43.5–81.7
Ludhiana	15.1–22.0	3.1–12.2	0.0–24.3	86.9–100	39.1–83.4
Amritsar	14.5–21.1	−0.7–9.2	0.0–32.8	-	-
Patiala	19.2–22.6	5.1–13.4	0.0–46.0	-	-
Bathinda	17.1–21.6	0.4–9.3	0.0–6.0	77.7–96.2	25.0–66.0
Faridkot	17.2–27.1	4.7–10.2	0.0–10.0	-	-
Average	16.7–22.5	2.6–10.8	0.0–25.6	82.9–98.0	35.9–77.0

Table 8. Comparison of optimum meteorological parameters during the Anthesis stage for the wheat crop at different locations in Punjab.

Stations	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RHmax (%)	RHmin (%)
Ballowal Saunkhari	15.1–22.5	4.5–6.9	0.0–89.8	84.2–98.4	43.9–78.3
Ludhiana	15.5–21.9	3.2–10.0	0.0–68.4	89.0–100	40.2–73.4
Amritsar	18.2–19.8	2.6–8.8	0.0–51.0	-	-
Patiala	16.0–23.2	6.4–10.6	0.0–50.1	-	-
Bathinda	13.8–22.4	4.4–8.3	0.0–10.8	80.8–97.8	34.2–77.8
Faridkot	14.4–22.0	4.1–9.8	0.0–12.0	-	-
Average	15.5–22.0	4.2–9.1	0.0–47.0	84.7–98.7	39.4–76.5

Table 9. Comparison of optimum meteorological parameters during the Grain development stage for the wheat crop at different locations in Punjab.

Stations	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RHmax (%)	RHmin (%)
Ballowal Saunkhari	20.4–29.7	6.8–13.4	0.0–52.0	82.5–90.0	37.9–73.1
Ludhiana	20.0–30.0	5.6–11.4	0.0–16.0	82.6–96.0	29.5–61.0
Amritsar	22.7–25.7	3.4–9.6	0.0–36.9	-	-
Patiala	23.8–31.2	9.8–14.4	0.0–34.2	-	-
Bathinda	20.3–26.9	8.3–14.9	0.0–14.4	74.6–90.0	28.7–62.8
Faridkot	19.2–25.0	9.4–13.4	0.0–9.3	-	-
Average	21.1–28.1	7.2–12.8	0.0–27.1	79.9–92.0	32.0–65.6

Table 10. Comparison of optimum meteorological parameters during the Physiological Maturity stage for the wheat crop at different locations in Punjab.

Stations	Tmax (℃)	Tmin (℃)	Rainfall (mm)	RHmax (%)	RHmin (%)
Ballowal Saunkhari	23.3–32.6	10.1–16.2	0.0–60.2	73.7–87.2	33.6–67.0
Ludhiana	24.4–32.6	8.1–16.5	0.0–24.3	78.4–86.7	30.4–52.2
Amritsar	25.3–29.8	8.0–13.4	0.0–33.6	-	-
Patiala	28.5–33.4	13.6–17.1	0.0–27.3	-	-
Bathinda	26.0–31.1	11.7–17.3	0.0–14.8	71.4–84.8	27.4–56.4
Faridkot	23.5–30.3	12.8–17.2	0.0–16.6	-	-
Average	25.2–31.6	10.7–16.3	0.0–29.5	74.5–86.2	30.5–58.5

Table 11. Comparison of optimum meteorological parameters during different crop stages stage for the wheat crop in Punjab.

Stages	Tmax (℃)	Tmin (℃)	Rainfall (mm)	RHmax (%)	RHmin (%)
Sowing–Emergence	23.4–30.4	10.4–16.0	0.0–11.7	81.0–97.4	32.5–65.1
Vegetative	16.7–22.5	2.6–10.8	0.0–25.6	82.9–98.0	35.9–77.0
Flowering	15.5–22.0	4.2–9.1	0.0–47.0	84.7–98.7	39.4–76.5
Grain development	21.1–28.1	7.2–12.8	0.0–27.1	79.9–92.0	32.0–65.6
Physiological maturity	25.2–31.6	10.7–16.3	0.0–29.5	74.5–86.2	30.5–58.5

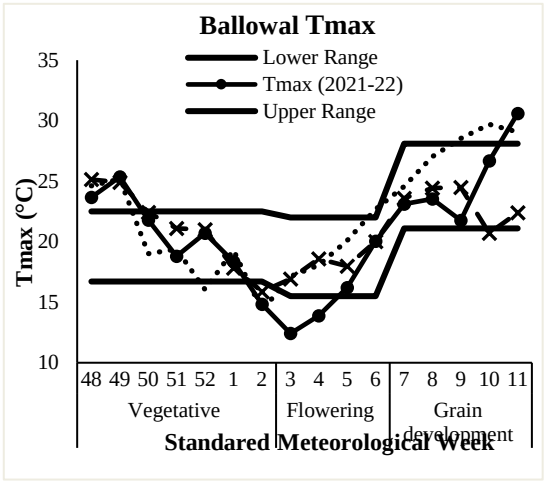
The range of optimum meteorological parameters for three locations during the high-yield years was analyzed by deriving their mean and standard deviations, and the optimized ranges of each parameter were derived. The data given in **Table 12** revealed that in Punjab state, for achieving a high yield of wheat, the maximum/minimum temperature, maximum/minimum relative humidity, and rainfall, respectively, should be within the range of 16 to 22/3 to 11 ℃, 82% to 98%/36% to 77%, and up to 26 mm during the vegetative period; 15 to 22/4 to 9 ℃, 85% to 99%/40% to 76%, and up to 47 mm during the flowering growth period; and 21 to 28/7 to 13 ℃, 80% to 92%/32% to 65%, and up to 27 mm during the grain development period.

