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Article

Weather based thumb rule models for formulating the crop insurance schemes for wheat in Punjab

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Abstract: Weather-based crop insurance schemes play an important role in helping farmers recover their financial losses incurred due to aberrant meteorological parameters. Wheat is a major winter season crop grown in Punjab state. To formulate the weather-based "weekly and monthly thumb rule models" for predicting the high yield of wheat, a study with meteorological and crop data (2007–2008 to 2021–2022) was conducted for three major wheat growing locations in the state. The results revealed that ideally the monthly maximum/minimum temperatures/rainfall/sunshine duration during the months of December, January, February and March in the range of 20–23 °C/5–9 °C/0–38 mm/5–8 h, 17–20 °C/3–8 °C/2–57 mm/4–6 h, 19–25 °C/5–11 °C/0–79 mm/5–8 h and 25–30 °C/10–15 °C/0–56 mm/8–9 h, respectively are optimum for high yield of wheat. The ideally humid (maximum/minimum relative humidity between 90%–97%/36%–63%) weather from November to February is favourable for the optimum growth and development of the wheat crop. Similarly, the maximum/minimum temperatures/rainfall/sunshine duration for anthesis and grain filling stage in the range of 14–23 °C/3–10 °C/0–55 mm/2–9 h and 18–30 °C/5–15 °C/0–26 mm/4–10 h are favourable for high yield of wheat crop. The maximum temperature of >18 °C during the grain filling stage is optimum for a potential yield of wheat. The abiotic stresses like heavy rainfall, and heat stress during the grain filling stage are not favourable for the productivity of the crop. So, these critical limits of weather parameters are the basis for providing weather-based insurance to the farmers of the region.

Keywords: crop insurance; Punjab; rainfall; temperature; thumb rule model; wheat

1. Introduction

Agriculture holds a crucial role as the mainstay of the Indian economy and is deeply impacted by shifts in climate [1]. Inter- and intra-seasonal variability in weather plays an essential role in agriculture and the changes in weather patterns can have a significant impact on crop yields [2]. The livelihood of farmers is highly dependent on the final yield of the crop. At this juncture, agricultural insurance plays an important role in ascertaining the stability of a farmer's income. Moreover, it also helps in reducing the vulnerability of the global food system to acute food shocks, thereby contributing to food security's resilience and sustainability [3]. The information on thresholds of weather parameters for optimum yield of crops and the rate of decrease of yield with increase or decrease of relevant weather parameters or their indices are essential components in weather-index-based crop insurance [4]. Hence weather-based crop advisory services can provide real-time information about weather patterns, crop health, and appropriate measures to the farmers. This empowers farmers to make informed decisions regarding diverse crop management practices, ultimately resulting in elevated yields and augmented income [5].

Wheat (*Triticum aestivum* L.) is a major cereal crop in the *Poaceae* family and is grown over 218 million hectares worldwide and plays a substantial role in the global agricultural economy, surpassing the contribution of other food crops [6]. Wheat is a *rabi* (winter) season crop and is particularly sensitive to climate variations. Studies indicate that for every 1oC increase in temperature, wheat yields are projected to decline by 6% [7]. Wheat plays a vital part in global food security, making up nearly 20% of total caloric intake and proteins both nationally and globally [8]. Wheat crop during the year 2022–2023, was grown on 30.4 Mha with a total production of 112.74 Mt and productivity of 35.07 q ha^{-1} [9]. While in Punjab, it was grown over 3.52 Mha of area of which nearly 97% is irrigated and the total productivity was 42.06 q ha^{-1} [10]. The state is commonly known as the "food bowl of India" since it contributes ~40% of wheat to the central food grain pool of the nation [11]. Wheat holds a crucial position as a staple food crop for the masses, and projections for 2050 anticipate a 70% increase in its global demand, necessitating an escalation from the current growth levels of 1% to 1.7% [12]. The optimum temperature for vegetative, flowering and grain-filling stages is 20–29, 18–28, and 20–25 °C [13]. However, a daily average temperature >35 °C is detrimental for the wheat plant [14]. The relative humidity (RH) in the range of 50%–60% is optimum for wheat crops [15]. However bright sunshine hours contribute positively towards wheat yield.

Winter wheat growth is generally threatened by scorching temperatures during the post-heading stages (from anthesis to maturity) [16], i.e., it is only weather in the spring that makes much difference to the yield of the crop [17,18]. Heat stress had a severe impact on wheat production in 2022, as intense heat wave conditions arrived weeks earlier than usual in the northern wheat-growing regions of India. The rise in maximum temperatures proved detrimental to wheat productivity. In 2023, the weather took a turn around mid-March, with gale-force winds and precipitation causing damage to the wheat crop in Uttar Pradesh, Madhya Pradesh, Punjab, Haryana, and Rajasthan. In view of trends towards increased temperature and its adverse effects on wheat yield, it is necessary to provide insurance coverage for high-temperature risk in wheat, as an adaptation strategy to climate change [4].

