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Research Article

Phenology and Agroclimatic Indices of Wheat under Happy Seeder and Conventional Sowing in Central Punjab

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ABSTRACT

In Punjab, rice stubble burning has traditionally been practiced to clear fields quickly for next crop sowing but this practice contributes significantly to air pollution and poses serious environmental and health hazards. To address this issue, several innovative sowing methods such as Happy Seeder, Surface Seeder, Zero-Till Drill, Super Seeder Sowing etc. have been developed. These techniques enable wheat to be sown directly into the fields containing rice residues, thereby eliminating the need for stubble burning. Among them, the Happy Seeder emerged as one of the effective solution. In the present study, wheat was sown with Happy Seeder, which not only reduces stubble burning but also offers multiple benefits as it improves soil health, conserves water and ensures timely wheat sowing after paddy harvest. A field experiment was conducted at the Research Farm of Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana during *rabi* season of 2023-24, to study the phenological behaviour and agro climatic indices of wheat sown under conventional sowing and happy seeder sowing. Two wheat varieties (PBW 725 and PBW 869) were used for this experiment. The phenological observations were recorded visually. Different agro climatic indices *viz.* growing degree days, helio-thermal units, photo-thermal units, hygro-thermal units, heat use efficiency and photo-thermal use efficiency were computed at different phenological stages. Results of the field experiment revealed that maximum number of days (164 and 161 days) were taken by happy seeder sown crop (variety PBW 869 and variety PBW 725) compared to conventional sown crop (154 and 153 days),. Among varieties, variety PBW 869 took maximum number of days to attain different phenological stages as compared to variety PBW 725. Different agroclimatic indices like growing degree days, helio-thermal units, photo-thermal units, hygro-thermal units, heat use efficiency (HUE) and photo-thermal use efficiency (PTUE) were higher under happy seeder sown crop as compared to conventional sown crop. The study revealed that higher heat use efficiency (3.28) photo-thermal use efficiency (2.89) was observed under happy seeded sown crop, primarily due to its longer duration compared to conventional sowing. Analysis of field data showed positive linear relationships between grain yield and different agro climatic indices (growing degree days, helio-thermal units, photo-thermal units and heat use efficiency). Among these, grain yield exhibited significant correlations with photo-thermal use efficiency and heat use efficiency with R^2 values of 0.70 and 0.71 respectively. These results highlight that wheat yield is strongly influenced by the efficiency with which crops utilize accumulated heat and radiation units, reinforcing the importance of agroclimatic indices as predictors of crop performance Wheat crop sown with Happy Seeder requires less operational time and energy while maintaining yield levels. The retention of soil moisture and in-situ management of rice straw make this technology both environmentally sustainable and farmer friendly. Nevertheless, the long term impacts of Happy Seeder technology on natural resource conservation, flora and fauna, farmer adoption further needs investigation.

Key words*:* Wheat, Phenology, Agro climatic indices, Happy seeder sowing, Conventional sowing

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Introduction

Temperature plays a vital role in the growth and development of crops by regulating their physiological, biological, and chemical processes. Each plant species requires a specific amount of accumulated heat units, often referred to as growing degree days (GDD), to progress through its phenological stages. (Kumar *et al*., 2014). These stages include germination, vegetative growth, flowering, and maturity. The transition from one stage to another depends on whether the plant has received the necessary thermal time.

Wheat (*Triticum aestivum* L.), being a cool-season crop, is particularly sensitive to heat stress at all stages of growth and development. Heat stress adversely affects wheat's physiological and phenological processes, significantly shortening its growth and duration, ultimately reducing overall yield. The ideal temperature ranges for critical growth stages such as heading, anthesis, and grain filling are 12°C, 23°C, and 21°C, respectively. However, damage to these stages may occur if the maximum temperature rises above 22°C, 32°C, and 34°C, respectively (Kaur and Dhaliwal, 2018). Understanding the thermal sensitivity and phenological behaviour of wheat under varying conditions is essential for developing effective management practices to ensure crop productivity.

