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Impact of different sowing dates and weed management strategies on phenological development, productivity, and thermal efficiencies of direct seeded rice

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Abstract: Background: Sowing dates and weed management practices could alter several phenological phases of direct seeded rice. However, limited is known about the impacts of these aspects on phenology, thermal efficiencies, and agro-meteorological indices of direct seeded rice. **Objective:** The objective of the study was to evaluate the effect of sowing dates and weed management strategies on phenology, thermal efficiencies, and agro-meteorological indices of direct seeded rice. **Methods:** Two sowing dates [10th May (early) and 3rd June (late)] and six weed management strategies [i.e., weedy-check, 4-time mechanical weeding (weed-free), bensulfuron methyl + pretilachlor as pre-emergence, oxyfluorfen as pre-emergence, bensulfuron methyl + pretilachlor as pre-emergence + 2,4-D as post-emergence, and oxyfluorfen as pre-emergence + 2,4-D as post-emergence] were included in the study. **Results:** Early sowing took more days to reach various phenological phases, accumulated higher heat units, and recorded significantly higher thermal efficiencies, and yield than late sowing. Mechanical weeding took more time to complete different developmental stages, hence, accumulated higher heat units and recorded significantly higher thermal-use efficiencies and yield followed by application of bensulfuron methyl + pretilachlor as pre-emergence + 2,4-D as post-emergence. **Conclusion:** Earlier sowing with 4 mechanical weedings or successive pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D is recommended for better phenological development and yield of direct seeded rice.

Keywords: Agrometeorological Indices; Drum Direct Seeded Rice; Heat Units; Phenology

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1. Introduction

Rice is a significant crop providing nourishment to more than half of the global population (Bin Rahman, Zhang, 2023). Rice is an important crop in India as it plays significant cultural and economic roles in the country (Ahuja and Ahuja, 2014). India produces 122 million tons of rice annually on an area of 44.4 million hectares making it the main food crop in the country (US Department of Agriculture, 2021). Transplanting is the traditional way of growing rice in India. However, labour and water shortages, and rising cultivation expenses has resulted in the transition to direct seeding of rice in the country. Direct seeded rice (DSR) has revolutionized the industry by eliminating the problems associated with traditional transplanting methods. It offers several benefits, such as a 40–45% reduction in labour requirements (Kumar, Ladha, 2011), 30–40% water saving (Ladha et al., 2016), 60–70% energy saving (Mohammad et al., 2018), 20% saving of irrigation water (Bhullar et al., 2018), faster and convenient planting with 7-10 days earlier maturity of rice crop (Sidhu et al., 2014), and higher economic returns with substantially higher benefit cost ratio (Soriano et al., 2018). Hence, direct seeding of rice is gaining popularity among the farmers in the country. However, phenological development of DSR under various weed management strategies remains unexplored in the country.

Meteorological conditions play a critical role in sustainable rice production by impacting growth, phenological development, and crop productivity (Bishnoi et al., 1995; Ji et al., 2007). Agro-meteorological factors such as maximum and minimum temperatures, rainfall, relative humidity, and sunshine hours have a substantial impact on the phenology, development, and growth of crops (Charalampopoulos, 2021). Agro-meteorological indices like growing degree days (GDD) (Reasor et al., 2018), photothermal units (PTU), heliothermal units (HETU), and hydrothermal units (HTU) etc. are utilized for assessing the impact of climatic variables on a particular crop during different phenological stages (Hussain et al., 2012). Distinct temperatures are necessary for a plant to complete different phenological phases.

Accumulated heat units or GDD serve as a reliable indication for estimating the duration required for a crop to reach certain phenological phases (Bhat et al., 2015). The accomplishment of a certain phenological phase requires the accumulation of a specific quantity of heat units, which changes for each phenological stage. The time required to reach a certain phenological phase is directly proportional to the difference between the mean and base temperatures, according to the GDD principle (Gouri et al., 2005). The phenology of the crop determines the best date and time for a developing phase. Common techniques for evaluating the correlation between plant growth, sunshine hours, temperature, and day length include GDD, HTU, PTU, and phenothermal index (PTI). The climate and other meteorological conditions have a crucial influence in determining the heat unit need of crops at each stage of growth, which subsequently impact development and biomass accumulation of crops (Golla et al., 2018; Xu et al., 2021). Aligning the timing of crop phenology with suitable meteorological conditions is crucial for optimizing productivity and enhancing resource use efficiency.

The GDD is a widely used metric throughout the growing season to demonstrate the correlation between weather conditions and crop development and yield. The efficient use of heat in connection to dry matter production or yield is a crucial factor with several applications. To comprehend the phenology and planting schedules of various crop cultivars at a regional and temporal level, one must possess knowledge of GDD, HTU, PTU, and HUE (Amgain, 2013). Several studies have inferred the impacts of sowing dates on yield and morphological attributes of rice (Wu et al., 2020; Zhou et al., 2023); however, limited studies have evaluated their influence on agroclimatic indices (Sultana et al., 2020).

Weed-crop competition is a prevalent challenge faced by Please change to DSR due to slower growth compared to weeds (Dass et al., 2017; Shekhawat et al., 2020). Intense competition among rice plants and weeds for sunshine, nutrients, and water leads to reduced crop output and worse grain quality. Weed mismanagement is the second most significant impediment to yield in DSR worldwide after water scarcity (Shekhawat et al., 2020). Weeds are responsible for about 10% out of the 40% decrease in rice yield attributed to pests. However, the loss caused by weeds might potentially rise to 32% in DSR. Nevertheless, some reports also indicate 67% yield loss in DSR caused by weeds (Al Mamun, 2014; Javaid et al., 2022; Kashyap et al., 2021). Hence, weed control is a crucial agronomic management strategy in DSR for enhancing yield (Xu et al., 2019). Improving the initial growth of rice seedlings might help in weed management.