Since the start of the 21st century in Punjab state some prominent climatic extremes during the winter season such as snowfall in Pathankot (January 2011), prolonged winters in 2012, extremely low temperature of −0.4 °C in Bathinda (February 2012) were unfavourable for the crops [19]. Certainly, having timely predictions of these weather parameters can mitigate some of the yield losses that primarily heat stress during vegetative, anthesis, and grain development stages in Punjab state. This information can be disseminated to the farmers in the form of weather-based advisory bulletins and can prove helpful [20]. Such advisories have the potential to decrease the cost of crop production and minimize losses attributed to weather irregularities, ultimately enhancing crop productivity and contributing to the profitability of farm income [21].

In today's context, farmers are increasingly recognizing the value of weather-related agricultural services as powerful tools for enhancing farm productivity [22]. Weather-based agro advisories can guide farmers in decision-making both before and during the crop season, facilitating the reduction of production costs, crop losses, and carbon footprints, ultimately leading to increased farm profitability [20,23]. The information on critical limits of weather variables for important crop stages is the basis for the formulation of term sheets for crop-weather insurance [24]. Crop insurance emerges as a crucial alternative for risk-sharing and income stabilization. Heavy subsidies on insurance premiums aim to encourage more farmers to participate, enhancing risk-sharing and, consequently, the long-term efficiency of insurance programs [25]. These schemes can help provide farmers the risk cover for long-duration crops like wheat whose duration is nearly 130–150 days in Punjab. Moreover, during the vegetative stage of wheat weather is cool up to January month, and later during March and April months, the temperatures start increasing. Consequently, the present study was undertaken to develop weather-based "weekly and monthly thumb rule models" applicable for crop weather insurance as well as weather-based advisory bulletin and predicting the high yield of wheat crops in Punjab.

2. Materials and methods

2.1. Data collection

The crop data was obtained from Statistical Abstracts of Punjab covering a period of 15 years (2007–2008 to 2021–2022) for major wheat growing locations, i.e., Ludhiana, Patiala, and Amritsar which were then categorized as low, medium, and high yield crop years (**Table 1**). At Ludhiana, the high yield (>5100 kg/ha) of wheat was reported during 4 years (2011–2012, 2013–2014, 2017–2018 and 2018–2019) and a low yield (<4600 kg/ha) during 3 years (2008–2009, 2014–2015 and 2021–2022). Similarly, at Patiala high yields (>5000 kg/ha) of wheat were reported during 4 years (2011–2012, 2016–2017, 2017–2018, and 2018–2019) and low yields (<4500 kg/ha) during 2 years (2014–2015, 2021–2022). At Amritsar, the high yield (>4850 kg/ha) of wheat was reported during 4 years (2011–2012, 2013–2014, 2016–2017, and 2017–2018) and low yield (<4200 kg/ha) during 3 years (2008–2009, 2009–2010 and 2014–2015).

Table 1. Categorization of wheat yield during 2007–2008 to 2021–2022 at three locations in Punjab.

Yield category	Ludhiana	Patiala	Amritsar
High yield years	**(>5100 kg ha^{-1})** 2011–2012, 2013–2014, 2017–2018, 2018–2019	**(>5000 kg ha^{-1})** 2011–2012, 2016–2017, 2017–2018, 2018–2019	**(>4850 kg ha^{-1})** 2011–2012, 2013–2014, 2016–2017, 2017–2018
Medium yield years	**(4600–5100 kg ha^{-1})** 2007–2008, 2009–2010, 2010–2011, 2012–2013, 2015–2016, 2016–2017, 2019–2020, 2020–2021	**(4500–5000 kg ha^{-1})** 2007–2008, 2008–2009, 2009–2010, 2010–2011, 2012–2013, 2013–2014, 2015–2016, 2019–2020, 2020–2021	**(4200–4850 kg ha^{-1})** 2007–2008, 2010–2011, 2012–2013, 2015–2016, 2018–2019, 2019–2020, 2020–2021, 2021–2022
Low yield years	**(<4600 kg ha^{-1})** 2008–2009, 2014–2015, 2021–2022	**(<4500 kg ha^{-1})** 2014–2015, 2021–2022	**(<4200 kg ha^{-1})** 2008–2009, 2009–2010, 2014–2015

The data on different phenological stages of the wheat crop were collected from the field experiments conducted under the "All India Coordinated Research Project on Agrometeorology (AICRPAM)" operational in the Department of Climate

Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana. The sowing of wheat starts from mid-October and its harvesting is done during April in the state. Accordingly, by considering the early, normal, and late sown conditions for wheat in the state, the stages of wheat were broadly categorized into sowing-emergence (43–47 standard meteorological week (SMW)), vegetative (48–2 SMW), anthesis (3–6 SMW), grain filling (7–11 SMW) and physiological maturity (12–15 SMW). The daily weather data (maximum and minimum temperature, maximum and minimum relative humidity, rainfall, rainy days, evaporation, sunshine hours, and wind speed) of recent 15 years (as per availability) for Ludhiana, Patiala, and Amritsar were collected to work out the weekly and monthly climatic average. These climatic averages were then used for comparing the actual data of those high-yield years.

2.2. "Critical limits" of the meteorological parameters

The weekly and monthly deviations of meteorological parameters for different growth stages for the three locations were computed by comparing the actual meteorological data of each high-yield crop year with the average meteorological data. In the present study it was hypothesized that (1) a high yield of the wheat crop was realized during those respective years due to favourable ranges of the meteorological parameters, and (2) over the recent 15 years time period the changes/advancement in crop management practices were not significantly changed. So then by comparing the ranges of weekly and monthly deviations for each of the high-yield years, the "critical limits" of meteorological parameters for high yield of wheat crop for each location were summarized.