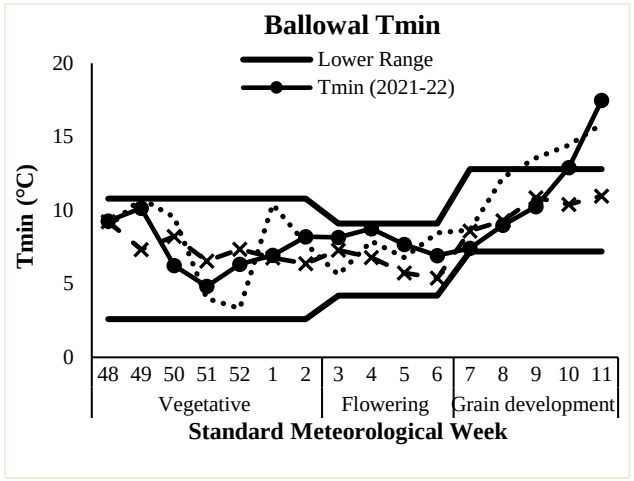
Table 12. Values of weekly parameters for higher productivity of wheat in Punjab.

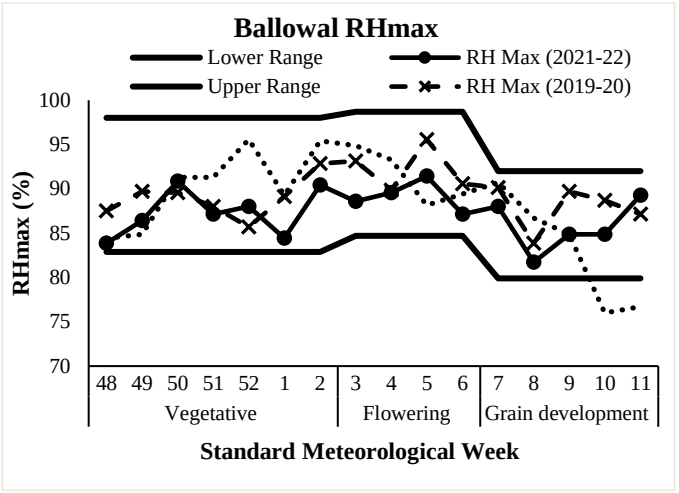
Crop Stage	Temperature (℃)		Rainfall (mm)	Relative Humidity (%)	
	Maximum	Minimum		Maximum	Minimum
Vegetative	16–22	3–11	26	82–98	36–77
Flowering	15–22	4–9	47	85–99	40–76
Grain development	21–28	7–13	27	80–92	32–65

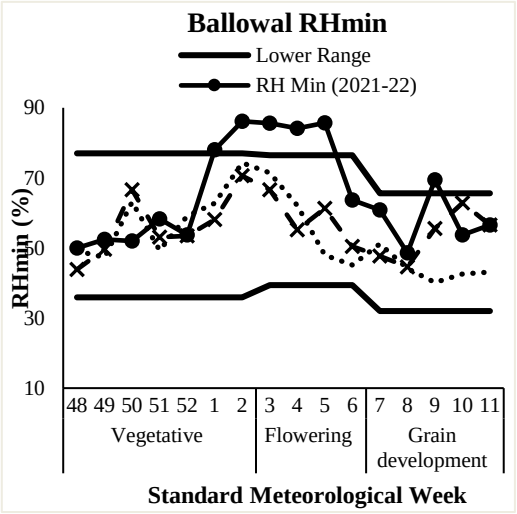
3.3. Validation of upper and lower range of meteorological parameters

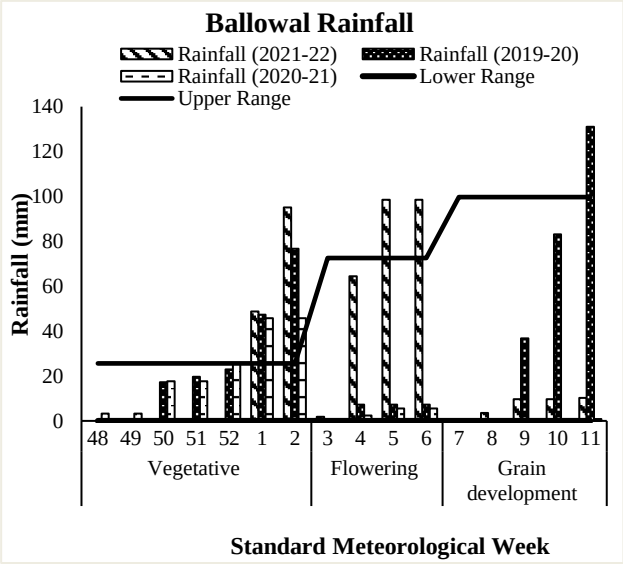
The validation of the upper and lower range of meteorological parameters was conducted for three years (2019–20, 2020–21, and 2021–22) using the yield data for the six locations collected from statistical abstracts. The validation results revealed that low, medium, and high yields of wheat achieved at each location could be explained by the outlaying of temperature, humidity, and rainfall within the lower and upper range of the meteorological parameters (**Figures 2–7**).











High Yield—5078 kg/ha (2019–20)

1. Tmax- Mostly remained within the optimum ranges and was slightly above during start of the season.
2. Tmin- Remained within the optimum ranges.
3. RHmax- Remained within the optimum ranges.
4. RHmin- Mostly remained within the optimum ranges.
5. Rainfall- The rainfall received during vegetative and grain development stage was beneficial to get higher yield.