Wheat requires the accumulation of a specific number of heat units to progress through its phenological stages, including emergence, crown root initiation (CRI), tillering, jointing, booting, heading, anthesis, milking, and maturity. These heat units, often measured using agroclimatic indices such as growing degree days (GDD), helio-thermal units (HTUs) and photo-thermal units (PTUs), provide valuable insights into the crop's development. The accumulation of heat units varies among wheat varieties and is influenced by sowing practices that alter the microclimatic environment. Different sowing methods, such as happy-seeded sowing, play a critical role in modifying the crop's microclimatic conditions. These methods influence soil temperature, soil moisture levels, evaporation, and air movement within the crop canopy, which in turn affect the accumulation of degree days and the duration of each growth stage. Happy seeder is used for direct sowing of wheat in fields with rice residues after rice harvest, and for spreading rice straw as mulch in the field, which provides several benefits, such as soil moisture conservation, reduced evaporation, and better regulation of soil temperature. Rice straw mulching creates an insulating effect, improving the microclimate within the crop canopy.

The present investigation was carried out to analyse the phenological behaviour and agroclimatic indices of wheat varieties under different sowing methods in the central Punjab region. The study aimed to assess how varying sowing practices influence the thermal environment and phenological progression of wheat, thereby affecting its growth, development, and yield. By understanding these interactions, the research provides valuable recommendations for optimizing sowing methods to improve wheat production under the climatic conditions of central Punjab.

Material and Methods

The field experiment was conducted at the Research Farm of the Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University in Ludhiana situated at 30°54′N latitude and 75°48′E longitude with an elevation of 247 m above mean sea level during the *rabi* season of 2023-24. This location experiences a sub-tropical climate with cold winters and hot summers. Ludhiana receives an average annual rainfall of 840 mm. The experiment was laid out in Strip plot design with three replications with plot size of 5 metre × 4 metre. The treatments comprised two sowing methods (S1-Conventional sowing and S2-Happy seeded sowing), two wheat varieties (PBW 725 and PBW 869), and two irrigation treatments (I1=Recommended irrigation and I2=One extra than recommended after 15th March). Crop was sown on 3rd November. The recommended PAU Packages of Practices were followed to raise the crop. Observations on different phenophases, viz., complete emergence, tillering, heading, booting, anthesis, milking, and physiological maturity, were recorded. Different agroclimatic indices were calculated in EXCEL by different formulas (Table 1).

Table 1. Formulae used for computation of different thermal indices

Agroclimatic indices	Formula	Reference
Growing degree days	$GDD = \frac{T_{max}+T_{min}}{2} - T_{base}$	Nuttonson (1995)
	For wheat crop Tbase= 5°C (Slafer and Savin 1991)	
Photo-thermal units	PTU (°C day hours) = GDD × day length	Rajput (1980)
Helio-thermal units	HTU (^{o}C day hour) = GDD × actual bright sunshine hours	Rajput (1980)
Hygro-thermal units	HgTU (^{o}C day per cent) = GDD × RH	Sastry *et al* (1985)
Heat use efficiency	HUE(kg ha^{-1}/°C day hours) = Dry matter or Grain yield/GDD	(Major *et al* 1975)
Photo-thermal use efficiency	PTUE (kg ha^{-1}/°C day hours) = Dry matter or Grain yield/PTU	Sastry *et al* (1985)

Results and Discussion

Crop phenology

Crop phenology refers to the periodic occurrence of developmental stages in the life cycle of a crop, largely determined by environmental conditions. These stages, such as germination, vegetative growth, flowering, and maturity, are critical checkpoints that reflect how plants respond to their surroundings. Understanding phenology is essential for assessing biomass partitioning (how plants allocate energy to roots, stems, leaves, and grains) and for evaluating stress factors that may hinder growth (Goswami *et al*., 2006).