2.3. Thumb rule models for predicting the high yield of wheat crop in Punjab

On the basis of the "critical limit" of each meteorological parameter for a high yield of wheat, the monthly and weekly crop stage-wise thumb rule models for predicting the high yield of wheat under Punjab conditions were worked out.

3. Results

3.1. Range of monthly meteorological parameters during the wheat season in Punjab

The actual daily meteorological data (2007–2008 to 2021–2022) collected for three locations in the state were analysed and their respective monthly averages were worked out (**Table 2**). In Punjab the range of actual average of monthly maximum/minimum temperature, maximum /minimum relative humidity, rainfall, sunshine hour, evaporation and wind speed was 31.8–32.7/17.9–18.7 °C, 89.6%/41.6%, 10.3–12.5 mm, 7.2 h, 100.3 mm and 2.2 km/h, respectively during October; 26.7–28.0/10.4–12.2 °C, 91.6%/37.6%, 4.6–9.7mm, 5.2 h, 61.5 mm and 2.1 km/h, respectively during November; 20.2–21.4/5.4–7.9 °C, 94.5%/50.0%, 7.9–11.9 mm, 5.4 h, 42.3 mm and 2.4 km/h, respectively during December; 17.1–18.4/4.3–7.8 °C, 95.1%/58.6%, 29.8–31.4 mm, 4.5 h, 39.5 mm and 3.4 km/h, respectively during January; 21.3–22.9/7.2–9.6 °C, 93.1/52.4%, 26.7–39.1 mm, 6.7 h, 59.2 mm and 3.8 km/h, respectively during February; 27.0–28.8/11.9–14.5 °C, 89.2%/43.6%, 24.5–34.8 mm, 8.5 h, 114.8 mm and 4.0 km/h, respectively during March and 34.4–36.1/17.2–19.8 °C, 66.4%/28.1%, 19.2–26.5 mm, 9.4 h, 208.6 mm and 4.8 km/h, respectively during April month.

Table 2. Average monthly meteorological parameters during wheat crop season in Punjab (2007–2008 to 2021–2022).

Month	**Temperature (°C)**		**Relative humidity (%)**		**Rainfall (mm)**	**Sunshine hours(h)**	**Evaporation (mm)**	**Wind speed (km h^{-1})**
	Maximum	**Minimum**	**Maximum**	**Minimum**				
Ludhiana								
October	31.8	18.1	89.6	41.6	12.5	7.2	100.7	2.2
November	26.6	11.4	91.6	37.6	4.6	5.7	61.5	2.1
December	20.2	7.0	94.5	50.0	11.9	5.4	42.3	2.4
January	17.3	7.8	95.1	58.6	30.5	4.5	39.5	3.4
February	21.5	8.9	93.1	52.4	36.1	6.7	59.2	3.8
March	27.8	13.4	89.2	43.6	24.5	8.5	114.8	4.0
April	35.1	18.7	66.4	28.1	19.2	9.4	208.6	4.8
Patiala								
October	32.7	18.7	-	-	10.3	-	-	-
November	28.0	12.2	-	-	6.4	-	-	-
December	21.4	7.9	-	-	11.0	-	-	-
January	18.4	7.0	-	-	29.8	-	-	-
February	22.9	9.6	-	-	26.7	-	-	-
March	28.8	14.5	-	-	34.8	-	-	-
April	36.1	19.8	-	-	21.9	-	-	-
Amritsar								
October	32.1	17.9	-	-	12.0	-	-	-
November	26.7	10.4	-	-	9.7	-	-	-
December	20.4	5.4	-	-	7.9	-	-	-
January	17.1	4.3	-	-	31.4	-	-	-
February	21.3	7.2	-	-	39.1	-	-	-
March	27.0	11.9	-	-	29.7	-	-	-
April	34.4	17.2	-	-	26.5	-	-	-

Table 3. Average stage-wise range of meteorological parameters during wheat crop season in Punjab (2007–2008 to 2021–2022).

Month	**Temperature (°C)**		**Relative Humidity (%)**		**Rainfall (mm)**	**Sunshine hours (h)**	**Evaporation (mm)**	**Wind speed (km h^{-1})**
	Maximum	**Minimum**	**Maximum**	**Minimum**				
Ludhiana								
Sowing-emergence	25.5–30.4	9.5–15.2	88.2–92.4	35.0–38.4	0.1–3.5	4.7–7.0	14.0–20.5	1.9–2.3
Vegetative	16.6–24.6	5.1–9.2	93.1–95.5	38.4–60.8	0.7–8.5	3.0–6.0	7.8–12.2	1.9–3.4
Anthesis	16.8–20.0	6.5–7.7	94.0–95.3	53.5–61.7	4.5–11.7	4.0–6.4	8.7–13.2	3.4–3.9
Grain filling	21.2–27.1	7.8–12.1	90.3–93.3	45.3–52.2	5.1–9.6	7.0–8.5	14.2–24.1	3.5–4.3

Table 3. (*Continued*).