Several weed management strategies, i.e., mechanical, and manual weeding are used to control weeds in DSR; however, high labour costs, labour shortages, and the difficulty in differentiating between weeds and crop plants limit the use of these management strategies (Kumar, Ladha, 2011). Although herbicide resistance, shifts in weed flora, and unavailability of new broad-spectrum herbicides are the major issues in chemical weed control, it remains essential in DSR. Careful use of herbicides according to established protocols can result in successful weed management in DSR (Javaid et al., 2022).

The weed seed bank is concentrated in upper 2–3 cm of soil in DSR; therefore, application of pre-emergence herbicides results in successful weed management (Chauhan, Johnson, 2009). Several herbicides are available which effectively control weeds in DSR. Pendimethalin, oxadiazon, oxadiargyl, pretilachlor are the major pre-emergence herbicides. Similarly, bispyribac-sodium, penoxsulam, fenoxaprop, azimsulfuron, 2,4-D, and metsulfuron-methyl are frequently used post emergence herbicides. A combination of pre- and post-emergence herbicides have been proved successful for weed management in DSR (Singh et al., 2008). However, the impacts of herbicides on agroclimatic indices remains elusive.

Optimum sowing date and weed management strategy are needed for improving rice productivity and agroclimatic indices. However, little is known about the phenological fluctuations caused by different sowing dates and weed management strategies. Therefore, this study investigated the impact of different sowing dates and weed management strategies on agroclimatic indices of DSR. It was hypothesized that different sowing dates and weed management strategies would result in different indices and results would help to choose the optimum sowing date and weed management strategy.

2. Material and Methods

2.1 Experimental Site

The current study was conducted at Agronomy Research Farm, Faculty of Agriculture, Wadura, Sopore, SKUAST-K during *Kharif* seasons of 2018 and 2019. The experimental site is located between 34° 21¢ North latitude and 74° 23¢ East longitude. The region falls in temperate zone having freezing winter and hot summer. Growing period of rice in the region is 140–150 days. The initial soil nutrient contents of the experimental field were analysed, which revealed that the texture of soil was silty-clay-loam (10.5% sand, 54.2% silt, and 35.3% clay) with high organic carbon content (0.97%), neutral pH (6.9), and medium level of available nitrogen (N), phosphorus (P) and potassium (K) (325, 16.9, and 245 kg ha^{-1}, respectively).

2.2 Weather Conditions

The weather condition of the experimental site varied throughout the crop growing duration. The mean maximum and minimum temperatures were 32.46 °C and

17.24 °C in 2018 and 27.94 °C and 12.92 °C in 2019. The average precipitation was 168.06 mm and 402.80 mm in 2018 and 2019, respectively. The mean of total sunshine hours for standard meteorological weeks was summed up as 172.38 in 2018 and 154.89 in 2019. The average maximum and minimum relative humidity were 90.45% and 62.21%, respectively in 2018 while it was 77.58% and 54.16% in 2019.

2.3 Experimental Design and Treatment Details

The study comprised of two factors (i.e., two sowing dates and 6 weed management strategies). Two sowing dates (D_1: 10th May and D_2: 3rd June) were kept in main plot and six weed management strategies were randomized in sub-plots. The weed management strategies included in the study were: W_1 = weedy-check, W_2 = four time mechanical weeding at 15, 30, 45 and 60 days after sowing (DAS) (equivalent to weed-free), W_3 = pre-emergence application of 60 g a.i. ha^{-1} Bensulfuron-methyl (BSM) + 600 g a.i. ha^{-1} Pretilachlor, W_4 = pre-emergence application of 750 g a.i. ha^{-1} Oxyfluorfen, W_5 = W_3 + post emergence application of 0.75 kg a.i. ha^{-1} 2,4-D (30–35 DAS) and W_6 = W_4 + post emergence application of 0.75 kg a.i. ha^{-1} 2,4-D (30–35 DAS). The area of the treatment units was 15 m^2 (5 m × 3 m) and a half meter buffer zone was maintained between the sub-plot treatments to avoid herbicides' drift. Mechanical weeding was done four times at 15, 30, 45 and 60 DAS to keep the field weed-free, while weedy-check treatment received no weed control and weeds were allowed to grow. Herbicides having granular formulation were mixed with sand and applied as per treatments. A knapsack sprayer equipped with flat fan nozzle was utilized for application of liquid herbicides at an application pressure of 5.6 Kg cm^{-2} and discharge of 500 mL min^{-1}.

2.4 Crop Management

The experimental field was ploughed by using a tractor-drawn disc-plough followed by primary tillage. On the next day, the field was levelled manually, after three ploughings that had prepared the soil to a smooth and fine texture. The rice variety 'Shalimar Rice-3' with an average yield potential of 7.0–7.5 t ha^{-1} and 135–140 days growing period was used in the study. The pre-germinated seeds were sown in rows in the north-east direction using a six-row drum seeder with a spacing of 20 × 10 cm. The well decomposed farmyard manure (10 t ha^{-1}) was applied at field preparation. The primary nutrients, i.e., N, P_2O_5 and K_2O (120:60:30 kg ha^{-1}) were incorporated in the experimental field through commercial formulations, i.e., urea, diammonium phosphate and muriate of potash, respectively. The recommended doses of P and K and half dose of N was applied as a basal dose before seed sowing. The remaining half of N was supplied to the crop in two equal splits at tillering and panicle initiation stages.

