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Thermal indices as indicators of soybean phenological development under different sowing windows

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ABSTRACT

Soybean (*Glycine max* (L.) Merrill) phenology and productivity are closely governed by the thermal and photothermal environment during crop development. A field experiment was conducted during kharif 2023 and 2024 at the Department of Agricultural Meteorology, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, to quantify agrometeorological indices of soybean under different sowing windows. Four sowing windows, viz., 25th, 26th, 27th and 28th standard meteorological weeks (SMW), were evaluated in a split-plot design with three replications. Sowing time altered the accumulation of Growing Degree Days (GDD), Helio-thermal Units (HTU) and Photo-thermal Units (PTU). In 2023, the 25th SMW accumulated 1734 °C days GDD, 7596 °C day hrs HTU and 20,390 °C day hrs PTU, compared with 1469 °C days, 6558 °C day hrs and 17,070 °C day hrs, respectively, under the 28th SMW. A similar trend was observed in 2024, with accumulation of 1826 °C days GDD, 7671 °C day hrs HTU and 21,911 °C day hrs PTU under the 25th SMW, declining to 1527 °C days, 6353 °C day hrs and 18,325 °C day hrs under the 28th SMW. Pooled seed yield was highest under the 26th SMW (1725 kg ha⁻¹), comparable with the 25th SMW (1701 kg ha⁻¹), and declined to 1353 kg ha⁻¹ under the 28th SMW. Timely sowing enhanced thermal and photothermal accumulation and productivity, while delayed sowing shortened crop duration and reduced yield under rainfed conditions.

Keywords: Agrometeorological Indices, Soybean, Phenological Stages, GDD, HTU, PTU

1. Introduction

Crop productivity heavily relies on the specific climate conditions required by each crop. Soybean (*Glycine max* (L.) Merrill) is predominantly cultivated in tropical, subtropical, and warm-temperate regions worldwide. It is an important rainfed oilseed crop in central India, where its productivity is closely associated with the timing and distribution of monsoon rainfall and the prevailing thermal environment. Throughout various phenological stages, soybeans encounter diverse weather conditions, leading to significant fluctuations in growth and yield. Being a short-day and photosensitive crop, soybeans thrive in warm and moist climates and respond to changes in the thermal and photoperiodic environment, which consequently influence the duration of vegetative and reproductive phases, flowering, pod development and maturity. Temperature, a crucial weather factor, profoundly influences crop growth, development, and yield. Soil temperature of 15.5 °C and above is ideal for rapid germination and robust seedling growth (Patil *et al.*, 2014) [1]. For most soybean varieties, optimal germination temperature ranges between 26 °C and 30 °C, with a base temperature of 10 °C (Chavan *et al.*, 2018) [2]. Temperature and photoperiod jointly dictate sowing timing and subsequently affect the duration of phenophases, influencing pre- and post-flowering stage development rates. Given these factors, understanding the precise duration of different phenophases and their correlation with yield determinants is paramount for achieving high crop yields. The thermal unit method, commonly used for assessing crop thermal relationships, was employed in this study to investigate the impact of temperature on soybean phenology and yield (Ramteke *et al.*, 1996) [3]. This investigation aims to analyze how accumulated heat units, such as growing degree days (GDD), photothermal units (PTU), and helio-thermal units (HTU), at various phenophases, influence soybean crop performance under different sowing dates.

2. Materials and Methodology

2.1 Experimental site and crop establishment

The field experiment was conducted at the experimental farm of the Department of Agricultural Meteorology, Vasantao Naik Marathwada Agriculture University, Parbhani, located at 76° 46' E longitude, 19° 16' N latitude, and an altitude of 409 m above mean sea level, during the kharif season 2023 and 2024. The area is situated in the central Maharashtra plateau zone (M-7), experiences a semi-arid climate charac

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terized by dry winters, hot and dry summers, and moderate rainfall during the monsoon season, with an average annual rainfall of 916.0 mm.

The experiment was conducted under rainfed conditions. A split-plot design with three replications was used. Four sowing windows were considered: D₁ = 25th SMW, D₂ = 26th SMW, D₃ = 27th SMW and D₄ = 28th SMW. The subplot treatments consisted of soybean cultivars MAUS-612, MAUS-725 and JS-20-116. Standard recommended crop management practices were followed and the crop was harvested at physiological maturity.