The field experiment results revealed that different sowing methods and crop varieties significantly influenced all growth stages, leading to variation in the overall duration of the crop (Table 2). It was observed that conventional sowing required fewer days to reach successive phenological stages compared to a happy-seeded crop. Specifically, Happy-seeded varieties PBW 725 and PBW 869 required 161 and 164 days, respectively, from sowing to physiological maturity. Conventional sown varieties reached physiological maturity earlier, requiring 153 and 154 days, respectively. Variety PBW 725 consistently matured earlier than PBW 869 under both sowing methods, indicating its relatively shorter growth duration. The delayed physiological maturity observed in happy-seeded crops was attributed to lower soil temperature and higher soil moisture, conditions that slowed down crop development compared to conventional sowing. Happy-seeded sowing benefits from reduced weed growth, water savings, improved soil health, and

Table 2. Phenological behaviour of wheat varieties under different methods of sowing during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	6	7	9	10
CRI	19	20	23	25
Maximum tillering	42	43	48	51
Jointing (start)	58	59	66	70
Flag leaf initiation	71	72	81	85
Booting (start)	84	85	94	99
Heading (start)	97	98	108	114
Anthesis (start)	103	104	117	123
Milking (start)	114	115	128	133
Soft dough (start)	125	126	139	144
Hard dough (start)	139	140	149	154
Physiological maturity	153	154	161	164

environmental quality, leading to better growth of the happy-seeded crop (Sharma and Singh, 2020). Happy seeded sown crop matures late as compared to the conventional sown crop, as reported by Singh *et al*. (2023). Similarly, Korav *et al*. (2020) also reported that rice residues placed on the soil surface affect the growth stages of the wheat crop.

Agroclimatic indices

Accumulated growing degree days (AGDD)

Growing degree days (GDD) are a simple tool for determining the relationship between plant growth and average air temperature. According to Nuttonson (1955), there is a direct relationship between temperature and growth. Various phenophases of the crop are initiated when a specific temperature regime is available (Basu *et al.*, 2012). According to Nath *et al.* (1999), GDD represents the crop's thermal environment. It can be used as the best index to predict different growth stages of wheat crop under Punjab conditions (Hundal *et al*., 1997).

The variation in accumulated growing degree days under different treatments and growth stages is presented in Table 3. Results of the field experiment revealed that, owing to the longer duration of the happy-seeded sown crop, more GDDs were accumulated at various phonological stages as compared to the conventional sown crop. Variety PBW 869 recorded the highest accumulation, with 1881.6°C days under happy seeded sowing, followed by 1676.4°C days under conventional sowing from sowing to physiological maturity. This indicates that extended crop duration under happy seeding leads to higher GDD accumulation. These findings are consistent with earlier studies. Singh *et al.* (2001) reported that a longer-duration wheat crop accumulates more GDDs than a shorter-duration wheat crop. Similarly, Mallick *et al*. (2006) observed comparable trends, reinforcing the relationship between crop duration and accumulated heat units.

Accumulated helio-thermal units (AHTU)

Helio-thermal units (HTU) measure the cumulative effect of solar radiation (sunlight) and temperature on plant growth and development. Helio-thermal units significantly influence crop phenology by regulating the timing and duration of growth stages, such as germination, flowering and maturity. Adequate HTU accumulation ensures the crop's progress through its phenological stages optimally, while deviations can lead to delay, early flowering or incomplete flowering. This directly affects the productivity and quality of the crop (Ali *et al*., 2004). The results of the field experiment indicate that maximum helio-thermal units were accumulated by the happy-seeded sown crop compared to the conventional sown crop (Table 4). Accumulated

Table 3. Growing degree days (°C day) accumulation of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	119.0	133.0	160.2	174.1
CRI	303.1	316.1	354.0	379.1
Maximum tillering	561.4	569.4	612.9	640.5
Jointing (start)	692.8	697.2	725.7	740.1
Flag leaf (start)	745.4	747.8	785.3	805.8
Booting (start)	798.2	805.8	882.5	920.0
Heading (start)	902.9	911.2	1018.4	1082.1
Anthesis (start)	960.6	970.9	1115.4	1181.6
Milking (start)	1082.1	1092.6	1236.4	1305.7
Soft dough (start)	1200.9	1212.1	1397.3	1489.9
Hard dough (start)	1397.3	1416.9	1586.4	1676.4
Physiological maturity	1657.4	1676.4	1817.9	1881.6

