



## Temporal optimisation of sowing windows for enhancing off-season soybean (*Glycine max*) seed yield

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### ABSTRACT

The seed production and quality of soybean (*Glycine max* L.) gets affected due to erratic rainfalls during the season, leading to exploration in off-season cultivation to meet out the demand. Therefore, the experiment was conducted to identify the optimal sowing window for off-season seed production of soybean during the years 2022–23 and 2023–24 in the North Eastern Dry Zone of Karnataka. The experiment was laid out in a split-plot design with three replications, comprising two varieties (JS 335 and DSB 21) and six sowing dates. Results revealed that sowing during the first fortnight of November (D1) consistently recorded superior performance in both the years and pooled analysis. This treatment significantly improved key phenological parameters, including longer duration from planting to one open flower at any node on the main stem, extending reproductive phase (R1: Beginning bloom to R8: Full maturity), and higher days to 50% flowering in both varieties. The favourable growth period under D1 contributed to better crop development and efficient resource utilisation. Consequently, the highest seed yield/plot was also recorded under this sowing window, with JS 335 outperforming DSB 21. Therefore, it can be concluded that sowing soybean during the first fortnight of November may be the most suitable window for off-season seed production in the North Eastern Dry Zone of Karnataka, ensuring better growth and higher seed yield.

**Keywords:** Erratic rainfall, Phenological parameters, Seed production, Sowing time

Soybean (*Glycine max* L.) is an important oilseed crop valued for its high protein and oil content, and is widely adapted across diverse agro-climatic regions (Gurav *et al.* 2022). In India, it is predominantly cultivated during the *kharif* season under rainfed conditions, where unpredictable rainfall, especially during maturity and harvest, often results in poor seed quality and reduced germination (Gowda *et al.* 2001, Malik *et al.* 2007, Biswas *et al.* 2024). This has necessitated the exploration of off-season (*rabi*/summer) cultivation as an alternative approach for producing high-quality seeds.

Soybean is a short-day plant, highly sensitive to photoperiod and temperature, which significantly influence its growth, phenology, and yield. Among various agronomic practices, sowing time plays a critical role in determining

crop performance, as it governs the exposure of plants to prevailing environmental conditions during different growth stages. Variations in sowing dates can alter vegetative and reproductive development due to changes in temperature, day length, and moisture availability (Kumudini *et al.* 2007, Chen and Wiatrak 2010, Hu and Wiatrak 2012). Moreover, climate variability further emphasises the need to optimise sowing windows for stable productivity (Mourtzinis *et al.* 2019).

Despite its importance, limited information is available on suitable sowing windows for off-season soybean seed production in the North Eastern Dry Zone of Karnataka. Additionally, varietal response to different sowing dates under these conditions remains inadequately explored. Therefore, the present study was undertaken to identify the optimal sowing window for off-season seed production of soybean and to evaluate the performance of different varieties under varying sowing dates to enhance crop growth, phenology, and seed yield.

### MATERIALS AND METHODS

The experiment was conducted during late winter (*rabi*) and early summer seasons of 2022–23 and 2023–24 in the North Eastern Dry Zone of Karnataka. The experiment

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was laid out in a split-plot design with three replications with two genotypes [JS 335 ( $V_1$ ) and DSB 21 ( $V_2$ )] in main plots and in subplots, six sowing windows, viz.  $D_1$ , 14<sup>th</sup> November;  $D_2$ , 28<sup>th</sup> November;  $D_3$ , 14<sup>th</sup> December;  $D_4$ , 30<sup>th</sup> December;  $D_5$ , 13<sup>th</sup> January;  $D_6$ , 27<sup>th</sup> January at a spacing of 30 cm  $\times$  10 cm. Standard agronomic practices were followed uniformly for all treatments, and plots were isolated by 3 m to maintain genetic purity. Observations on growth and phenological parameters including plant height (cm) at 30 and 60 DAS and at harvest, number of branches, canopy spread (cm), days to 50% flowering, days to maturity, and duration from planting to R1 and R1 to R8 stages were recorded. The R1–R8 stages denote the reproductive phase of soybean development, as established by Fehr and Caviness. R1, Beginning of flowering stage; R2, Full flower stage; R3, Pod set stage; R4, Pod development stage; R5, Seed set stage; R6, Seed filling stage; R7, Initial maturity stage; and R8, Full maturity stage. Yield parameters such as seed yield/plant (g), seed yield/plot (kg), and seed yield (q/ha) were recorded following standard procedures (Xin *et al.* 2008).