2.5 Computation of agro-meteorological indices and thermal use efficiencies

Different weather attributes, i.e., maximum, and minimum temperatures, day length, sunshine hours, and mean relative humidity were used for computation of agro-meteorological indices. GDD, HTU, PTU, HyTU and PTI were computed at various crop phenological stages employing the formulas given below. All the mentioned indices were computed from the sowing date to each phenological phase with a base temperature of 9 °C.

$$GDD=\frac{T^{max}-T^{min}}{2}\,T_b \qquad (1)$$

Here T_{max} indicates daily maximum temperature, T_{min} indicates daily minimum temperature, and T_b indicates base temperature (growth of plant species ceases below this temperature).

$$HTU=GDD \times SSH \qquad (2)$$

Here SSH (hour) indicates the daily sunshine hours.

$$PTU=GDD \times DL \qquad (3)$$

Here DL (hour) depicts the day length.

$$HyTU=GDD \times RH \qquad (4)$$

Here RH (%) depicts the daily mean relative humidity.

$$PTI=\frac{\text{Heat units consumtion between two phenologocal stages}}{\text{Time between two phenophases}} \qquad (5)$$

Grain and biological yields were divided by respective agro-meteorological indices for the computation of HUE, HTUE, PTUE and HyTUE.

2.6 Statistical Analysis

The data was analysed using analysis of variance technique (ANOVA) (SAS Software packages, SAS EG v4.3, SAS Institute, Cary, NC, USA) and comparison among the treatment means was done based on critical difference (CD) tested at a significance level of 5%. The differences among years were tested first, which were non-significant. Therefore, the data of both years were pooled for analysis. As per ANOVA, data analysis of crop phenology and grain yield was conducted using statistical procedure followed in split-plot design. The degree of relation between grain and biological yield with respective indices was determined by linear regression. The ANOVA indicated that the interaction between sowing dates and weed management strategies was non-significant; therefore, individual effects were presented and interpreted in the current study.

3. Results and Discussion

A total 11 weed species belonging to 7 families were recorded from the study area. Poaceae and Cyperaceae were the most represented families with 3 species, whereas remaining 5 families were presented with 1 species. The weed species recorded during the study were; *Echinochloa crus-galli* (L.) P.Beauv., *Echinochloa colonum* (L.) Link, *Cynodon dactylon* (L.) Pers., *Ammannia baccifera* L., *Marsilea quadrifolia* L., *Pontederia vaginalis* Burm.f., *Alisma plantago-aquatica* L., *Potamogeton distinctus* A.Benn., *Cyperus iria* L., *Cyperus difformis* L., and *Fimbristylis littoralis* Gaudich.

Significant variation was recorded among different sowing dates and weed management practices for attaining various phenological stages (Table 1). Earlier sowing date (10th May) took more days to reach various phenological phases than late sowing (3rd June). The prevalence of cooler temperatures on earlier sowing date increased the number of days, demanding more days to complete different phenological phases and reach maturity (Chander Shekhar Dagar et al., 2017; Sarangi et al., 2021). Weedy-check treatment completed lifecycle in lesser number of days to reach various phenological phases. The highest number of days to reach maturity were recorded for mechanical weeding. Similarly, pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D took more time to reach maturity due to suppression of weeds and favouring luxuriant rice crop growth reducing intra and inter plant competition for different growth factors (Ahmed et al., 2020).

Varied sowing dates and weed management strategies resulted in significant difference in heat unit accumulation by crop at different phenological phases (Table 2). The highest heat units (1741.51 °C day) were accumulated by earlier sowing as compared to late sowing (1553.98 °C day). The highest heat unit accumulation in earlier sowing was due to optimum weather conditions and extended crop duration, while delayed sowing resulted in substantially lower reproductive growth and duration of crop (Dar et al., 2018; Singh Brar et al., 2016). Mechanical weeding and pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D accumulated higher heat units (1661.53 °C day) than other weed management approaches. Weedy-check treatment accumulated the lowest heat units (1633.35 °C day). This differences in heat unit accumulation can be owed to differences in crop growth under different weed management strategies (Punia et al., 2018; Rohit et al., 2019).

A significant variation was observed in HTUs at different phenological stages under varying sowing dates and weed management approaches (Table 3). The highest HTUs (12182.67 °C day) were accumulated in earlier sowing than late sowing (10965.63 °C day). The variation in temperature and sunshine hours, combined with the longer duration of early sowing resulted in higher HTUs (Sultana et al., 2020). Mechanical weeding and pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D significantly consumed higher HTUs (11659.47 °C day) than other weed control treatments. Weedy-check treatment recorded the lowest HTUs (11484.86 °C day). Higher crop and weed competition for various resources

Table 1 - Phenology (days) of direct seeded rice under varying sowing dates and weed managing strategies

Treatments	Maximum Tillering	Panicle initiation	50% flowering	Milking	Dough	Harvest
Sowing dates						
10th May	57.76	71.10	85.86	109.96	128.59	137.84
3rd June	46.47	60.74	74.81	98.77	117.45	126.24
SE(m) ±	0.23	0.30	0.05	0.07	0.22	0.08
CD ($p \leq 0.05$)	1.52	2.01	0.32	0.51	1.46	0.56
Weed management strategies						
Weedy check	49.84	63.37	78.21	100.95	120.44	129.96
Mechanical weeding	54.38	68.46	82.89	107.47	125.94	133.93
BSM + PC (PE)	51.85	65.39	79.75	103.91	122.47	131.40
OF (PE)	51.01	64.46	78.90	103.27	121.89	130.64
BSM + PC (PE) + 2,4-D (PoE)	53.16	67.59	81.78	105.85	124.11	133.85
OF (PE) + 2,4-D (PoE)	52.44	66.27	80.53	104.74	123.30	132.50
SE(m)±	0.35	0.434	0.41	0.38	0.24	0.36
CD ($p \leq 0.05$)	1.04	1.28	1.22	1.13	0.71	1.07

SE: standard error of the means (n = 3); CD: critical difference BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence forces the plants to complete life cycle at a faster rate in a shorter time. Hence, the differences in the HTUs can be owed to competition among weed and rice plants (Punia et al., 2018; Rohit et al., 2019).