Table 4. Helio-thermal units (°C day hours) accumulation of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	508.2	508.2	770.7	900.0
CRI	1872.0	1933.1	2078.2	2127.5
Maximum tillering	3320.9	3380.1	3715.4	3870.7
Jointing (start)	3988.5	3988.5	3992.3	3996.2
Flag leaf (start)	3996.2	3999.5	4071.1	4168.6
Booting (start)	4117.7	4168.6	4359.7	4693.6
Heading (start)	4537.1	4620.1	5349.0	5947.5
Anthesis (start)	4979.1	5076.9	6170.5	6523.9
Milking (start)	5947.5	6034.7	7003.8	7575.6
Soft dough (start)	6710.5	6830.4	8484.9	9225.4
Hard dough (start)	8484.9	8676.9	9902.2	10798.2
Physiological maturity	10575.9	10798.2	12388.7	12518.5

helio-thermal units from sowing to physiological maturity were 12518 °C-day-hr and 10798.2 °C day hour in variety PBW 869 under happy-seeded and conventional methods, respectively. The higher HTUs accumulated by the happy-seeded sown crop may be due to the fact that the crop took a longer duration to reach different phenological stages. Khichar and Niwas. (2007) reported similar results for accumulated helio-thermal units under different sowing methods. Khavse *et al*. (2015) also revealed that short duration crop accumulates less helio-thermal units than long duration crop.

Accumulated photo-thermal units (APTU)

The photo-thermal unit concept provides a reliable index of crop progress that can be used to predict yield (Pal *et al*., 2013). PTUs measure the combined influence of temperature and day length (photoperiod) on crop growth and development. Photo-thermal units varied across different sowing methods. A happy-seeded sown crop resulted in higher accumulated photo-thermal units as compared to a conventional sown crop (Table 5). From sowing to physiological maturity, accumulated photo-thermal units were 18343.3 °C day hour (conven-

Table 5. Photo-thermal units (°C day hours) accumulation of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	1247.9	1393.9	1677.0	1821.4
CRI	3151.8	3285.2	3789.8	3929.7
Maximum tillering	5778.7	5859.4	6298.0	6576.2
Jointing (start)	7103.7	7148.2	7436.6	7583.1
Flag leaf (start)	7636.7	7661.1	8046.4	8258.4
Booting (start)	8179.7	8258.4	9058.2	9453.8
Heading (start)	9273.5	9361.2	10542.8	11255.3
Anthesis (start)	9901.3	10015.2	11630.9	12382.6
Milking (start)	11255.3	11373.5	13011.1	13817.3
Soft dough (start)	12603.4	12731.9	14922.8	16048.8
Hard dough (start)	14922.8	15160.4	17231.2	18343.3
Physiological maturity	18108.1	18343.3	20106.8	20927.7

tional) and 20106.8 °C day hour (happy seeded) in variety PBW 869. Mehta and Dhaliwal. (2020) also reported that higher photo-thermal units were taken by the crop, which took a larger number of days to move from one phenological stage to the next phenological stage.

Accumulated hygro-thermal units (AHgTU)

The hygro-thermal units determine the combined effect of temperature and humidity. High temperatures combined with low humidity can cause heat stress, reducing grain size and yield, while excessive humidity with low temperatures can promote diseases like rust, affecting crop health and productivity. The hygro-thermal units of wheat crop under different sowing methods are presented in Tables 6 and 7. Data indicate that from sowing to physiological maturity, the accumulated hygro-thermal units during morning hours were 146508.6 and 157687.1°day per cent in variety PBW 725 and 146508.6 and 157687.1°day per cent in variety PBW 869, under conventional and happy seeded sown crop, respectively. Similarly, accumulated hygro-thermal units during evening hours in variety PBW

Table 6. Hygro-thermal units (°C day per cent) accumulation during morning hours of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	10864.0	11942.0	14471.6	15764.3
CRI	27759.7	28955.7	32476.4	34776.5
Maximum tillering	51968.9	52688.9	56784.3	59432.4
Jointing (start)	64321.8	64321.8	67353.0	68714.9
Flag leaf (start)	69208.4	69441.2	72947.0	74919.6
Booting (start)	74182.4	74919.6	81956.1	85461.5
Heading (start)	83858.8	84639.0	94103.7	90312.2
Anthesis (start)	89344.0	90312.2	102354.4	107787.8
Milking (start)	99654.0	100557.0	112400.4	118281.6
Soft dough (start)	109205.4	110213.4	126033.6	132999.1
Hard dough (start)	126033.6	127386.0	140550.8	147933.6
Physiological maturity	146508.6	147933.6	157687.1	161963.4