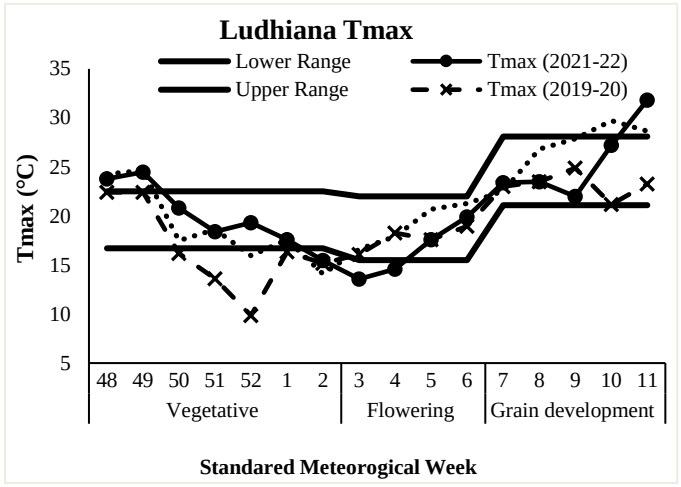
Medium Yield—4935 kg/ha (2020–21)

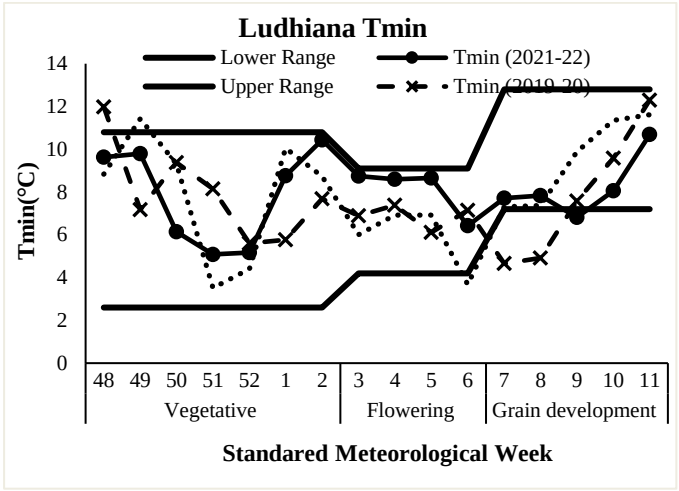
1. Tmax- Mostly remained within the optimum ranges. It was above upper range during vegetative and grain development.
2. Tmin- Remained within the optimum ranges. Tmin was above the upper range during grain filling stage.
3. RHmax- Remained within the optimum ranges except lower during grain development.
4. RHmin- Mostly remained within the optimum ranges.
5. Rainfall- Received during vegetative stage. Dry phase during flowering and grain development.

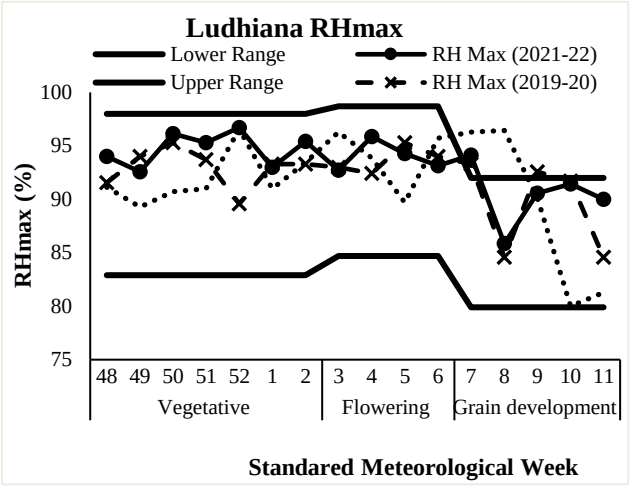
Low Yield—3862 kg/ha (2021–22)

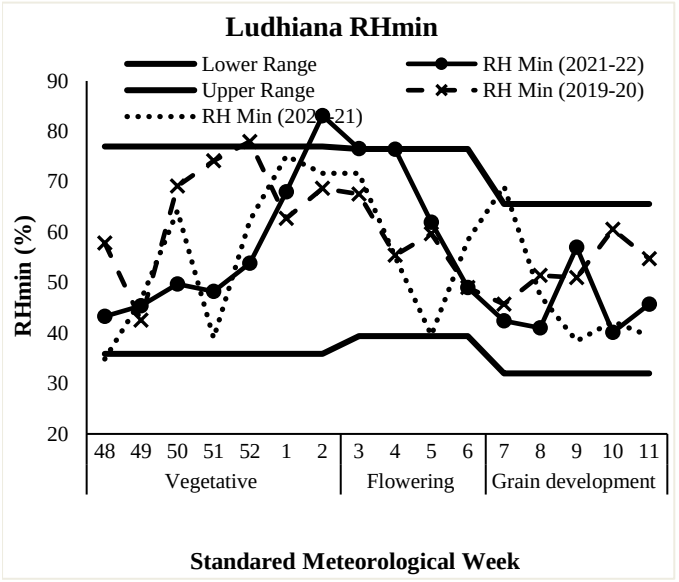
1. Tmax- Above upper range during early vegetative and grain development, below lower range during flowering stage.
2. Tmin- was above the upper range during grain filling stage.
3. RHmax- Remained within the optimum ranges
4. RHmin- Above upper range in vegetative & flowering stage.
5. Rainfall- High rainfall during Flowering stage.

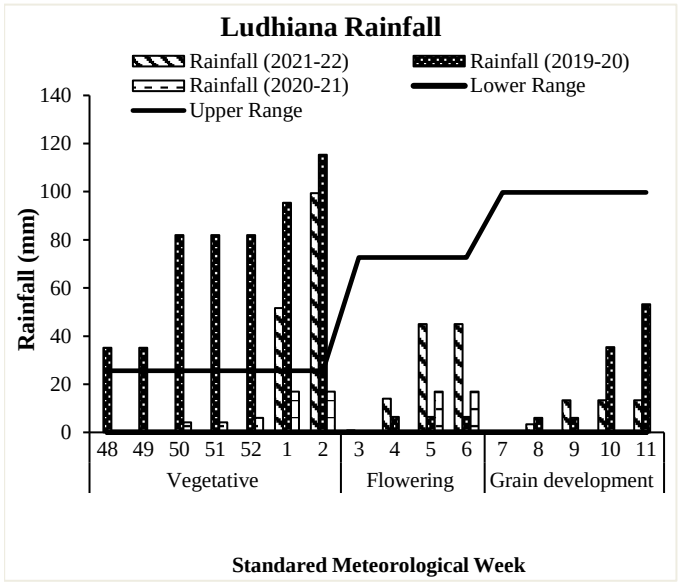
Figure 2. Comparison of actual weather data of Ballowal Saunkhari for validation of thumb rules for high yield >5000 kg/ha (2019–20), medium yield 4000–5000 kg/ha (2020–21) and low yield <4000 kg/ha (2021–22) of wheat.