The data were analysed using analysis of variance (ANOVA) as described by Fisher and Mackenzie (1923), and treatment means were compared using the critical difference (CD) at 5% level of significance (Panse and Sukhatme 1967). Data from both years were also pooled and analysed to assess the overall treatment effects.

## RESULTS AND DISCUSSION

**Planting to R1 duration:** The duration from planting to R1 stage was significantly influenced by sowing windows, while genotypic differences and their interaction with sowing dates were found to be non-significant (Table 1). Early sowing during the first fortnight of November ( $D_1$ ) recorded the longest duration to R1 stage (33.6, 34.6 and 34.1 in variety JS 335 in 2022–2023, 2023–2024 and pooled

data, respectively) and (34.0, 34.6 and 34.3 in variety DSB 21 in 2022–2023, 2023–2024 and pooled data, respectively) which was statistically on par with the second fortnight of November ( $D_2$ ) (Table 1). A progressive reduction in the duration was observed with delay in sowing, with the shortest duration recorded under late January sowing ( $D_6$ ).

Under early sowing, the extended vegetative phase is primarily attributable to synergistic effects of favourable environmental cues namely, optimal thermal regimes and inductive photoperiods which collectively sustain meristematic activity and delay floral initiation, thereby prolonging the pre-reproductive growth period. This delay is further reinforced by the downregulation of floral integrator genes such as *Flowering Locus T (FT)* and *Suppressor of Overexpression of Constans 1 (SOC1)* under cool, non-freezing conditions, independently of vernalisation pathways. Conversely, under delayed sowing conditions, crops are exposed to elevated ambient temperatures particularly increased minimum night temperatures and modified photoperiodic cycles, which accelerate developmental rates, reduce thermal time requirements for phenological progression, and promote earlier transition from vegetative to reproductive stages. Chronic mild heat stress during this period can prematurely downregulate cyclin-dependent kinases in the shoot apical meristem, shortening the proliferative phase of leaf primordia initiation. Moreover, the concept of photothermal units in delayed sowing reduces the duration of inductive photoperiods, while high temperatures lower the critical photoperiod threshold (Sanggonda *et al.* 2019), creating a non-linear compression of the vegetative window. These observations align with the findings of Lippmann *et al.* (2019) who demonstrated that supra-optimal temperatures expedite crop phenology by compressing the duration of the vegetative phase through enhanced thermal accumulation and accelerated apical development.

Table 1 Effect of sowing windows on the phenological duration from planting to R1 stage in soybean

| Treatment       | Planting to R1 duration (days) |       |              |           |       |              |             |       |              |
|-----------------|--------------------------------|-------|--------------|-----------|-------|--------------|-------------|-------|--------------|
|                 | 2022–2023                      |       |              | 2023–2024 |       |              | Pooled data |       |              |
|                 | $V_1$                          | $V_2$ | Mean         | $V_1$     | $V_2$ | Mean         | $V_1$       | $V_2$ | Mean         |
| $D_1$           | 33.6                           | 34.0  | 33.8         | 34.6      | 34.6  | 34.4         | 34.1        | 34.3  | 34.2         |
| $D_2$           | 32.3                           | 32.3  | 32.3         | 33.2      | 32.9  | 32.8         | 32.7        | 32.1  | 32.4         |
| $D_3$           | 30.6                           | 31.6  | 31.1         | 31.6      | 32.2  | 31.7         | 31.1        | 31.9  | 31.5         |
| $D_4$           | 30.0                           | 31.0  | 30.5         | 31.2      | 31.5  | 31.0         | 30.6        | 31.2  | 30.6         |
| $D_5$           | 29.3                           | 29.6  | 29.5         | 30.5      | 30.2  | 30.1         | 29.9        | 25.1  | 30.1         |
| $D_6$           | 28.6                           | 29.3  | 29.0         | 29.7      | 30.0  | 29.6         | 29.2        | 30.0  | 29.6         |
| Mean            | 30.7                           | 31.3  | 31.0         | 31.8      | 32.5  | 32.2         | 31.3        | 31.9  | 31.6         |
|                 | V                              | D     | $V \times D$ | V         | D     | $V \times D$ | V           | D     | $V \times D$ |
| SEM $\pm$       | 0.20                           | 0.47  | 0.64         | 0.27      | 0.54  | 0.76         | 0.23        | 0.46  | 0.64         |
| CD ( $p=0.05$ ) | NS                             | 1.39  | NS           | NS        | 1.58  | NS           | NS          | 1.37  | NS           |