The accumulation of photo-thermal units (PTUs) was significantly influenced by varying sowing dates and weed management strategies at various phenological stages (Table 4). The highest (22573.15 °C day) PTUs were accumulated in earlier sown crop than late sown crop (20683.70 °C day). The variation in temperature and sunshine hours, combined with the longer duration of early sowing resulted in higher accumulation of PTUs. Mechanical weeding and pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D accumulated higher PTUs (21774.19 0C day) than other weed control treatments. Weedy-check treatment recorded the lowest PTUs (21476.36 °C day) among all tested weed managing approaches because of severe crop-weed competition for various growth factors, completing life cycle at a faster rate and shorter time (Punia et al., 2018; Rohit et al., 2019).

Table 2 - Growing degree days (°C) of direct seeded rice under varying sowing dates and weed managing strategies

Treatments	Maximum Tillering	Panicle initiation	50% flowering	Milking	Dough	Harvest
Sowing dates						
10th May	641.18	840.83	1050.58	1409.50	1650.08	1741.51
3rd June	552.28	756.75	965.27	1303.10	1495.85	1553.98
SE(m) ±	1.84	5.15	1.44	1.07	2.20	1.42
CD ($p \leq 0.05$)	11.37	15.45	8.93	6.63	13.61	8.78
Weed management strategies						
Weedy check	563.67	761.18	978.91	1311.78	1546.76	1633.35
Mechanical weeding	628.30	838.85	1049.24	1393.97	1597.74	1661.53
BSM + PC (PE)	592.78	789.39	997.66	1349.70	1568.21	1642.68
OF (PE)	583.01	775.15	985.74	1341.49	1565.38	1638.64
BSM + PC (PE) + 2,4-D (PoE)	610.30	825.30	1025.58	1375.94	1583.29	1659.88
OF (PE) + 2,4-D (PoE)	602.31	802.89	1010.41	1364.94	1576.42	1650.42
SE(m) ±	6.12	6.97	6.27	4.85	2.36	3.19
CD ($p \leq 0.05$)	18.08	20.59	18.50	14.31	6.97	9.43

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence

Table 3 - Helio-thermal units (°C day hour) of direct seeded rice under varying sowing dates and weed managing strategies

Treatments	Maximum Tillering	Panicle initiation	50% flowering	Milking	Dough	Harvest
Sowing dates						
10th May	4399.41	5707.77	7076.901	9687.683	11456.8	12182.67
3rd June	3821.12	5103.84	6544.376	9117.583	10594.15	10965.63
SE(m) ±	14.81	45.25	10.99	10.71	19.07	14.76
CD ($p \leq 0.05$)	91.38	279.21	67.82	66.11	117.70	91.08
Weed management strategies						
Weedy check	3915.51	5128.83	6559.27	9080.90	10856.28	11484.86
Mechanical weeding	4352.82	5743.10	7169.62	9727.51	11175.55	11659.47
BSM + PC (PE)	4057.35	5303.07	6721.63	9323.43	11015.75	11543.43
OF (PE)	4011.35	5227.06	6612.91	9278.99	10995.01	11515.32
BSM + PC (PE) + 2,4-D (PoE)	4200.43	5617.01	6961.90	9553.02	11072.2	11644.00
OF (PE) + 2,4-D (PoE)	4124.14	5415.77	6838.50	9451.95	11038.06	11597.83
SE(m) ±	46.81	60.56	55.26	40.35	20.84	24.14
CD ($p \leq 0.05$)	138.14	178.71	163.06	119.06	61.50	71.25

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence

Significant variation was observed in HyTUs under varying sowing dates and weed management approaches (Table 5). Earlier sowing accumulated the highest (112570.1 °C day) HyTUs than late sowing (107640.3 °C day). The increased accumulation of HyTUs in early sowing can be owed to favourable weather, longer crop duration and more heat unit aggregation. Mechanical weeding and pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D resulted in higher accumulation of HyTUs (111016.8 °C day) than other weed control treatments. Weedy-check treatment resulted in the lowest accumulation of HyTUs (109090.9 °C day) than the rest of the weed management approaches due to completion of life cycle in short time due to stress created by weeds to crop plants (Punia et al., 2018; Rohit et al., 2019).