Medium Yield –5098 kg/ha (2019-20)

1. Tmax- Mostly remained within the optimum ranges. It was below the lower range during vegetative stage.
2. Tmin- Remained within the optimum ranges. It was below the lower range during grain development stage.
3. RHmax- Remained within the optimum ranges.
4. RHmin- Remained within the optimum ranges.
5. Rainfall- It was received during vegetative stage.

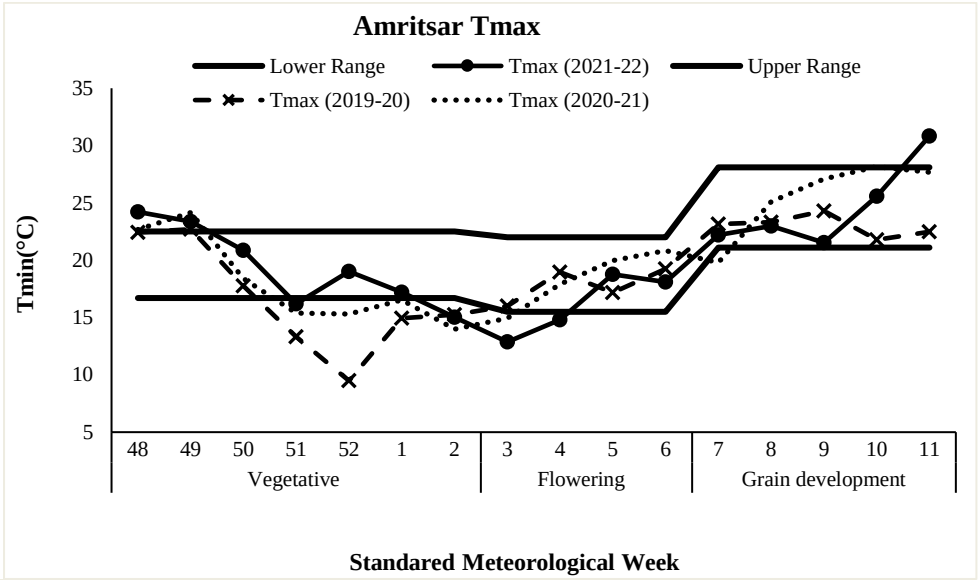
Medium Yield – 4968 kg/ha (2020-21)

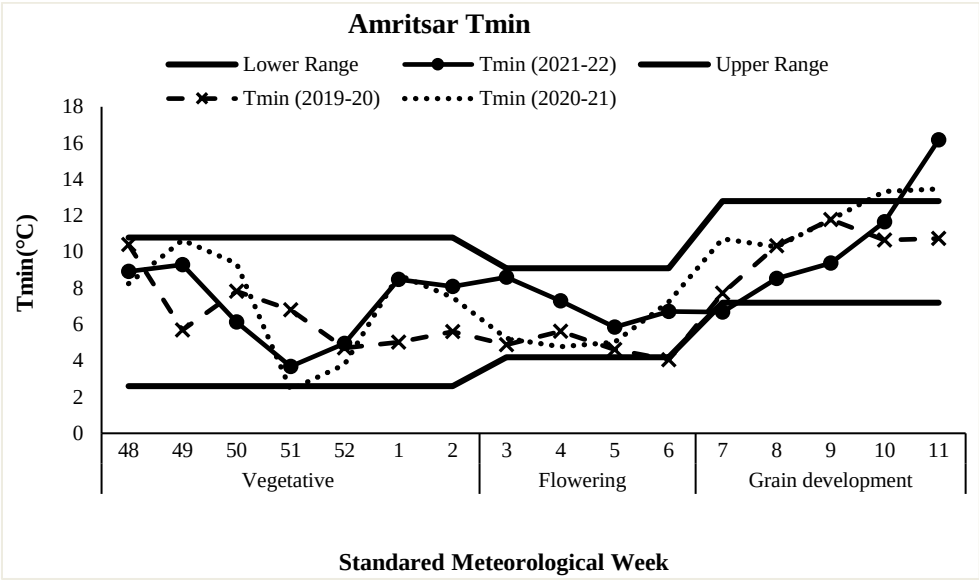
1. Tmax- Mostly within optimum ranges. I*t* was above upper range in vegetative & grain development stage.
2. Tmin- Remained within the optimum ranges.
3. RHmax- Remained within the optimum ranges except during grain filling stage.
4. RHmin- Remained within the optimum ranges.
5. Rainfall- Low rainfall in vegetative & flowering stage

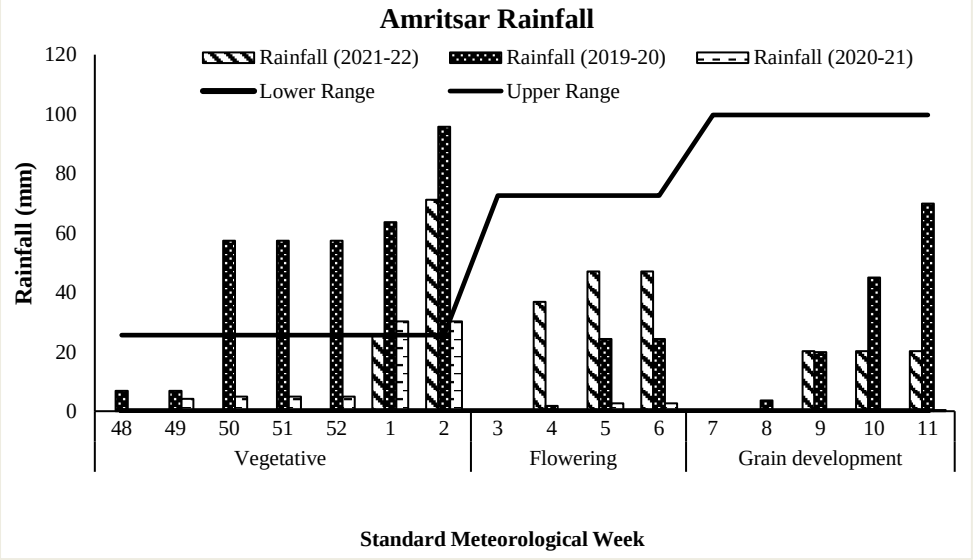
Low Yield–4275 kg/ha (2021-22)

1. Tmax- was above upper range during early vegetative, below lower range during flowering phase and then above upper range during grain development phase.
2. Tmin- Remained within the optimum ranges.
3. RHmax- Remained within the optimum ranges
4. RHmin- Mostly remained within the optimum ranges, was above the upper range during late vegetative phase.
5. Rainfall- Higher rainfall during later vegetative stage.