2.2 Weather observations and phenology

Daily weather data throughout the experiment were collected from the agrometeorological observatory of the Department of Agricultural Meteorology, VNMKV, Parbhani. Five plants were selected randomly from each replication (three) to study the different phenological events. The occurrence of different phenophases (number of days required for various growth stages) of the crop was observed on the basis of external morphological characteristics under different dates of sowing. The crop life cycle was divided into ten phenophases: P₁- sowing to emergence; P₂- emergence to seedling; P₃- seedling to branching; P₄- branching to flowering; P₅- flowering to pod formation; P₆- pod formation to grain formation; P₇- grain formation to pod development; P₈- pod development to pod containing full-size grain; P₉- full-size grain to dough stage; and P₁₀- dough stage to physiological maturity.

2.3 Computation of agrometeorological indices

2.3.1 Growing degree days (GDD)

The daily GDD would be calculated by taking the mean daily temperature ($T_{\max} + T_{\min}$)/2 and subtracting the base temperature of the crop. The GDD was calculated by considering a base temperature of

10 °C (Chavan *et al.*, 2018) [2]. The method used for calculating the accumulated growing degree days (GDD) is expressed by the following formula (Rajput, 1980) [4]

$$\text{Accumulated GDD} = \sum_{ds} \left[\frac{T_{\max} + T_{\min}}{2} \right] - T_b$$

Where,

GDD - Growing degree days (°C day)

$T_{\max}$ - Maximum temperature (°C)

$T_{\min}$ - Minimum temperature (°C)

T_b - Base temperature (10 °C)

d_s - Date of emergence.

d_h - Date of harvest.

2.3.2 Helio thermal units (HTU)

The HTU is defined as the product of total GDD and average daily bright sunshine hours. The sum total of HTU for each phenophase was calculated using the following formula (Rajput, 1980) [4]

$$\text{HTU} = (\text{GDD} \times \text{BSS})$$

Where,

GDD- Growing degree day

BSS- Bright sunshine hours

2.3.3 Photo thermal units (PTU)

The photothermal unit is defined as the product between GDD and day length. Total photothermal units for different phenophases were calculated by using the following equation (Rajput, 1980) [4]:

$$\text{Photo thermal units (°C day hrs)} = (\text{GDD} \times \text{D})$$

Where,

GDD- Growing degree days

D- Day length in hours

3. Result and Discussion

3.1 Phenological duration under different sowing windows

Sowing time markedly altered the duration of soybean development in both seasons (Table 1). During *kharif* 2023, the crop required 101 days to reach maturity under D₁ (25th SMW), compared with 99, 95 and 88 days under D₂, D₃ and D₄, respectively. Thus, a delay from the 25th to the 28th SMW shortened the crop cycle by 13 days (12.9%). The shortening was distributed across several phenophases. The seedling phase (P₂) declined from 23 days under D₁ to 19 days under D₄, while the branching-to-flowering phase (P₄) declined from 5 to 4 days. The later reproductive phases also showed moderate compression.

A similar response was observed in *kharif* 2024, although the overall crop duration was longer than in *kharif* 2023. The maturity period decreased from 106 days under D₁ to 96, 94 and 91 days under D₂, D₃ and D₄, respectively. The difference between D₁ and D₄ was therefore 15 days (14.2%). The longer duration of D₁ was associated with extended time available for completion of successive phenological stages, while delayed sowing compressed the crop cycle. This response is consistent with the thermal-time concept that crop development progresses according to the prevailing temperature environment rather than calendar date alone. Neog *et al.* (2008) [5] similarly reported substantial variation in soybean maturity duration and thermal requirements among cultivars and growing seasons. Bhan *et al.* (2019) also showed that changes in the thermal environment were associated with differences between actual and normal crop duration in soybean.

Table 1. Mean duration (days) of soybean phenophases under different sowing windows during *kharif* 2023 and 2024.

Phenophases	<i>kharif</i> 2023				<i>kharif</i> 2024			
	D ₁	D ₂	D ₃	D ₄	D ₁	D ₂	D ₃	D ₄
P ₁ : Sowing to emergence	7	5	5	5	6	5	4	5
P ₂ : Emergence to seedling	23	22	20	19	24	23	23	20
P ₃ : Seedling to branching	8	8	7	6	8	9	8	7
P ₄ : Branching to flowering	5	5	4	4	6	5	5	5
P ₅ : Flowering to pod formation	9	10	8	8	7	5	7	6
P ₆ : Pod formation to grain formation	8	10	9	8	7	6	6	7
P ₇ : Grain formation to pod development	14	12	15	14	9	8	7	8
P ₈ : Pod development to full-size grain	7	8	7	7	10	10	10	9