PTI based on degree days per growth day showed increased trend from maximum tillering to 50% flowering,

Table 4 - Photo-thermal units (°C day hour) of direct seeded rice under varying sowing dates and weed managing approaches

Treatment	Maximum Tillering	Panicle initiation	50% flowering	Milking	Dough	Harvest
Sowing dates						
10th May	8279.48	11001.12	13820.79	18512.22	21505.91	22573.15
3rd June	8041.60	10791.28	13538.32	17821.25	20081.28	20683.70
SE(m) ±	25.53	55.68	18.67	13.11	19.07	19.34
CD ($p \leq 0.05$)	157.52	161.24	115.21	80.93	117.70	119.32
Weed management strategies						
Weedy check	7710.02	10389.35	13296.91	17608.51	20488.19	21476.36
Mechanical weeding	8590.94	11434.58	14223.11	18637.72	21071.80	21774.19
BSM + PC (PE)	8106.71	10770.15	13544.71	18085.49	20742.68	21573.39
OF (PE)	7973.39	10577.51	13387.30	17983.09	20711.84	21531.39
BSM + PC (PE) + 2,4-D (PoE)	8345.85	11252.34	13912.12	18412.11	20912.47	21757.80
OF (PE) + 2,4-D (PoE)	8236.33	10953.27	13713.21	18273.48	20834.60	21657.43
SE(m) ±	83.33	93.72	83.11	60.55	28.85	35.43
CD ($p \leq 0.05$)	245.88	276.55	245.24	178.69	85.13	104.54

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence

Table 5 - Hydro-thermal units (°C day %) of direct seeded rice under varying sowing dates and weed managing approaches

Treatments	Maximum Tillering	Panicle initiation	50% flowering	Milking	Dough	Harvest
Sowing dates						
10th May	39868.80	54609.43	68536.47	91849.23	106568.9	112570.1
3rd June	38388.79	51691.45	66491.82	90462.78	103776.9	107640.3
SE(m) ±	130.90	242.55	229.83	421.21	97.98	75.17
CD ($p \leq 0.05$)	807.59	1496.42	1417.92	1263.72	604.50	463.80
Weed management strategies						
Weedy check	36805.74	50645.44	65423.17	88238.05	103467.4	109090.9
Mechanical weeding	41259.72	55785.81	70675.70	93512.08	106857.4	111016.8
BSM + PC (PE)	38868.65	52539.33	66602.77	90752.35	104848.0	109772.0
OF (PE)	38187.97	51567.55	65858.41	90185.72	104616.4	109503.5
BSM + PC (PE) + 2,4-D (PoE)	40067.09	54900.10	69088.83	92481.01	105873.0	110909.4
OF (PE) + 2,4-D (PoE)	39583.63	53464.41	67435.99	91766.8	105375.2	110338.3
SE(m) ±	428.84	460.14	623.52	313.62	153.73	222.67
CD ($p \leq 0.05$)	1265.39	1357.74	1839.81	925.41	453.63	657.03

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence and then decreased till maturity revealing declining everyday thermal consumption towards maturity. The PTI for successive growth phases of DSR varied significantly under different sowing dates and weed management aproaches (Table 6). Early sown crop recorded higher values of PTI (9.88) than late sowing (6.61). Early sowing recorded higher PTI due to longer duration. Mechanical weeding recorded significantly higher value PTI (9.01) than other weed control treatments included in the study. Weedy check treatment recorded the lowest PTI (7.89) due to stress imposed by weeds leading to shorter life span ultimately accumulating lower PTUs (Punia et al., 2018; Rohit et al., 2019).

Grain and biological yields were significantly affected by varying sowing dates and weed management strategies (Table 7). Early sowing resulted in higher grain and biological yields (7.33 t ha^{-1} and 16.33 t ha^{-1}) than late sowing (6.08 t ha^{-1} and 14.01 t ha^{-1}). The lower yield in late sowing may be due to the high temperature, which caused more respiration and reduced net photosynthesis, resulting in less translocation of assimilate. Higher grain and straw production in early sowing can be attributed to significantly better performance of yield-related factors because of lesser competition and optimum use of inputs. It might also be attributed to the fact that yield at any condition of environment is the result of yield components assimilated at various phases of growth and development (Bashir et al., 2010; Sreenivas et al., 2007).

Mechanical weeding and pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D resulted in higher grain (7.79 t ha^{-1}) and biological (17.31 t ha^{-1}) yields compared to weedy check and other weed management strategies included in the study. Sequential application of pre- and post-emergence herbicides significantly increased grain, and biological yields than their individual application and weedy-check. Besides an improvement in each yield parameter, the reduction in crop-weed competition in weed-free treatment increased yield. This can be attributed to enhanced growth and development, such as increment in total dry matter production, increased crop leaf area and photosynthesis. Crop growth and yield-attributing traits improved under low weed-crop competition, which favoured the growth of crop plants than weeds (Rawat et al., 2012). Weedy check treatment significantly reduced grain (4.25 t ha^{-1}) and biological yield (11.11 t ha^{-1}) because of severe weed competition leading to lower yield attributes (Ahmed et al., 2020; Ganai et al., 2014; Nazir et al., 2020).

Although crop plants do not fully utilise heat energy in dry matter accumulation, the genetic composition and crop management factors that influence potential yield of crops may be evaluated based on thermal efficiencies (Table 7). Significantly higher values of thermal use efficiencies, i.e., HUE (4.21 and 9.38 kg ha^{-1} °C^{-1} day), HTUE (0.60 and 1.34 kg ha^{-1} °C^{-1} day), HyTUE (0.065 and 0.145 $kgha^{-1}$ °C^{-1}day) and PTUE (0.325 and 0.723 kg ha^{-1} °C^{-1} day) in relation to grain and biological yields were recorded for earlier sown crop than late sown crop. Higher values of thermal use efficiencies in earlier sowing may be attributed to lengthier crop duration and higher grain and biological yields than late sowing. Among the tested weed managing approaches, mechanical weeding recorded significantly higher values of thermal use efficiencies, i.e., HUE (4.80 and 10.42 kg ha^{-1} °C^{-1} day), HTUE (0.68 and 1.48 kg ha^{-1} °C^{-1} day), HyTUE (0.072 and 0.156 $kgha^{-1}$ °C^{-1}day) and PTUE (0.366 and