Month	Temperature (°C)		Relative Humidity (%)		Rainfall (mm)	Sunshine hours (h)	Evaporation (mm)	Wind speed (km h^{-1})
	Maximum	Minimum	Maximum	Minimum				
Physiological maturity	29.6–35.2	13.3–16.0	69.5–88.2	27.4–40.2	2.4–6.4	8.5–9.4	28.8–46.4	4.0–4.8
Patiala								
Sowing-emergence	26.9–31.6	10.4–15.9	-	-	0.0–1.8	-	-	-
Vegetative	17.7–25.8	5.9–10.3	-	-	0.1–8.0	-	-	-
Anthesis	18.1–21.4	7.2–8.3	-	-	3.7–10.2	-	-	-
Grain filling	22.6–27.7	9.3–13.9	-	-	3.9–11.5	-	-	-
Physiological maturity	30.7–35.7	16.0–19.2	-	-	2.9–5.2	-	-	-
Amritsar								
Sowing-emergence	25.5–30.4	8.6–15.3	-	-	0.1–5.9	-	-	-
Vegetative	16.3–24.7	4.0–7.7	-	-	0.5–9.7	-	-	-
Anthesis	16.7–20.0	4.1–6.2	-	-	5.5–9.2	-	-	-
Grain filling	21.0–26.2	7.3–11.2	-	-	5.9–11.7	-	-	-
Physiological maturity	28.9–33.8	13.4–16.8	-	-	2.4–6.1	-	-	-

3.2. Range of meteorological parameters during different growth periods for wheat in Punjab

The wheat crop data were categorized into different growth stages, i.e., sowing to emergence, vegetative, anthesis, grain filling, and physiological maturity. The actual daily meteorological data were analysed on a weekly basis as per the various crop stages to work out their actual ranges (**Table 3**). In Punjab, the average weekly maximum/minimum temperature, maximum/minimum relative humidity, and sunshine hours during the sowing-emergence period varied between 25.5–31.6/8.6–15.9 °C, 88.2%–92.4%/35.0%–38.4% and 4.7–7.0 h, respectively; during vegetative stage the values varied between 16.3–25.8/4.0–10.3 °C, 93.1%–95.5%/38.4%–60.8% and 3.0–6.0 h, respectively; during anthesis stage varied between 16.7–21.4/4.1–8.3 °C, 94.0%–95.3%/53.5%–61.7% and 4.0–6.4 h, respectively; during grain filling stage varied between 21.0–27.7/7.3–13.9 °C, 90.3%–93.3%/45.3%–52.2% and 7.0–8.5 h, respectively and during physiological maturity varied between 28.9–35.7/13.3–19.2 °C, 69.5%–88.2%/27.4%–40.2% and 8.5–9.4 h, respectively.

3.3. Weekly thumb rule models for predicting the high yield of wheat crop

The comparison of the average (2007–2008 to 2021–2022) weekly meteorological parameters with those observed during the respective high-yield crop years for wheat crops was done. Then the "Weekly Thumb Rules Models" were developed (**Figures 1–3**) to predict the yield of wheat crops for three different locations in Punjab. The favourable and optimum range of weekly meteorological parameters for different growth stages of wheat grown for high yield are:

Sowing-emergence (43–47 SMW): It requires maximum/minimum temperature within 23–33/8–17 °C, maximum/minimum relative humidity within 88%–98%/26%–54%, rainfall up to 17 mm on 1 rainy day, sunshine hours 0–9 h, evaporation 9–22 mm and wind speed 0–3 km/h for high yield of wheat.

Vegetative stage (48–2 SMW): The vegetative stage of wheat i.e., CRI (crown root initiation), tillering, and jointing requires maximum/minimum temperature 16–27/0–12 °C, maximum/minimum relative humidity 88%–99%/31%–74%, rainfall up to 38 mm in 2 rainy days, sunshine hours 2–9 h, evaporation 5–15 mm and wind speed 1–4 km/h for high yield.

Anthesis stage (3–6 SMW): The anthesis stage of wheat is very critical and any abrupt deviation in any meteorological parameter may adversely affect the productivity of wheat. The maximum/minimum temperature with 14–23/3–10 °C, maximum/minimum relative humidity within 90%–97%/40%–81%, rainfall up to 55 mm on 2 rainy days, sunshine hours within 2–9 h, evaporation within 8–15 mm and wind speed within 2–4 km/h are favourable for high yield of wheat.

Grain filling stage (7–11 SMW): The grain filling stage is highly influenced by adverse events of abiotic stresses, so optimum ranges of meteorological parameters are required for obtaining high yield. Maximum/minimum temperature within 18–30/5–15 °C, maximum/minimum relative humidity.