(continued on next page)

Phenophases	kharif 2023				kharif 2024			
	D ₁	D ₂	D ₃	D ₄	D ₁	D ₂	D ₃	D ₄
P ₉ : Full-size grain to dough stage	9	9	9	8	14	11	11	12
P ₁₀ : Dough stage to maturity	11	10	11	10	16	14	13	12
Total maturity duration (days)	101	99	95	88	106	96	94	91

3.2 Weather environment during crop growth

The weather environment associated with each sowing window differed mainly in rainfall amount and distribution and, to a lesser extent, in sunshine duration (Table 2). During *kharif* 2023, seasonal rainfall during the crop period decreased from 565.2 mm under D₁ to 460.0 mm under D₄, while the number of rainy days decreased from 30 to 25. Mean temperature also declined slightly from 27.1 °C under D₁ to 26.7 °C under D₄. Bright sunshine increased from 4.3 to 4.8 h day⁻¹ with delayed sowing. In *kharif* 2024, rainfall was higher than in *kharif* 2023 for all sowing windows, ranging from 741.6 mm under D₁ to 640.8 mm under D₄. Mean temperature remained close to 27 °C across the sowing windows, whereas bright sunshine increased from 3.7 h day⁻¹ under D₁ to 4.4 h day⁻¹ under D₄.

3.3 Growing degree days

The accumulated GDD differed clearly among sowing windows in both seasons (Tables 3 and 4). During *kharif* 2023, total GDD was 1734 °C day under D₁, 1661 °C day under D₂, 1593 °C day under D₃ and 1469 °C day under D₄. The total GDD under D₄ was 15.3%

lower than under D₁. Phenophase-wise, relatively large accumulation occurred during P₂, while the later stages generally contributed smaller increments.

During *kharif* 2024, total GDD ranged from 1527 °C day under D₄ to 1826 °C day under D₁. D₂ and D₃ accumulated 1626 and 1582 °C day, respectively. The difference between D₁ and D₄ was 16.4%. The largest single phenophase accumulation under D₁ occurred during P₁₀ (285 °C days); while the lowest recorded phenophase value in the table was 84 °C day during P₄ under D₃.

The consistent decline in total GDD with delayed sowing was closely associated with shortening of the crop duration. Earlier sowing gave the crop a longer period to accumulate temperatures above the 10 °C base temperature before reaching physiological maturity. Therefore, the higher GDD recorded under D₁ does not mean that the crop required more heat to complete its growth. Instead, it was mainly due to the longer duration of crop growth under the earlier sowing condition. This interpretation agrees with Kaushik *et al.* (2015) [6], who observed a progressive reduction in soybean GDD with delayed sowing, and Nath *et al.* (2017) [7] also found higher GDD under earlier sowing in the Vidarbha region of Maharashtra.

Table 2. Seasonal weather environment associated with the four sowing windows during soybean crop growth.

Sowing Window	Rainfall (mm)	Rainy days	Tmax (°C)	Tmin (°C)	Tmean (°C)	Mean RH (%)	BSS (h day ⁻¹)	Evap. (mm)	Wind (km h ⁻¹)
kharif 2023									
25 th SMW	565.2	30	31.6	22.7	27.1	73	4.3	4.1	4.2
26 th SMW	571	30	31.5	22.4	26.9	74	4.2	3.8	4
27 th SMW	540	26	31.5	22.3	26.9	74	4.5	3.9	4
28 th SMW	460	25	31.5	22.2	26.7	74	4.8	3.9	4
kharif 2024									
25 th SMW	741.6	33	31.1	22.9	27	79	3.7	3.2	2.8
26 th SMW	721.9	31	31.1	22.9	27	78	3.7	3.2	2.5
27 th SMW	691.8	29	31.4	22.7	27.1	78	4.3	3.3	2.5
28 th SMW	640.8	25	31.2	22.7	27	78	4.4	3.4	2.4

3.4 Helio-thermal units

HTU integrates thermal accumulation with actual bright sunshine and therefore responds to both temperature and the radiation environment. In *kharif* 2023, total HTU decreased from 7596 °C day h under D₁ to 7096, 7085 and 6558 °C day h under D₂, D₃ and D₄, respectively. The reduction from D₁ to D₄ was 13.7%. The highest phenophase-wise HTU under D₁ occurred during P₇ (1725 °C day h), reflecting the combined contribution of accumulated heat and sunshine during that stage.