Table 6 - Pheno-thermal index of direct seeded rice under varying sowing dates and weed management strategies

Treatments	MT-PI	PI-50% FLW	50% FLW –M	M-D	D-H
Sowing dates					
10th May	39868.80	54609.43	68536.47	91849.23	106568.9
3rd June	38388.79	51691.45	66491.82	90462.78	103776.9
SE(m) ±	130.90	242.55	229.83	421.21	97.98
CD ($p \leq 0.05$)	807.59	1496.42	1417.92	1263.72	604.50
Weed management practices					
Weedy check	36805.74	50645.44	65423.17	88238.05	103467.4
Mechanical weeding	41259.72	55785.81	70675.70	93512.08	106857.4
BSM + PC (PE)	38868.65	52539.33	66602.77	90752.35	104848.0
OF (PE)	38187.97	51567.55	65858.41	90185.72	104616.4
BSM + PC (PE) + 2,4-D (PoE)	40067.09	54900.10	69088.83	92481.01	105873.0
OF (PE) + 2,4-D (PoE)	39583.63	53464.41	67435.99	91766.8	105375.2
SE(m) ±	428.84	460.14	623.52	313.62	153.73
CD ($p \leq 0.05$)	1265.39	1357.74	1839.81	925.41	453.63

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence, MT: maximum tillering, PI: panicle initiation, 50% FLW: 50% flowering, M: milking, D: dough, H: harvest

Table 7 - Yield and thermal use efficiencies of direct seeded rice under varying sowing dates and weed management strategies

Treatments	Grain Yield (t ha^{-1})	Thermal efficiencies			
		Heat use efficiency (kg/ha/°C/day)	Heliothermal units (°C day hour)	Hydrothermal units (°C day %)	Photothermal units (°C day hour)
Sowing dates					
10th May	7.33	4.21	0.60	0.065	0.325
3rd June	6.08	3.91	0.55	0.056	0.294
SE(m) ±	0.04	0.006	0.001	0.0001	0.0005
CD ($p \leq 0.05$)	0.14	0.04	0.02	0.004	0.01
Weed management strategies					
Weedy check	4.25	2.60	0.37	0.039	0.198
Mechanical weeding	7.97	4.80	0.68	0.072	0.366
BSM + PC (PE)	6.95	4.23	0.60	0.063	0.322
OF (PE)	6.51	3.97	0.57	0.059	0.302
BSM + PC (PE) + 2,4-D (PoE)	7.50	4.52	0.64	0.068	0.345
OF (PE) + 2,4-D (PoE)	7.06	4.28	0.61	0.064	0.326
SE(m) ±	0.16	0.02	0.003	0.0003	0.0015
CD ($p \leq 0.05$)	0.47	0.06	0.01	0.009	0.03
Sowing dates					
	Biological Yield (t ha^{-1})				
10th May	16.33	9.38	1.34	0.145	0.723
3rd June	14.01	9.02	1.28	0.130	0.677
SE(m) ±	0.09	0.012	0.002	0.0002	0.0009
CD ($p \leq 0.05$)	0.26	0.08	0.01	0.01	0.004
Weed management strategies					
Weedy check	11.11	6.80	0.97	0.102	0.517
Mechanical weeding	17.31	10.42	1.48	0.156	0.795
BSM + PC (PE)	15.53	9.45	1.35	0.141	0.720
OF (PE)	14.84	9.06	1.29	0.136	0.689
BSM + PC (PE) + 2,4-D (PoE)	16.43	9.90	1.41	0.148	0.755
OF (PE) + 2,4-D (PoE)	15.80	9.57	1.36	0.143	0.730
SE(m) ±	0.19	0.04	0.006	0.0006	0.0031
CD ($p \leq 0.05$)	0.58	0.12	0.03	0.02	0.008

SE: standard error of the means (n = 3); CD: critical difference; BSM: Bensulfuron methyl, PC: Pretilachlor, OF: Oxyfluorfen, PE: pre-emergence, and PoE: post-emergence

0.795 kg ha^{-1} °C^{-1} day) on grain yield and biological yields. Among all tested herbicides, pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D recorded significantly higher values of all the thermal use efficiencies compared to the rest of herbicides treatment and weedy check included in the current study. The lowest values of all thermal use efficiencies were recorded for weedy check treatment. The variations in thermal use efficiencies may be due to differences in grain and biological yields, GDD, HTU, HyTU and PTU under different weed management practices (Punia et al., 2018; Rohit et al., 2019).

Regression coefficient indicated that agro-meteorological indicators and thermal use efficiency had a profound influence on overall grain and biological yields. The regression equations were non-significant for agrometeorological indices (Table 8), whereas significant for thermal efficiencies (Table 9). For grain and biological yields, coefficient of determination extended from 0.06 to 0.14 and 0.05 to 0.13 with agro-meteorological indices, respectively (Figure 1). The GDD accounted for

Table 8 - Parameters of regression equations used to interpret the relationship between various agrometeorological indices and grain and biological yields of direct seeded rice

Variable	Standard error	T-statistics	P value
Growing degree days – Grain yield	1.74	1.79	0.082
Heliothermal units – Grain yield	0.17	1.46	0.153
Photothermal units – Grain yield	0.11	1.50	0.142
Hydrothermal units – Grain yield	0.04	2.37	0.024
Growing degree days – Biological yield	4.30	1.61	0.115
Heliothermal units – Biological yield	0.43	1.27	0.212
Photothermal units – Biological yield	0.27	1.32	0.195
Hydrothermal units – Biological yield	0.09	2.21	0.033