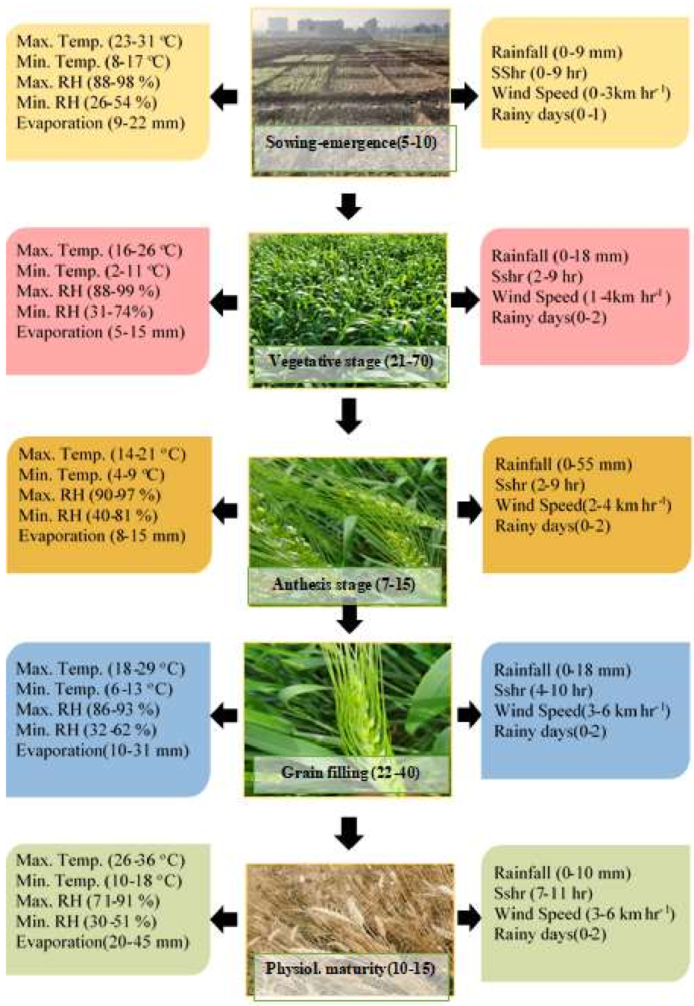

Figure 1. Weekly thumb rule model for Ludhiana for prediction of potential yield of wheat.

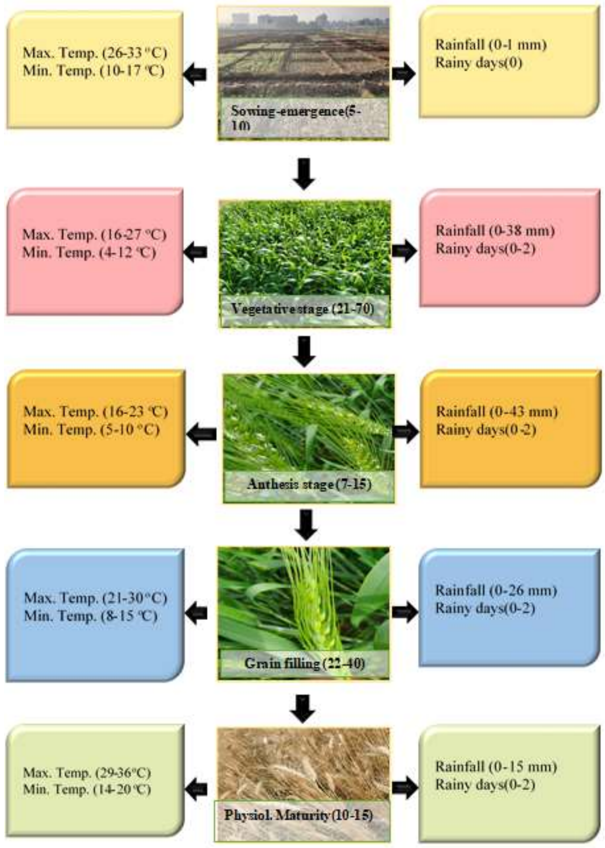

Figure 2. Weekly thumb rule model for Patiala for prediction of potential yield of wheat.

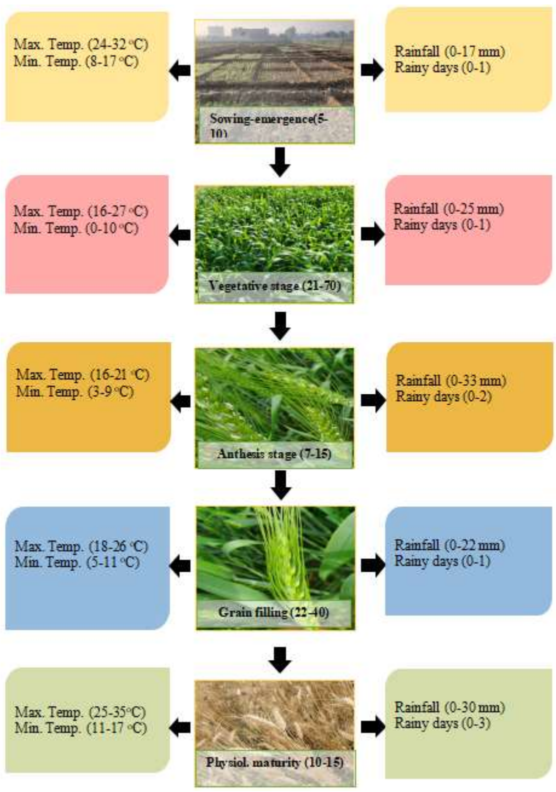

Figure 3. Weekly thumb rule model for Amritsar for prediction of potential yield of wheat.