In *kharif* 2024, total HTU was highest under D₁ (7671 °C day h), followed by D₄ (6353), D₂ (6260) and D₃ (6145 °C day h). The D₁-to-D₄ difference was 17.2%, but unlike GDD and PTU, HTU did not decline strictly in sequence from D₁ to D₄. The slightly higher HTU under D₄ than D₃ was associated with the greater sunshine duration recorded under the later sowing environment. At the phenophase level, the highest HTU was recorded during P₂ under D₁ (1757 °C day h), while P₃ under D₁ recorded only 29 °C day h.

These results demonstrate that HTU is more sensitive than GDD to variation in actual sunshine duration. Thus, two sowing dates can accumulate similar thermal time but differ in HTU when cloudiness or sunshine duration differs. The overall pattern of higher HTU under

early sowing agrees with Singh *et al.* (2007) [8] and Kaushik *et al.* (2015) [6], who reported greater helio-thermal accumulation under earlier soybean sowing environments.

3.5 Photo-thermal units

PTU combines accumulated thermal time with day length and therefore represents the combine influence of temperature and photoperiod. In *kharif* 2023, PTU was highest under D₁ (20390 °C day h), followed by D₂ (19928), D₃ (19113) and D₄ (17070 °C day h). The reduction from D₁ to D₄ was 16.3%. The largest phenophase-wise PTU under D₁ occurred during P₂ (4139 °C day h), while relatively high values were also observed during P₇ and P₁₀.

In *kharif* 2024, total PTU followed the same descending trend as GDD: D₁ (21911), D₂ (19507), D₃ (18986) and D₄ (18325 °C days h). The difference between D₁ and D₄ was 16.4%. The highest phenophase-wise PTU was recorded during P₂ under D₁ (5095 °C day h). The greater PTU accumulation under earlier sowing indicates that the crop experienced a longer period of combined thermal and photoperiodic exposure before maturity. The phenophase-wise differences demonstrate that day length modified the amount of PTU accumulated within individual development stages. The present results are comparable with Kaushik *et al.* (2015) [6].

Table 3. Accumulated Growing Degree Days (GDD) (°C days), Total Helio-thermal Units (HTU) (°C day hrs.) and Total Photo Thermal Units (PTU) (°C day hrs.) at different dates of sowing during Kharif 2023

Treatments	PHENOLOGICAL STAGES										TOTAL	MEAN
	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈	P ₉	P ₁₀		
	Dates of Sowing											
	Growing Degree Days (°C days)											
25 th SMW	197	345	132	76	161	133	242	121	149	177	1734	173
26 th SMW	82	379	132	79	174	156	212	130	145	172	1661	166
27 th SMW	97	327	117	69	142	152	250	109	148	181	1593	159
28 th SMW	81	297	110	69	126	140	235	116	133	163	1469	147
	Helio-thermal Units (°Cday hrs.)											
25 th SMW	1005	1281	144	138	676	612	1725	577	599	838	7596	760
26 th SMW	175	1275	145	230	931	780	1494	428	826	813	7096	710
27 th SMW	514	533	299	259	829	855	1550	505	595	1145	7085	708
28 th SMW	301	318	460	445	564	1029	1242	517	611	1071	6558	656
	Photo Thermal Units (°Cday hrs.)											
25 th SMW	2360	4139	1586	916	1516	1597	2908	1457	1786	2125	20390	2039
26 th SMW	980	4549	1588	954	2087	1877	2539	1554	1735	2063	19928	1993
27 th SMW	1169	3929	1399	828	1702	1826	3000	1308	1777	2175	19113	1911
28 th SMW	972	2999	1315	829	1514	1678	2819	1388	1597	1959	17070	1707

Table 4. Accumulated Growing Degree Days (GDD) (°C days), Total Helio-thermal Units (HTU) (°C day hrs.) and Total Photo Thermal Units (PTU) (°C day hrs.) at different dates of sowing during Kharif 2024