The bold values in the p value column denote that the relevant regression was statistically significant

Table 9 - Parameters of regression equations used to interpret the relationship between various thermal use efficiencies and grain and biological yields of direct seeded rice

Variable	Standard error	T-statistics	P value
Heat use efficiency – Grain yield	105.29	15.18	**<0.0001**
Heliothermal units' efficiency – Grain yield	970.32	10.23	**<0.0001**
Photothermal units' efficiency – Grain yield	1577.96	12.58	**<0.0001**
Hydrothermal units' efficiency – Grain yield	4570.46	24.91	**<0.0001**
Heat use efficiecny – Biological yield	100.40	15.89	**<0.0001**
Heliothermal units' efficiency – Biological yield	924.87	10.78	**<0.0001**
Photothermal units' efficiency – Biological yield	1503.63	13.21	**<0.0001**
Hydrothermal units' efficiency – Biological yield	4375.26	25.92	**<0.0001**

The bold values in the p value column denote that the relevant regression was statistically significant

9% variability against grain yield and 7% to biological yield. Furthermore, agro-mteorological indices, i.e., HTU, PTU and HyTU resulted in 6%, 6% and 14% variability of with grain yield and 5%, 5% and 13% with biological yield, respectively. The coefficient of determination of grain yield with thermal use efficiencies ranged from 0.76 to 0.95 and it varied from 0.77 to 0.94 with biological yield, respectively (Figure 2). The highest degree of variability in grain yield and biological was accounted for by thermal use efficiencies. The highest variability of thermal use efficiencies on grain yield basis was shown by HyTUE (95%) and the highest variability of thermal use efficiencies on biological yield basis was shown by HyTUE (94%). The HUE, HTUE and PTUE on grain yield accounted for 87%, 76% and 82% variability the variability for biological yield was 87%, 77% and 83%, respectively (Esfandiary et al., 2009; Jan et al., 2022; Selvaganesan et al., 2020).

4. Conclusions

Different sowing dates and weed management strategies exerted significant impact on phenological development, thermal use efficiencies, and productivity of DSR. Earlier sowing mechanical weeding or successive pre-emergence application of bensulfuron methyl + pretilachlor followed by post-emergence application of 2,4-D is recommended for better phenological development under the temperate environment to accumulate higher heat units with increased thermal use efficiencies and higher grain yield.

Author's contributions

All authors read and agreed to the published version of the manuscript. MSM, PS, RHK, SF, MAA, and ZAS: Conceptualization of the manuscript and development of the methodology. TAB, and ZAS: data collection and curation. ZAS, and EAD: data analysis. All authors. data interpretation. TAB, MAA, and MSE: funding acquisition and resources. TAB, MAA, and MSE: project administration. TAB: supervision. ZAS, and EAD: writing the original draft of the manuscript. MSM, PS, RHK, TAB, SF, MAA, and MSE: writing, review and editing.