Figure 3. Comparison of actual weather data of Ludhiana for validation of thumb rules for Medium yield 4500–5100 kg/ha (2019–20 and 2020–21) and Low yield <4500 kg/ha (2021–22) of wheat.







Medium Yield–4533 kg/ha (2019-20)

1. Tmax- Mostly remained within the optimum ranges. Tmax was below the lower range during the vegetative stage.
2. Tmin- Remained within the optimum ranges.
3. Rainfall- The rainfall received during the vegetative stage was high as compared to rainfall received during the flowering and grain development stages.

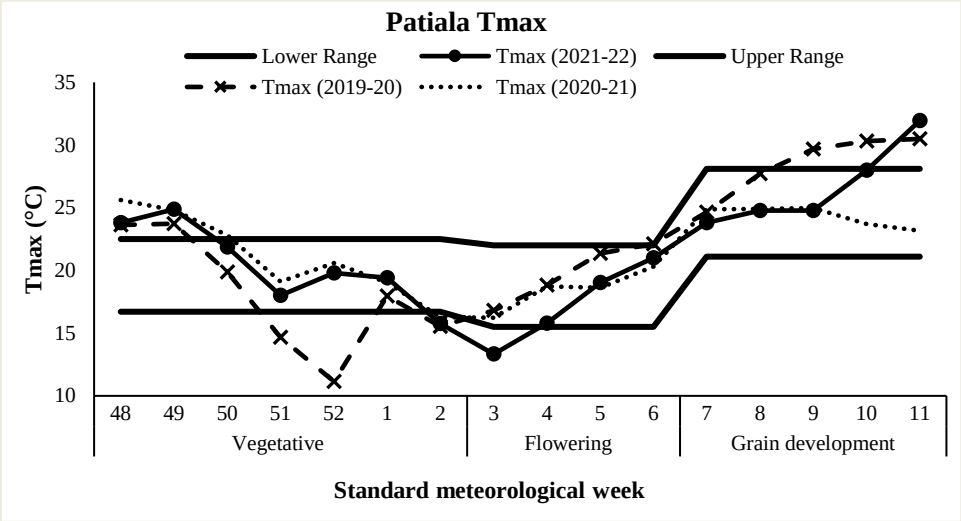
Medium Yield– 4763 kg/ha (2020-21)

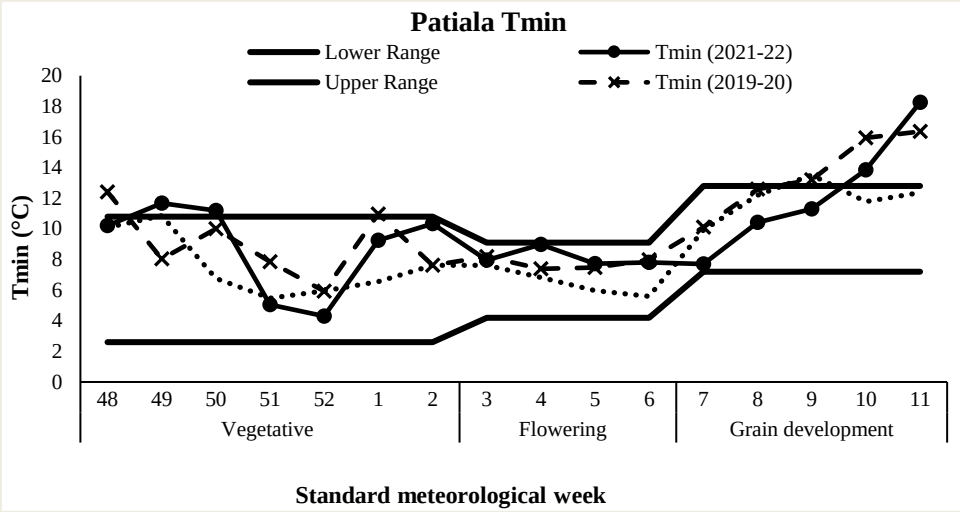
1. Tmax- Mostly remained within the optimum ranges. Tmax was below the lower range during vegetative stage.
2. Tmin- Remained within the optimum ranges except during grain development stage, It was slightly above the upper range.
3. Rainfall- The rainfall was received during vegetative stage. Dry conditions during flowering and grain development stages.