Table 7. Hygro-thermal units (°C day per cent) accumulation during evening hours of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Phenological stages	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
Complete emergence	4713.2	5833.2	7175.6	7759.4
CRI	12538.5	13097.5	14761.4	16164.6
Maximum tillering	25146.1	25498.1	27246.3	28666.7
Jointing (start)	32589.1	32589.1	35171.7	36266.6
Flag leaf (start)	36618.4	36812.8	39554.8	40716.7
Booting (start)	40344.3	40716.7	45904.7	47544.1
Heading (start)	46852.0	47159.1	51743.8	49625.5
Anthesis (start)	49254.7	49625.5	55369.4	58410.8
Milking (start)	54058.4	54352.4	60473.8	63510.8
Soft dough (start)	59089.3	59526.1	67017.1	70838.3
Hard dough (start)	67017.1	67918.7	75030.9	77869.6
Physiological maturity	77451.6	77869.6	80795.7	83401.8

869 were 77869.6°day per cent (conventional) and 83401.8 °day per cent (happy seeder), and in variety PBW 725, accumulated 77451.6°C day per cent (conventional) and 80795.7°C day per cent (happy seeder). Higher hygro-thermal units were accumulated by a happy seeder sown crop, followed by a conventional sown crop, which took a lesser number of days to reach physiological maturity. Korav *et al*. (2022) also reported that a happy-seeded sown crop took a larger number of days to attain physiological maturity. Kamboj *et al*. (2022) also reported that accumulated hygro-thermal units were higher in the crop that took the longest to reach different growth stages.

Heat use efficiency

Heat use efficiency is the plant's ability to manage and utilise heat effectively, which affects various biochemical and physiological processes essential for plant growth. According to Liu *et al*. (2020), heat use efficiency is key to optimising crop production, as it helps to assess how well a plant can yield under different environmental conditions. Heat use efficiency was calculated for dry matter accumulation (from 45 to 105 days after sowing) and for maturity using grain yield (Tables 8 and 10). It showed an increasing trend from 45 days after sowing to 105 days after sowing, and maximum heat use efficiency was observed under the happy-seeded sown variety PBW 869 (1.60 kg/ha/°C days), followed by variety PBW 725 (1.56 kg/ha/°C days) at 105 DAS. Heat use efficiency from 45 DAS up to 120 DAS was higher in variety PBW 869 as compared to variety PBW 725. At maturity, comparatively the heat use efficiency was higher for happy seeded sown crop as compared to conventional sown crop. The reason for low efficiency in terms of heat use efficiency was short growth period of conventional sown wheat varieties which accumulates less dry matter as compared to long duration varieties. Kaur *et al.* (2016) also reported that heat use efficiency started increasing from vegetative growth up to physiological maturity. Bhardhwaj and Bhardwaj. (2022) also reported that heat use efficiency is higher in a crop which takes a larger number of days to reach maturity as compared to a conventional sown crop which matures early.

Photo-thermal use efficiency

Photo-thermal use efficiency relates to how well plants convert solar energy into chemical energy through photosynthesis, while also accounting for the heat generated during this process (Holzworth *et al.*, 2014). It is the measure of the ability of a plant to convert absorbed photosynthetically active radiation (PAR) and thermal energy into biomass production. From 45 to 105 DAS, dry matter accumulation was used to calculate it, and for maturity, grain yield was used, as presented in Tables 9 and 10. The results revealed that maximum photo-thermal use efficiency was observed under a happy-seeded sown crop, followed by a conventional sown crop, from 45 DAS to 105 DAS. The highest photo-thermal use efficiency (0.306 kg ha^{-1}/°C day hours) was observed for variety PBW 869, followed by variety PBW 725 (0.298 kg ha^{-1}/°C day hours) at maturity. Sourour *et al*. (2016) reported similar results that the time required to reach different phenological stages affects the photo-thermal use efficiency of the wheat crop. Gupta *et al*. (2020) also reported that the highest photo-thermal use efficiency was observed in the crop which took more number of days to reach maturity.