Within 86–93/35–62%, rainfall up to 26 mm on 2 rainy days, sunshine hours within 4–10 h, evaporation within 10–31 mm, and wind speed within 3–6 km/h are favourable for high yield of wheat.

Physiological maturity (12–15 SMW): The maximum/minimum temperature within 25–36/10–20 ℃, maximum/minimum relative humidity within 71%–91%/30%–51%, rainfall up to 30 mm in up to 3 rainy days, sunshine hours within 7–11 h, evaporation within 20–45 mm and wind speed within 3–6 km/h are favourable for high yield of wheat.

3.4. Monthly thumb rule models for predicting the high yield of wheat

The comparison of the average (2007–2008 to 2021–2022) monthly meteorological parameters with those observed during the respective high-yield crop years for wheat crops was done. Then the “Monthly Thumb Rules Models” were developed (**Figures 4–6**) to predict the yield of wheat crops for three different locations in Punjab. The favourable and optimum range of monthly meteorological parameters for high yield of the wheat crop is:

October: Maximum/minimum temperature, maximum/minimum relative humidity, and sunshine hours for high yield of the crop are 31–34/17–20 ℃, 89%–91%/37%–47%, and 5–8 h, respectively.

November: Maximum/minimum temperature 25–29/10–14 ℃, maximum/minimum relative humidity 90%–95%/36%–47%, and sunshine hours 4–7 h are favourable for the high yield of the crop.

December: Maximum/minimum temperature 20–23/5–9 ℃, maximum/minimum relative humidity 91%–97%/43%–53%, and sunshine hours 5–8 h are favourable for high yield of the crop.

January: Maximum/minimum temperature 17–20/3–8 ℃, maximum/minimum relative humidity 92%–96%/52%–63%, and sunshine hours 4–6 h are favourable for high yield of the crop.

February: Maximum/minimum temperature 19–25/5–11 ℃, maximum/minimum relative humidity 90%–93%/46%–61%, rainfall 0–79 mm, rainy days 0–5, sunshine hours 5–8 h, evaporation 47–67 mm, and wind speed 3–4 km/h are favourable for high yield of the crop.

March: Maximum/minimum temperature 25–30/10–15 ℃, maximum/minimum relative humidity 86%–90%/36%–51%, rainfall 0–56 mm in 4 rainy days, and sunshine hours 8–9 h are favourable for high yield of the crop.

April: Maximum/minimum temperature 32–37/14–21 ℃, maximum/minimum relative humidity 63%–79%/27%–36%, rainfall 10–59 mm in 1–5 rainy days 1–5, sunshine hours 8–10 h, evaporation 165–210 mm and wind speed 4–6 km/h are favourable for high yield of the crop.

The sowing to maturity period of wheat extends from October to April months. The above-given ranges of meteorological parameters are conducive to high productivity of wheat crops and these can be used to develop the monthly term sheets for weather-based crop insurance in Punjab state.

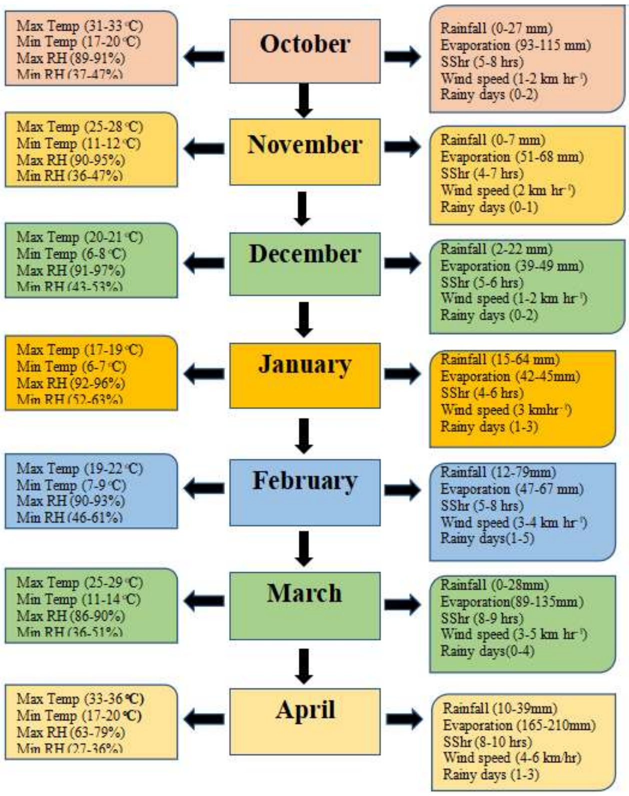

Figure 4. Weather-based monthly "thumb rule models" for prediction of high yield of wheat at Ludhiana (2007–2008 to 2021–2022).