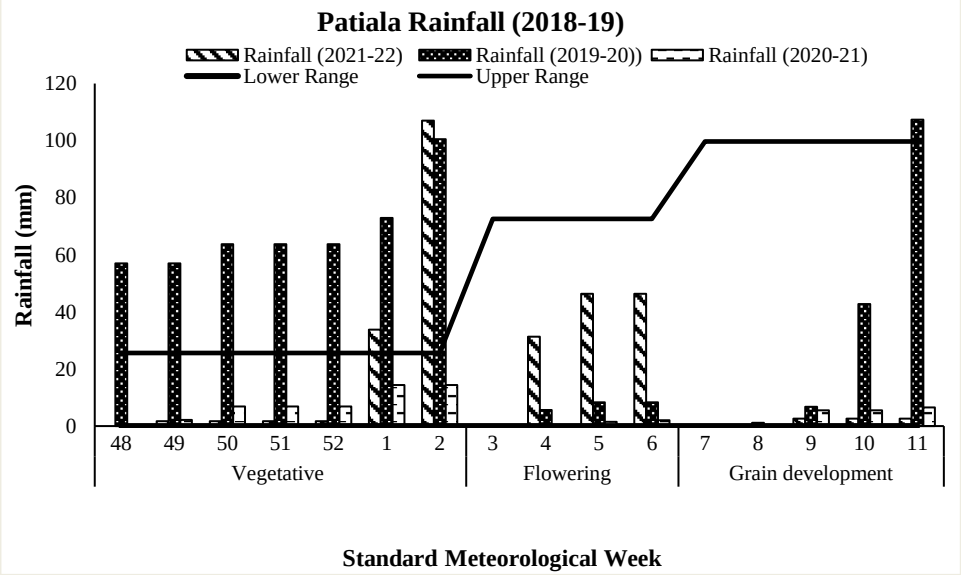
Medium Yield–4451 kg/ha (2021-22)

1. Tmax- was above upper range during vegetative and grain development stage.
2. Tmin- Remained within the optimum ranges except during grain development stage it was above the upper range.
3. Rainfall- higher amount of rainfall received during later vegetative stage.

Figure 4. Comparison of actual weather data of Amritsar during 2019–20, 2020–21 and 2021–22 for validation of thumb rules for Medium yield 4200–4850 kg/ha of wheat.







Medium Yield - 4771 kg/ha (2019-20)

1. Tmax- Mostly within optimum ranges. It was below the lower range during the vegetative stage and above the upper range during the grain development stage.
2. Tmin- Remained within optimum ranges except during the grain development stage it was above the upper range.
3. Rainfall- The amount of rainfall received during vegetative was high as compared to flowering and grain development stages.

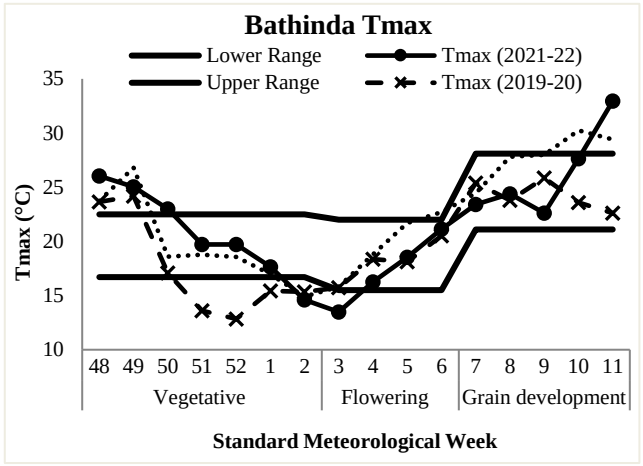
Medium Yield– 4974 kg/ha (2020-21)

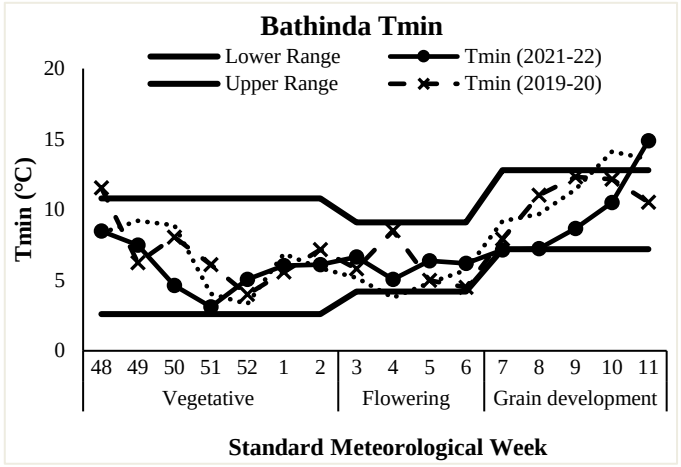
1. Tmax- Mostly remained within the optimum ranges. Tmax was above the upper range during vegetative stage.
2. Tmin- Remained within the optimum ranges except during grain development stage it was slightly above the upper range.
3. Rainfall- The low amount of rainfall was received during vegetative, flowering and grain development stages.

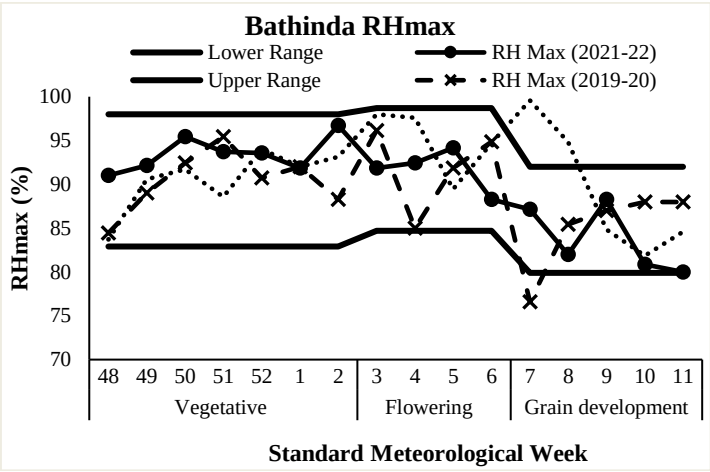
Low Yield–3883 kg/ha (2021-22)

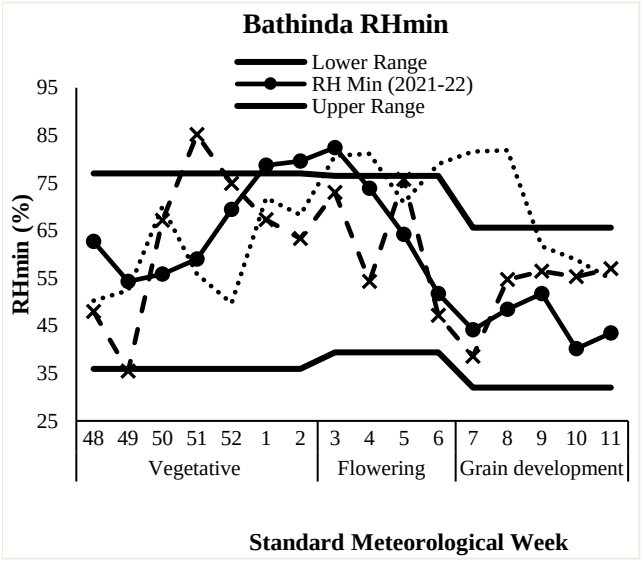
1. Tmax- was above the upper range during the vegetative stage and grain development stage. But it was below the lower range during the flowering stage.
2. Tmin- was above the upper range during vegetative and grain development stages.
3. Rainfall- Heavy rainfall received during the late vegetative stage.