V, Variety; D, Sowing window; NS, Non-significant. Treatment details are given under Materials and Methods.

Table 2 Genotypic and sowing window effects on the R1–R8 phenological interval in soybean across two growing seasons

| Treatment            | R1–R8 duration (days) |                |       |                |                |       |                |                |       |
|----------------------|-----------------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|
|                      | 2022–2023             |                |       | 2023–2024      |                |       | Pooled data    |                |       |
|                      | V <sub>1</sub>        | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  |
| D <sub>1</sub>       | 47.6                  | 47.3           | 47.5  | 49.6           | 48.6           | 49.1  | 48.6           | 48.0           | 48.3  |
| D <sub>2</sub>       | 47.0                  | 46.6           | 46.8  | 49.3           | 47.6           | 48.1  | 48.3           | 47.1           | 47.7  |
| D <sub>3</sub>       | 47.3                  | 46.6           | 47.0  | 48.6           | 47.3           | 48.3  | 47.8           | 47.0           | 47.4  |
| D <sub>4</sub>       | 46.3                  | 46.0           | 46.1  | 48.3           | 47.0           | 47.6  | 47.3           | 46.5           | 46.9  |
| D <sub>5</sub>       | 45.6                  | 45.33          | 45.5  | 47.6           | 46.6           | 47.1  | 46.6           | 46.0           | 46.3  |
| D <sub>6</sub>       | 45.3                  | 44.6           | 45.0  | 46.0           | 46.3           | 46.1  | 45.6           | 45.5           | 45.5  |
| Mean                 | 46.5                  | 46.1           | 46.3  | 48.2           | 47.2           | 47.7  | 48.6           | 48.0           | 48.3  |
|                      | V                     | D              | V × D | V              | D              | V × D | V              | D              | V × D |
| SEM±                 | 0.10                  | 0.56           | 0.73  | 0.20           | 0.81           | 1.06  | 0.15           | 0.63           | 0.82  |
| CD ( <i>p</i> =0.05) | NS                    | 1.66           | NS    | NS             | 1.58           | NS    | NS             | 2.06           | NS    |

V, Variety; D, Sowing window; NS, Non-significant. Treatment details are given under Materials and Methods.

**R1–R8 duration:** The period from R1–R8 stages was significantly affected by different sowing windows, whereas variations among genotypes and their interaction with sowing dates did not show any significant effect (Table 2). Among the different sowing windows, D<sub>1</sub> recorded the longest reproductive duration (47.6, 49.6, 48.0 days in JS 335; 47.3, 48.6 and 48.0 days in DSB 21 in 2022–23, 2023–24 and pooled data, respectively), whereas delayed sowing, particularly at D<sub>6</sub>, resulted in the shortest duration (45.3, 46.0, 45.6 days in JS 335; 44.6, 46.3 and 45.5 days in DSB 21 in 2022–23, 2023–24 and pooled data, respectively).

A declining trend in the duration from R1–R8 stage was observed with delay in sowing. Early sowing extended the reproductive phase due to optimal thermal and photoperiodic regimes, facilitating prolonged seed filling and assimilates partitioning. In contrast, late sowing exposed the crop to relatively higher temperatures during the reproductive stage, leading to accelerated physiological processes and shortened crop duration. The extended reproductive window under early sowing enhanced biomass accumulation and seed development, thereby supporting greater yield potential (Lippmann *et al.* 2019).