Treatments	PHENOLOGICAL STAGES										TOTAL	MEAN
	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈	P ₉	P ₁₀		
	Dates of Sowing											
	Growing Degree Days (°Cday)											
25 th SMW	107	425	125	92	117	127	151	168	230	285	1826	183
26 th SMW	87	391	148	89	90	113	131	154	188	234	1626	163
27 th SMW	74	383	129	84	125	103	112	157	179	236	1582	158
28 th SMW	81	322	123	90	111	110	125	145	197	223	1527	153
	Helio-thermal Units (°Cday hrs.)											
25 th SMW	682	1757	29	71	198	578	594	805	1276	1682	7671	767
26 th SMW	443	1157	102	142	273	526	607	666	1052	1292	6260	626
27 th SMW	412	624	179	248	643	459	558	667	1239	1116	6145	614
28 th SMW	388	206	212	616	352	567	377	869	1148	1618	6353	635
	Photo Thermal Units (°Cday hrs.)											
25 th SMW	1289	5095	1495	1099	1409	1523	1810	2018	2755	3421	21911	2191
26 th SMW	1043	4690	1780	1074	1081	1356	1575	1851	2251	2804	19507	1951
27 th SMW	888	4593	1546	1014	1501	1237	1348	1881	2152	2826	18986	1899
28 th SMW	976	3860	1474	1078	1326	1326	1496	1744	2365	2680	18325	1832

3.6 Integration of agrometeorological indices with soybean productivity

Considering crop duration, thermal-time accumulation and yield together gives a better understanding of the suitability of different sowing windows than considering any single parameter alone. In the present study, delayed sowing shortened the crop duration in both seasons. Crop duration decreased from 101 to 88 days in *kharif* 2023 and from 106 to 91 days in *kharif* 2024 between the 25th and 28th standard meteorological weeks. The reduction in crop duration was also associated with lower accumulation of GDD, HTU and PTU, indicating that late-sown crops completed their growth and development within a shorter thermal and photothermal period.

The yield results were in agreement with these observations. Pooled seed yield was 1701 kg ha⁻¹ under the 25th SMW and 1725 kg ha⁻¹ under the 26th SMW, while it decreased to 1521 and 1353 kg ha⁻¹ un-

der the 27th and 28th SMW, respectively. Compared with the 28th SMW, seed yield was 27.5% higher under the 26th SMW and 25.7% higher under the 25th SMW. Since the 25th and 26th SMW were statistically at par for seed yield, these results indicate that both weeks provided a favourable sowing window rather than suggesting a single fixed sowing date.

The response of the varieties also showed that genotype influenced productivity under the prevailing thermal conditions. MAUS-725 recorded the highest pooled seed yield (1823 kg ha⁻¹), followed by MAUS-612 (1641 kg ha⁻¹), while JS-20-116 recorded the lowest yield (1261 kg ha⁻¹). MAUS-725 also recorded the highest pooled biological yield (4071 kg ha⁻¹) and harvest index (44.8%). However, the interaction effect for seed yield was non-significant. Therefore, the results do not indicate the need to recommend a separate optimum sowing week for each of the varieties tested.

Table 5. Seed, Straw, Biological Yield (Pooled) and Harvest Index influenced by different sowing dates (Kharif 2023 & 2024)

Treatments	Yield (kg ha ⁻¹)						Harvest Index (%)		Mean
	Seed yield		Pooled	biological yield		Pooled			
	2023	2024		2023	2024		2023	2024	
	Date of sowing								
25 th SMW	1724	1677	1701	3913	3833	3873	44.1	43.7	43.9
26 th SMW	1842	1608	1725	4136	3669	3902	44.5	43.8	44.2
27 th SMW	1586	1455	1521	3600	3416	3508	44.1	42.6	43.3
28 th SMW	1423	1283	1353	3195	2974	3085	44.5	43.1	43.8
S.E. m±	74.37	74.42	31.91	82.2	59.91	40.61	-	-	-
C.D. @ 5%	257.4	257.5	110.44	284.4	207.3	140.52	-	-	-

4. Conclusion

The two-year study clearly showed that sowing time had a major influence on soybean development and productivity under the semi-arid conditions of Parbhani. The delayed sowing from the 25th to the 28th SMW progressively reduced crop duration and the accumulation of GDD, HTU and PTU, resulting in lower seed yield. The 25th and 26th SMW performed similarly, with pooled seed yields of 1701 and 1725 kg ha⁻¹, respectively, whereas yield declined considerably under the 28th SMW (1353 kg ha⁻¹). Thus, the 25th - 26th SMW can be considered a favourable sowing window under the conditions of the present study. Among the tested varieties, MAUS-725 showed better overall productivity, recording the highest pooled seed yield (1823 kg ha⁻¹), biological yield (4071 kg ha⁻¹) and harvest index (44.8%). The results also showed that thermal indices were useful in explaining the changes in crop duration and development associated with different sowing times.

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