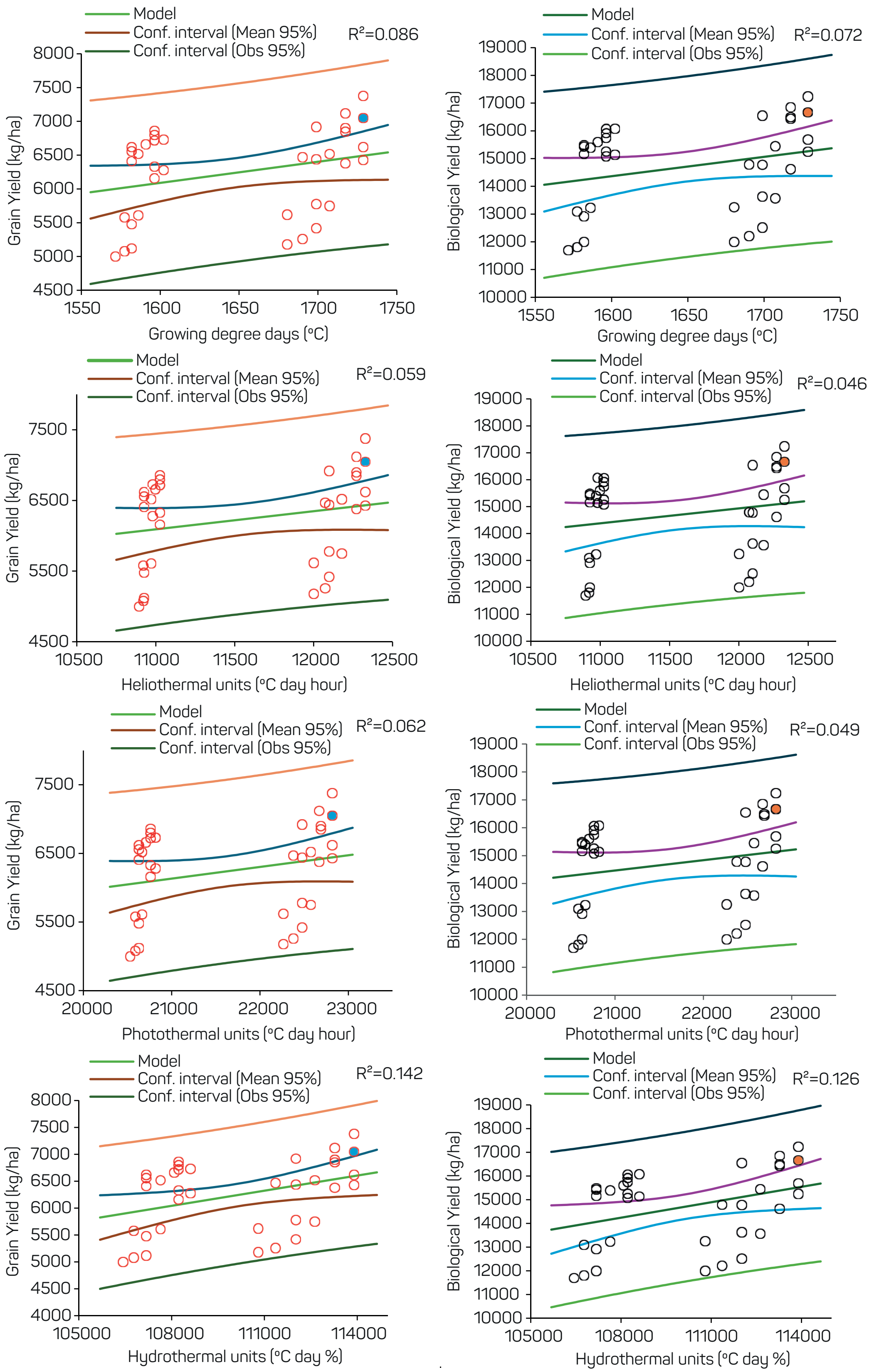

Figure 1 - Relationship between different agrometeorological indices and grain and biological yields of direct seeded rice determined by regression analysis

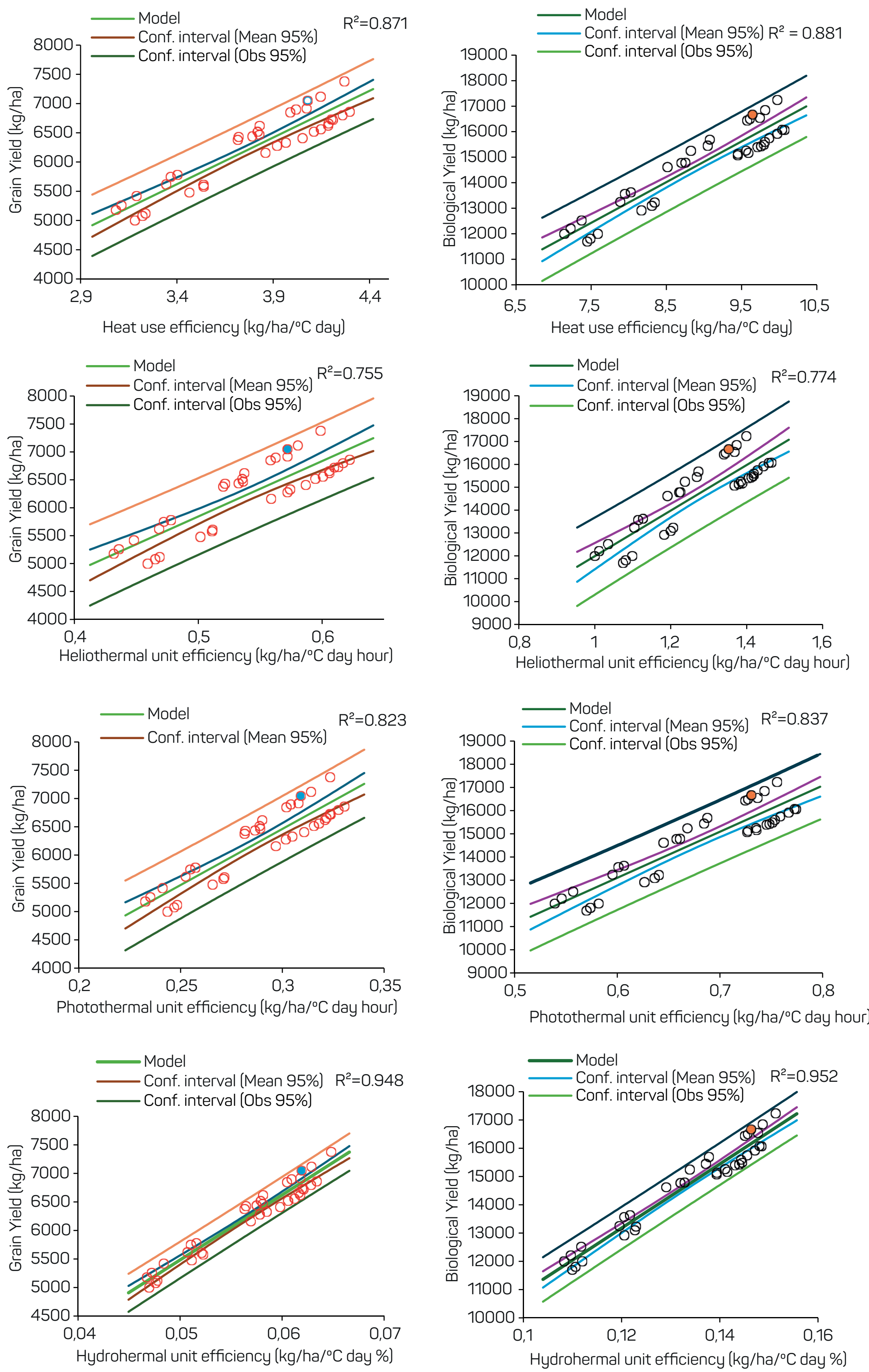

Figure 2 - Relationship between thermal efficiencies and grain and biological yields of direct seeded rice determined by regression analysis

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