Table 8. Heat use efficiency (kg/ha/°C day) of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Days after sowing	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
45 DAS	0.57	0.58	0.62	0.63
60 DAS	0.65	0.66	0.69	0.71
75 DAS	1.08	1.10	1.13	1.18
90 DAS	1.35	1.36	1.40	1.46
105 DAS	1.51	1.52	1.56	1.60
120 DAS	1.45	1.43	1.49	1.51

Table 9. Photo-thermal use efficiency (kg/ha/°C day hours) of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Days after sowing	Conventionally sown		Happy seeder sown	
	PBW 725	PBW 869	PBW 725	PBW 869
45 DAS	0.056	0.063	0.142	0.167
60 DAS	0.060	0.066	0.150	0.169
75 DAS	0.061	0.068	0.510	0.171
90 DAS	0.058	0.064	0.147	0.165
105 DAS	0.060	0.067	0.149	0.170
120 DAS	0.062	0.069	0.155	0.175

Table 10. Heat use efficiency and photo-thermal use efficiency (at maturity) of conventional and happy seeder sown wheat varieties during *rabi* 2023-24

Treatments	Heat use efficiency (kg/ha/°C day)		Photo-thermal use efficiency (kg/ha/°C/day hours)	
	PBW 725	PBW 869	PBW 725	PBW 869
Conventional sowing	2.85	3.34	0.261	0.306
Happy seeder sowing	3.23	3.34	0.293	0.282

Relationship of grain yield with different agroclimatic indices

Wheat crop experiences diverse weather conditions throughout its life cycle, which lead to significant variations in growth rate and yield. To quantify these effects, several agroclimatic indices (GDD, HTU, PTU and AHgTU) are commonly used to describe changes in crop phenology and growth parameters. In the present field experiment, the relationships between different agroclimatic indices (growing degree days, helio-thermal units, and photo-thermal units) and wheat grain yield were computed. Results revealed a positive linear relationship between grain yield and these indices, indicating that higher accumulation of thermal and radiation units corresponded to increased productivity. The higher R^2 values obtained in regression analysis further confirmed that grain yield was significantly influenced by these agroclimatic indices. This demonstrates that wheat yield potential is closely linked to the thermal and radiation environment experienced during its growth cycle, and that agroclimatic indices can serve as reliable predictors of crop performance under varying environmental conditions.

Relationship between grain yield and accumulated growing degree days (AGDDs)

The relationship between grain yield and accumulated growing degree days (AGDDs) under different sowing methods was computed and presented in Fig. 1. There was a positive and linear relationship between the grain yield and accumulated growing degree days. A higher R^2 value (0.71) indicates that 71% variation in grain yield can be explained by variations in accumulated growing degree days. It indicates that plants with more growing degree days produce higher grain yield. Kaur *et al*. (2016) observed a similar relationship between grain yield and growing degree days, and suggested that a larger number of days taken by the crop to complete its phenological stages had a positive effect on the grain yield of wheat. Dar *et al.* (2018) also reported that higher GDDs required to reach various phenological stages were associated with higher crop yields.

Relationship between grain yield and accumulated helio-thermal units (AHTU)

The relationship between the grain yield and accumulated helio-thermal units (AHTU) under