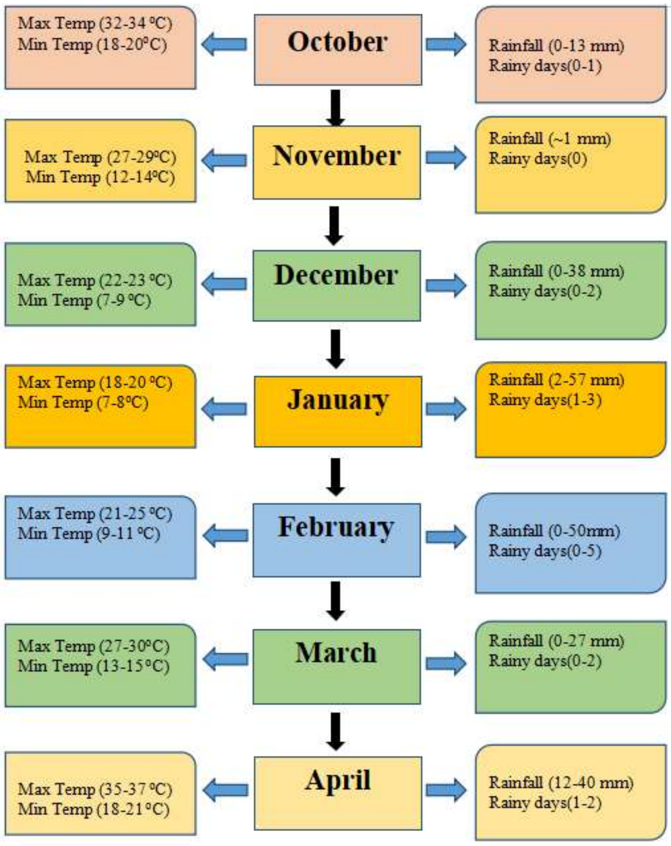

Figure 5. Weather-based monthly "thumb rule models" for prediction of high yield of wheat at Patiala (2007–2008 to 2021–2022).

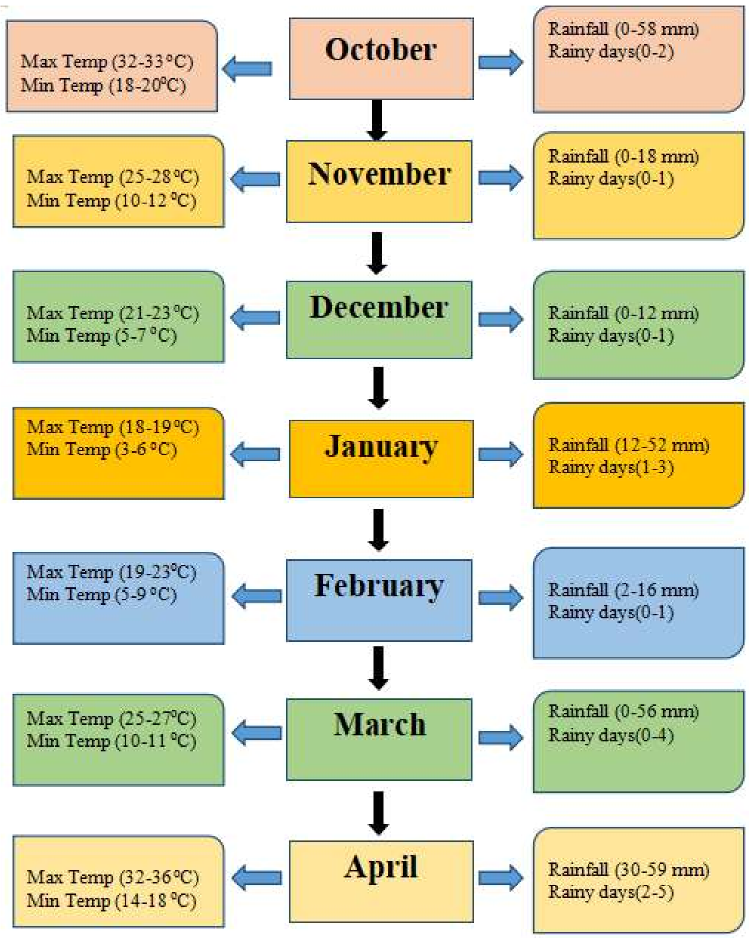

Figure 6. Weather-based monthly "thumb rule models" for prediction of high yield of wheat at Amritsar (2007–2008 to 2021–2022).

4. Discussion

4.1. Effect of meteorological parameters on wheat

The meteorological parameters (temperature, RH, wind speed, etc.) play an important role in determining the growth and productivity of a crop [26]. As per the record, among the major wheat-producing districts, Ludhiana alone contributes about 12% of the total wheat produced in Punjab state [27]. The study conducted [28] using the CERES-wheat model evaluated that the mean temperature and its range in the optimum sowing window was 22.3 °C and 20.6–23.9 °C, respectively, for central Punjab (Ludhiana) and remained almost the same till 2006. But during 2006–2015 the temperature range was higher or lower than the optimum range and these deviations led to lower simulated wheat productivity. A study conducted in Uttar Pradesh state of India [4] and reported that during anthesis, milk, dough, and maturity stages in wheat crops, the optimum range of maximum/minimum temperatures are 19.7–21.9/4.3–6.2, 24.2–26.5/8.3–9.7, 26.1–28.8/11.5–12.4 and 29.5–30.8/13.0–15.1 °C, respectively. An earlier simulation study [29] conducted using the CERES-Wheat model concluded that at Ludhiana the rise in temperature by 1.0, 2.0, and 3.0 °C from normal during January to February, mid-January to mid-March and from February to mid-March in case of early, timely and late sown wheat, respectively, led to a reduction in wheat yield. However, the temperature rise from December to January was beneficial for late-sown crops.