**Plant height:** Plant height at 30 days after sowing (DAS) was not significantly influenced by genotypes, whereas significant differences were observed at 60 DAS and at harvest. Sowing windows had a significant effect on plant height at later growth stages, and the interaction between genotypes and sowing dates was also found to be significant (Fig. 1).

Among the sowing windows, crops sown during the second fortnight of December (D<sub>4</sub>) recorded the highest plant height at both 60 DAS (45.9 cm, 43.0 cm and 44.4 cm in JS 335; 64.5 cm, 60.1 cm and 62.3 cm in DSB 21), followed by sowing in the first fortnight of January, D<sub>5</sub>

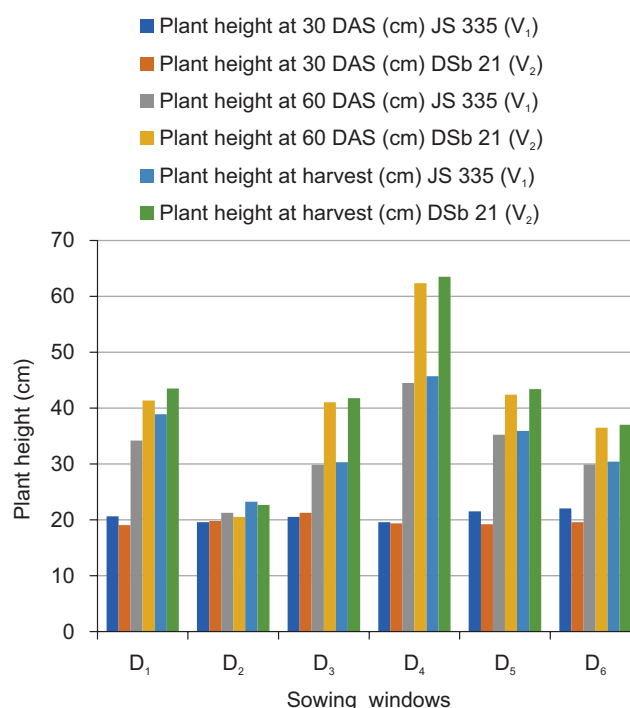


Fig. 1 Genotypic response of soybean plant height to varying sowing windows at 30 DAS, 60 DAS and harvest.

DAS, Days after sowing. Treatment details are given under Materials and Methods.

(36.3 cm, 34.1 cm and 35.2 cm in JS 335; 43.7 cm, 41.0 cm and 42.3 cm in DSB 21) and at harvest (46.4 cm, 44.9 cm and 45.7 cm in JS 335; 64.7 cm, 62.1 cm and 63.4 cm in DSB 21). In contrast, the lowest plant height was observed under the second fortnight of November, D<sub>2</sub> (23.0 cm, 20.8 cm and 21.2 cm in JS 335; 23.8 cm, 19.8 cm and 20.5 cm in DSB 21 at 60 DAS) and (23.2 cm, 23.2 cm and 23.2

Table 3 Sowing date  $\times$  genotype effects on soybean canopy spread

| Treatment       | Plant canopy at 60 DAS |                |              |                |                |              |                |                |              |
|-----------------|------------------------|----------------|--------------|----------------|----------------|--------------|----------------|----------------|--------------|
|                 | 2022–2023              |                |              | 2023–2024      |                |              | Pooled data    |                |              |
|                 | V <sub>1</sub>         | V <sub>2</sub> | Mean         | V <sub>1</sub> | V <sub>2</sub> | Mean         | V <sub>1</sub> | V <sub>2</sub> | Mean         |
| D <sub>1</sub>  | 42.1                   | 41.6           | 41.8         | 40.2           | 40.0           | 40.1         | 41.1           | 40.8           | 41.0         |
| D <sub>2</sub>  | 39.4                   | 38.5           | 38.9         | 37.8           | 37.0           | 37.4         | 38.6           | 37.7           | 38.2         |
| D <sub>3</sub>  | 38.5                   | 39.3           | 38.9         | 36.6           | 37.2           | 36.9         | 37.6           | 38.3           | 37.9         |
| D <sub>4</sub>  | 42.4                   | 44.5           | 43.4         | 40.3           | 41.3           | 40.8         | 41.3           | 42.9           | 42.1         |
| D <sub>5</sub>  | 38.1                   | 40.2           | 39.2         | 36.1           | 38.5           | 37.3         | 37.1           | 39.4           | 38.3         |
| D <sub>6</sub>  | 30.1                   | 35.8           | 32.9         | 27.7           | 33.3           | 30.5         | 28.9           | 34.5           | 31.7         |
| Mean            | 38.4                   | 40.0           | 39.2         | 36.5           | 37.9           | 37.2         | 37.5           | 38.9           | 38.2         |
|                 | V                      | D              | V $\times$ D | V              | D              | V $\times$ D | V              | D              | V $\times$ D |
| SEM $\pm$       | 0.97                   | 1.22           | 1.85         | 0.85           | 1.08           | 1.63         | 0.91           | 1.15           | 1.74         |
| CD ( $p=0.05$ ) | NS                     | 3.61           | NS           | NS             | 3.17           | NS           | NS             | 3.39           | NS           |