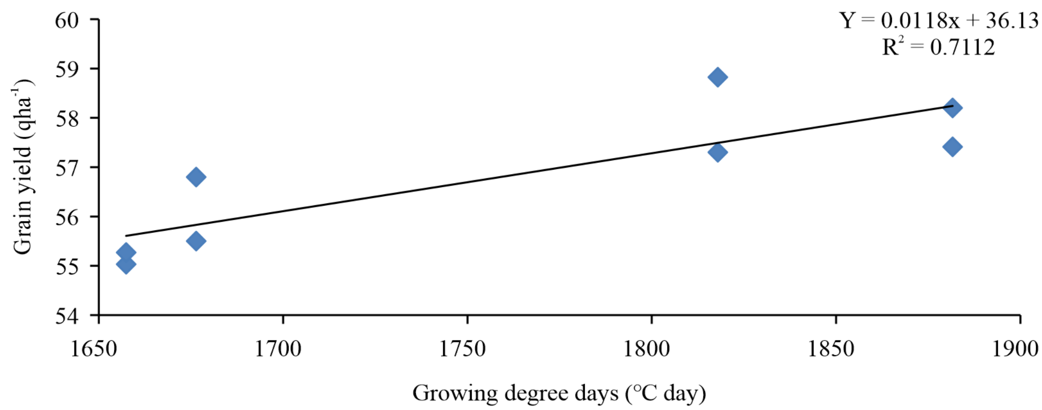

Fig. 1. Relationship between growing degree days and grain yield during *rabi* 2023-24

different sowing methods was computed, and a positive and linear relationship was observed for these variables as presented in Fig. 2 and explained 78% variations during the crop growing season. These findings are similar to those of Kaur (2022), who also observed a positive, linear relationship between grain yield and helio-thermal units. Sidhu *et al*. (2020) also reported that happy-seeded sown crop accumulated the highest heliothermal units as compared to conventional sown wheat. Singh (2019) reported similar results, that accumulated helio-thermal units were higher in residue retention treatment.

Relationship between grain yield and accumulated photo-thermal units (APTU)

The photo-thermal units (PTU) for a given day were calculated by multiplying the growing degree day by the duration of daylight on that particular day. The PTU is considered a more important metric than GDD, especially for photosensitive crops (Singh *et al.,* 2016). The relationship between grain yield and accumulated photo-thermal units (APTU) under different sowing methods was calculated for the *Rabi* season 2023-24 as shown in Fig. 3. A positive and linear relationship exists between grain yield and accumulated photo-thermal units, which explained 70% of the variability, indicating that as PTU increases, grain yield also increases. Brar *et al*. (2022) also reported more accumulated photo-thermal units in a crop that took a greater number of days to reach maturity, which leads to higher yield in a long-duration crop. These findings are also similar to those of Sidhu *et al.* (2020), who reported more accumulated photo-thermal units in a happy seeder-sown wheat crop, which took more days to reach different phenological stages.

Relationship between grain yield and heat use efficiency

A linear relationship was observed between grain yield and the heat use efficiency of wheat under different sowing methods (Fig. 4). The linear

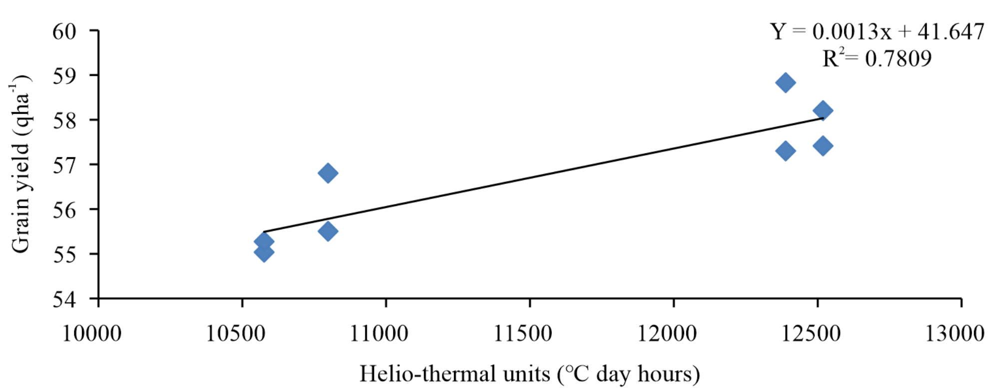

Fig. 2. Relationship between helio-thermal units and grain yield during *rabi* 2023-24