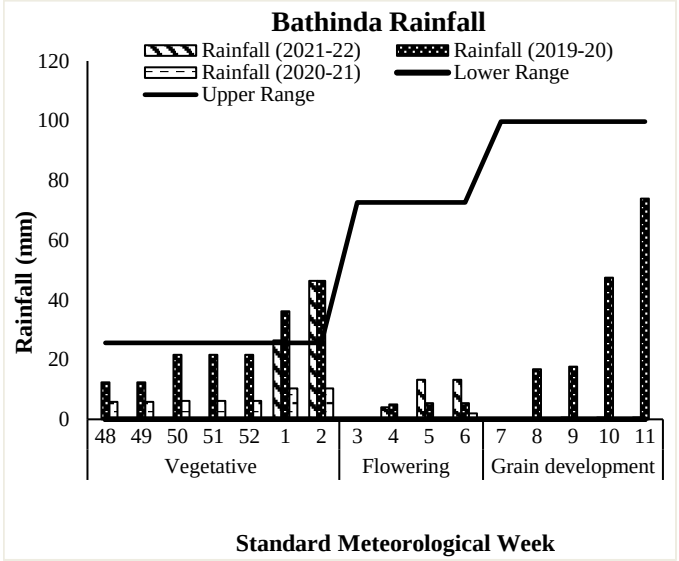
Figure 5. Comparison of actual weather data of Patiala for validation of thumb rules for medium yield 4500–5000 kg/ha (2019–20 and 2020–21) and low yield <4500 kg/ha (2021–22) of wheat.











High Yield– 5418 kg/ha (2019-20)

1. Tmax- Mostly remained within the optimum ranges and was below the lower range during vegetative stage.
2. Tmin- Remained within the optimum ranges.
3. RHmax- Remained within the optimum ranges.
4. RHmin- Mostly remained within the optimum ranges.
5. Rainfall- Well-distributed rainfall.

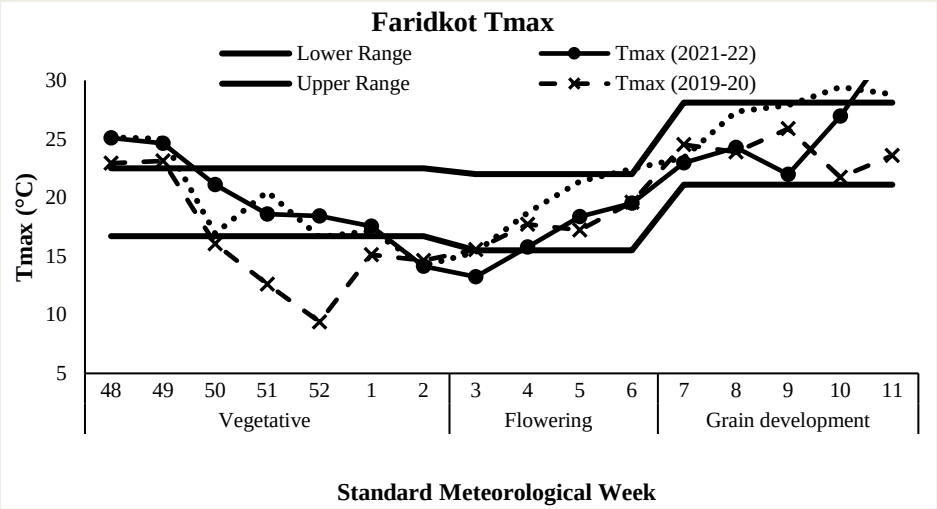
Medium Yield – 4951 kg/ha (2020-21)

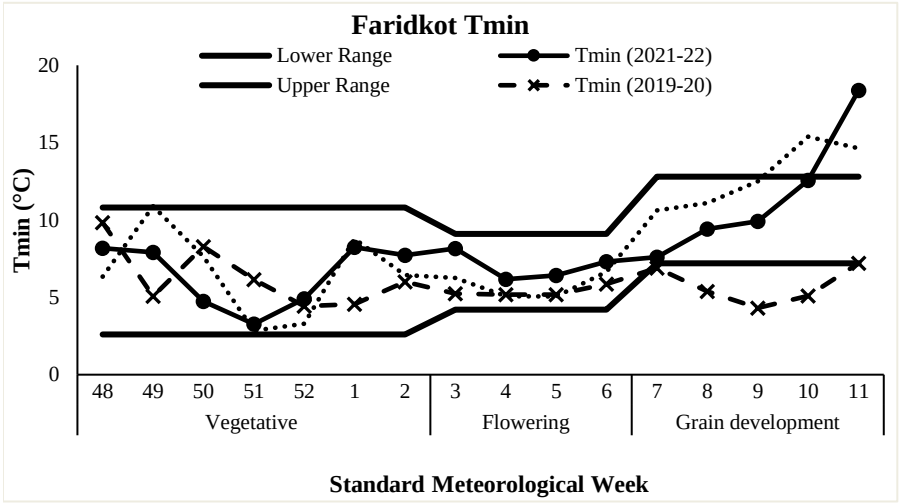
1. Tmax- Remained within the optimum ranges, above the upper range in vegetative & grain development stages.
2. Tmin- Remained within optimum ranges except during grain development stage.
3. RHmax- Remained within the optimum ranges but it was above the upper range during grain development stage.
4. RHmin- Mostly remained within optimum ranges, was above the upper range during grain development stage.
5. Rainfall- A low amount of rainfall was received.