V, Variety; D, Sowing window; NS, Non-significant; DAS, Days after sowing. Treatment details are given under Materials and Methods.

cm in JS 335; 24.2 cm, 21.1 cm and 22.6 cm in DSB 21) at harvest in 2022–2023, 2023–2024 and in pooled data respectively.

The increased plant height observed under the D<sub>4</sub> sowing regime may be attributed to optimal thermoperiodic conditions during the critical ontogenetic window, which upregulate auxin (IAA) biosynthesis and signaling cascades, thereby promoting internode elongation and overall stem extension. In contrast, the suppressed plant height under the early sowing date (D<sub>2</sub>) likely results from suboptimal nocturnal temperatures during the vegetative phase, imposing constraints on turgor driven cell expansion and limiting meristem derived longitudinal growth. Comparable dwarfing effects under low-temperature stress have been documented by Li *et al.* (2018), corroborating the role of thermal inhibition in cell wall extensibility. The substantial phenotypic plasticity in plant height across sowing windows underscores the pronounced influence of abiotic drivers particularly ambient thermal regimes on canopy architecture and organogenetic development. These results are consistent with the findings of Franklin *et al.* (2011), who identified temperature-modulated auxin flux as a key determinant of stem elongation dynamics, as well as with Goraya *et al.* (2017) and Lippmann *et al.* (2019), who highlighted the regulatory impact of thermal stress on plant physiological trajectories and morphogenetic responses.

**Plant canopy:** Among the treatments, D<sub>4</sub> recorded the highest canopy spread (43.4 cm, 40.8 cm and 42.1 cm) in pooled data compared to other dates of sowing. The lowest plant canopy was recorded on D<sub>6</sub> (32.9 cm, 30.5 cm and 31.7 cm) in pooled data (Table 3). Distinct alterations in canopy architecture were observed across sowing regimes, underscoring the regulatory influence of prevailing environmental conditions on vegetative ontogeny.

The enhanced canopy development observed under

the D<sub>4</sub> sowing window can be attributed to favourable thermoperiodic conditions during the active vegetative phase, which promote auxin-mediated cell expansion and above ground biomass accumulation. This response is largely regulated by the temperature-responsive transcription factor PHYTOCHROME-INTERACTING FACTOR 4 (PIF4), a central integrator of environmental signals that coordinates plant growth under elevated temperatures. PIF4 enhances vegetative vigour by stimulating auxin biosynthesis in a temperature-dependent manner, thereby contributing to improved canopy architecture and stratification. The phytohormone indole-3-acetic acid (IAA) plays a pivotal role in regulating shoot growth and overall plant development. Exposure to elevated temperatures increases IAA accumulation, resulting in enhanced hypocotyl elongation and vegetative growth through the activation of PIF4-mediated signaling pathways (Franklin *et al.* 2011). The PIF4 promotes auxin biosynthesis by directly activating key auxin biosynthetic genes, including *YUCCA8* (*YUC8*), through binding to G-box motifs in its promoter region, thereby increasing endogenous IAA levels under warm conditions. As a master regulator linking temperature and light signaling, PIF4 integrates environmental cues with hormonal regulation to facilitate adaptive growth responses. The resulting increase in auxin production stimulates cell elongation, leading to greater plant height, enhanced canopy expansion, and improved canopy stratification. Consequently, PIF4-mediated auxin signaling promotes vegetative vigour, optimises light interception, and supports higher biomass accumulation under favourable thermal conditions, explaining the superior canopy development observed in the D<sub>4</sub> sowing window (Franklin *et al.* 2011, Sun *et al.* 2012).