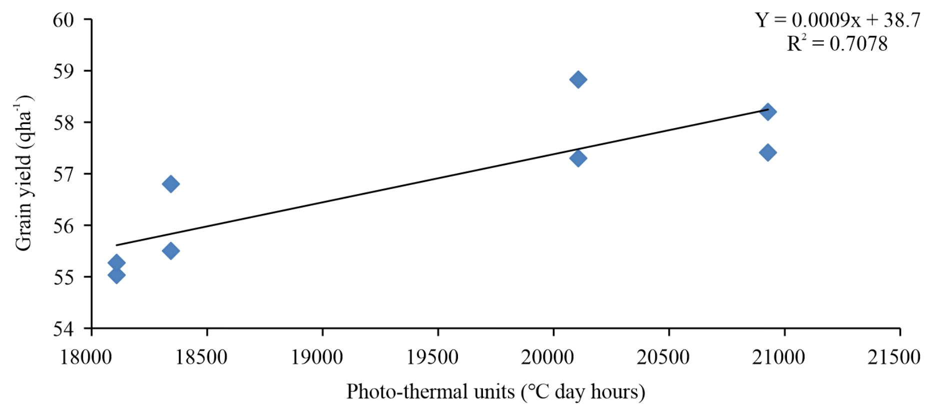

Fig. 3. Relationship between photo thermal units and grain yield during *rabi* 2023-24

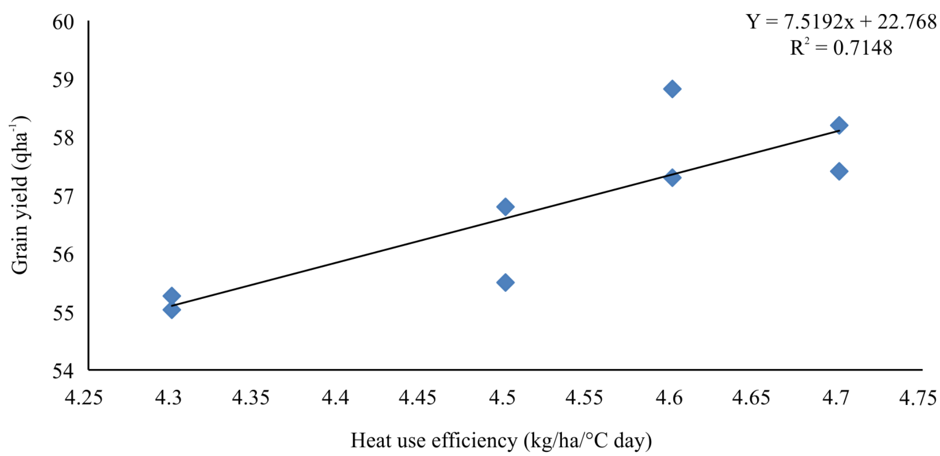

Fig. 4. Relationship between heat use efficiency and grain yield during *rabi* 2023-24

regression equation explained 71% of the variation in grain yield. It indicates that as heat-use efficiency improved at various stages of the crop, there was a corresponding increase in wheat grain yield. Singh *et al*. (2016) also found a linear relationship between grain yield and heat use efficiency of wheat. Similar findings were also reported by Mehta and Dhaliwal. (2020), who found a strong and positive relationship between heat use efficiency and grain yield of wheat crop.

Conclusions

Happy seeded sown varieties had taken a larger number of days to attain different phenological stages than conventional sown varieties. Delayed germination and slower early vegetative growth were observed in the happy-seeded crop. However, these varieties accumulated higher agroclimatic indices (GDD, HTU, PTU) than conventional sown varieties. Higher heat-use efficiency and photo-thermal use efficiency were observed under happy-seeded sown conditions, due to the extended crop duration. Regression analysis revealed positive linear relationships between different agroclimatic indices (growing degree days, helio-thermal units, photo-thermal units and heat use efficiency) and grain yield, confirming that yield performance is strongly influenced by thermal and radiation environments. It can be concluded that wheat crop sown with the Happy Seeder require less operational time and energy while maintaining yield levels. The retention of soil moisture and in-situ management of rice straw make this technology both environmentally sustainable and farmer-friendly. Nevertheless, the long-term impacts of Happy Seeder technology on natural resource conservation, biodiversity flora and fauna, and farmer adoption further need investigation to fully realise its potential in sustainable agriculture.

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