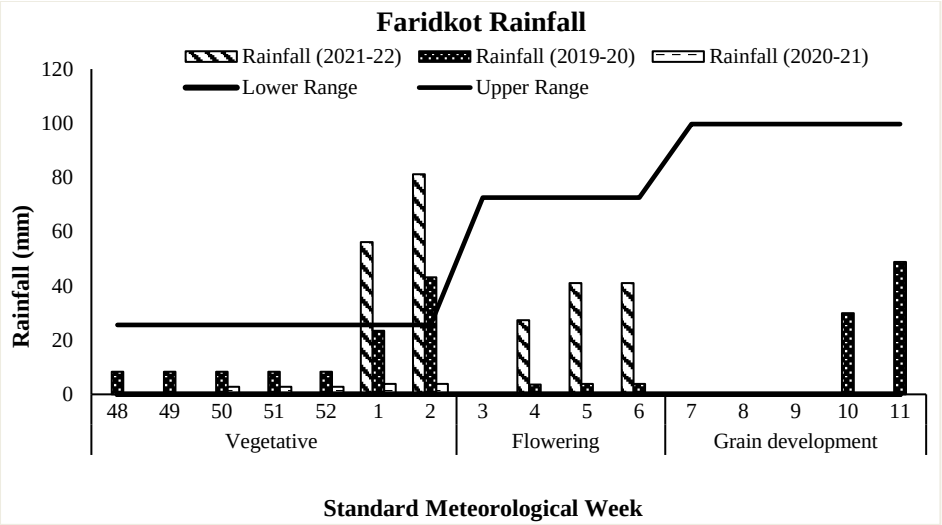
Medium Yield–4406 kg/ha (2021-22)

1. Tmax- Above upper range during vegetative & grain development stage, below lower range during flowering.
2. Tmin- Above upper range in grain development stage.
3. RHmax- Remained within the optimum ranges.
4. RHmin- Remained within optimum ranges, was above upper range during late vegetative & flowering phase.
5. Rainfall- Lower amount of rainfall received.

Figure 6. Comparison of actual weather data of Bathinda for validation of thumb rules for high yield >5000 kg/ha (2019–20) and medium yield—4000–5000 kg/ha (2020–21 and 2021–22) of wheat.







High Yield –5570 kg/ha (2019-20)

1. Tmax-Mostly remained within the optimum ranges.
2. Tmin-Remained within the optimum ranges except during grain development stage it was below the lower range.
3. Rainfall-Well-distributed rainfall.

Medium Yield – 5066 kg/ha (2020-21)

1. Tmax-Mostly remained within the optimum ranges. Tmax was above the upper range during vegetative and grain development stage.
2. Tmin-Remained within the optimum ranges except during grain development stage it was above the upper range.
3. Rainfall- Low rainfall received.

Medium Yield–4582 kg/ha (2021-22)

1. Tmax- was above the upper range during vegetative and grain development stage but it was below the lower range during early flowering stage.
2. Tmin-Remained within the optimum ranges except during grain development stage it was above the upper range.
3. Rainfall-The rainfall received during vegetative and flowering stages.

Figure 7. Comparison of actual weather data of Faridkot for validation of thumb rules for high yield >5100 kg/ha (2019–20) and medium yield—4200–5100 kg/ha (2020–21 and 2021–22) of wheat.

3.4. Reasons for achieving high yield

The high yield of wheat was observed during 2019–20 at Ballowal Saunkhri, Bathinda, and Faridkot because invariably both Tmax and Tmin remained within optimum ranges, or at some point they were below the lower range. The rainfall was well distributed, and hence the relative humidity was invariably within the optimum ranges.

3.5. Reasons for achieving medium yield

During the three crops wheat yield was mostly in this category, i.e., Ballowal Saunkhri (2020–21), Ludhiana and Patiala (2019–20 and 2020–21), Bathinda and Faridkot (2020–21 and 2021–22), and Amritsar (all three years) (**Figures 2–7**). The one major reason was the deviations in Tmax and Tmin above the upper ranges. The distribution pattern of rainfall, i.e., either a more positive distribution increased the relative humidity above the upper range or a more negative deviation decreased the relative humidity below the lower range.

3.6. Reasons for achieving low yield

The low yield of wheat was observed during 2021–22 at Ballowal Saunkhri, Ludhiana, and Patiala (**Figures 2**, **3** and **5**). The major reason was the heavy rainfall received during the late vegetative stage (SMW 1 and 2) when the wheat was in the jointing and flag leaf initiation stage. The second major reason was dry weather due to very little rainfall and subsequent rise in Tmax and Tmin during the later period of the grain filling stage, i.e., during SMW 10 and 11. This hastened the grain maturity in wheat, and so lower yields were recorded.

4. Conclusions

Wheat is a cool-season crop that is highly affected by the rise in temperature [14–16] both during the vegetative stage, which adversely affects the tillering [3], and during the grain filling stage, which hastens the grain maturity [9,10]. The results of the study revealed that in Punjab state, for achieving a high yield of >5000 kg/ha (in most suitable regions) to >4000 kg/ha (in a lesser suitable region), the maximum/minimum temperature and maximum/minimum relative humidity, respectively, should be within the range of 16–22/4–9 ℃ and 85%–99%/39%–77% during the vegetative period, 21–28/7–13℃ and 80%–92%/32%–66% during the flowering period, and 25–32/11–16℃ and 75%–86%/31%–59% during the grain filling period, coupled with a well-distributed rainfall of 25–50 mm growing the crop growing season.

This information can act as a guiding tool for agricultural scientists to optimize the sowing time for the wheat crop in Punjab State. The information will be useful to the policy planners while preparing the yield estimates for wheat in the region. The weather-based crop insurance schemes are based on the optimum limits required for the crop during its major growth stages. Hence, it can be used as a ready reckoner while preparing the term sheets for insurance schemes.

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