The growth period of early, normal, and late-sown wheat in Punjab extends from the end of October to April months. The results of the present study revealed that during these months, i.e., October, November, December, January, February, March, and April the maximum/minimum temperature in the range of 31–34/17–20, 25–29/10–14, 20–23/5–9, 17–20/3–8, 19–25/5–11, 25–30/10–15 and 32–37/14–21 °C, respectively; maximum/minimum RH in the range of 89%–91%/37%–47%, 90%–95%/36%–47%, 91%–97%/43%–53%, 92%–96%/52%–63%, 90%–93%/46%–61%, 86%–90%/36%–51% and 63%–79%/27%–36%, respectively; rainfall up to 58, 18, 38, 57, 79, 56 and 59 mm, respectively; sunshine hours in the range of 5–8, 4–7, 5–8, 4–6, 5–8, 8–9 and 8–10 h, respectively are favourable for high yield of wheat in Punjab state.

4.2. Weather-based agro-advisory for crop management

The information on critical limits of weather variables for different stages of a crop is very important while formulating the weather-based agro advisory for the farmers of the region. Further, it depends on the willingness of farmers to adopt the news aids for improving their farm productivity and the age of the adopter added to his experience in farm practices [30]. In India, both the India Meteorological Department (IMD) and the Indian Council on Agricultural Research (ICAR) disseminate block–level Agro-Advisory Service (AAS) throughout the country [22,23]. Recently, the "All India Coordinated Research Project on Agrometeorology (AICRPAM)" has developed dynamic crop weather calendars (DCWC) for automating agromet advisories using prevailing and forecasted weather [31]. To make farmers self–reliant, sensitizations of the farmers are necessary and provision of timely and accurate AAS with suitable crop–management advisory is to be ensured.

In Punjab state, the weather-based agro-advisory is prepared using the IMD forecasted values of 8 weather parameters, i.e., maximum and minimum temperature, maximum and minimum RH, rainfall, wind speed, wind direction and cloud cover for each district for the coming four days. The growth stages of wheat crops are very sensitive to temperature. In the present study, the information on favourable range of maximum/minimum temperature during sowing to emergence, vegetative, anthesis, grain filling stage, and physiological maturity at Ludhiana (23–31/8–17, 16–26/2–11, 14–21/4–9, 18–29/6–13 and 26–36/10–18 °C, respectively), Patiala (26–33/10–17, 16–27/4–12, 16–23/5–10, 21–30/8–15 and 29–36/14–20 °C, respectively) and Amritsar (24–32/8–17, 16–27/0–10, 16–21/3–9, 18–26/5–11 and 25–35/11–17 °C, respectively) are useful while formulating advisory for the wheat crop. A recent study in Punjab state [20] reported that the farmers who tailored their respective farm operations in accordance with the AAB (Agro Advisory Bulletins) were able to increase the yield of rice and wheat crops by 2.25–3.75 q/ha and 1.75–4.50 q/ha respectively.

4.3. Weather-based crop insurance

Weather-Index Insurance (WII) is an innovative form of index insurance that covers farmers against weather-related extreme events [32]. While formulating the weather-based crop insurance schemes (WBCIS) the information on critical limits of weather variables (like frost, heat, relative humidity, and un-seasonal rainfall) plays a significant role [33]. It is essential to urgently identify temperature thresholds for crop productivity. This is necessary to establish a foundation for evaluating risks associated with extreme temperatures and determining trigger values for weather-index-based crop insurance [34]. From the current study, it was observed that during sowing-emergence, vegetative stage, anthesis stage, grain filling stage, and physiological maturity the maximum/minimum temperature in the range of 23–33/8–17, 16–27/0–12, 14–23/3–10, 18–30/5–15 and 25–36/10–20 °C are optimum for the higher yield of wheat crop. The temperature thresholds above and below these values cause yield reductions. Once the most temperature-sensitive stages are identified, it becomes crucial to understand how grain yield responds to both the intensity and duration of heat stress [35]. The identification of the varied responses of crops to the temperature ranges aids in establishing different rates of payment of indemnity to account for yield losses in various crop cultivars.

5. Conclusion

Weather is one of the most important input variables that influences the growth of crops starting from sowing to harvesting. The cumulative effect of various parameters including precipitation and its distribution, relative humidity, sunshine, and air temperature influences wheat productivity while no one parameter can determine the growth and yield of the crop. The information on the effect of these weather variables on crop growth stages is vital while formulating the agro-advisory for the farmers. Hence these weather-based monthly and weekly thumb rules can be used to predict the high yield of the crop and this agro-advisory can help in tailoring the farm operations in accordance with the optimum range of maximum/minimum temperature and rainfall during the vegetative stage (16–27/0–12 °C and 38 mm) and grain filling stage (18–30/5–15 °C and 26 mm) helps in increasing the productivity of the crop. The crop yield predicted by these thumb rule models can be helpful for extension workers as well as policy planners. Thus, there has been increasing interest in the use and development of robust crop weather response models. The temperature thresholds at critical stages and measuring the impact of heat stress on crop yield can be valuable in developing crop insurance products based on weather indices for wheat crops.

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