Conversely, delayed sowing resulted in suppressed canopy elaboration, likely driven by suboptimal thermal

Table 4 Effect of sowing dates on days to 50% flowering in soybean genotypes (JS 335 and DSB 21)

| Treatment            | Days to 50% flowering |                |       |                |                |       |                |                |       |
|----------------------|-----------------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|
|                      | 2022–2023             |                |       | 2023–2024      |                |       | Pooled data    |                |       |
|                      | V <sub>1</sub>        | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  |
| D <sub>1</sub>       | 40.0                  | 39.6           | 39.8  | 41.3           | 40.6           | 41.0  | 40.6           | 40.1           | 40.4  |
| D <sub>2</sub>       | 38.3                  | 38.3           | 38.3  | 39.0           | 39.6           | 39.3  | 38.6           | 39.0           | 38.8  |
| D <sub>3</sub>       | 36.6                  | 37.6           | 37.1  | 37.3           | 38.3           | 37.8  | 37.0           | 38.0           | 37.5  |
| D <sub>4</sub>       | 35.6                  | 37.0           | 36.3  | 36.6           | 38.0           | 37.3  | 36.1           | 37.5           | 36.8  |
| D <sub>5</sub>       | 35.3                  | 35.6           | 35.5  | 36.3           | 36.3           | 36.3  | 35.8           | 36.0           | 35.9  |
| D <sub>6</sub>       | 35.0                  | 35.3           | 35.1  | 36.0           | 36.0           | 36.0  | 35.5           | 35.6           | 35.5  |
| Mean                 | 36.8                  | 37.2           | 37.0  | 37.7           | 38.1           | 37.9  | 37.3           | 37.7           | 37.5  |
|                      | V                     | D              | V × D | V              | D              | V × D | V              | D              | V × D |
| SEM±                 | 0.31                  | 0.51           | 0.72  | 0.34           | 0.54           | 0.78  | 0.32           | 0.52           | 0.74  |
| CD ( <i>p</i> =0.05) | NS                    | 1.50           | NS    | NS             | 1.61           | NS    | NS             | 3.38           | NS    |

V, Variety; D, Sowing window; NS, Non-significant. Treatment details are given under Materials and Methods.

and photoperiodic cues that constrain cellular proliferation and organ expansion.

**Days to 50% flowering:** Days to 50% flowering was significantly affected by sowing windows, whereas genotypic variation was relatively minor. Among the genotypes, DSB 21 exhibited a marginally longer duration to attain 50% flowering compared to JS 335 across both years as well as in the pooled analysis (Table 4). Among the sowing windows, D<sub>1</sub> recorded the highest number of days to 50% flowering (39.8, 41.0 and 40.4), which was on par with the second fortnight of November (D<sub>2</sub>: 38.3, 39.3, 38.8 days). In contrast, D<sub>6</sub> resulted in the earliest flowering (35.1, 36.0, 35.5 days) in 2022–2023, 2023–2024 and pooled data, respectively.

A distinct inverse relationship was observed between sowing delay and the duration to floral induction, with later sowings exhibiting progressively fewer days to anthesis. The extended pre-flowering phase under early sowing is attributable to permissive thermophotoperiodic regimes that prolong juvenility and delay floral transition. In contrast, delayed sowing exposed the crop to elevated thermal accumulation (increased growing degree days) and truncated photoperiods, which expedited phenological progression and hastened floral primordia initiation. These results corroborate the seminal findings of Singh *et al.* (2007) who documented accelerated reproductive onset under late sown conditions in soybean attributed to enhanced developmental velocity driven by supra optimal thermal inputs.

Table 5 Effect of sowing dates on days to maturity in soybean genotypes (JS 335 and DSB 21)

| Treatment            | Days to maturity |                |       |                |                |       |                |                |       |
|----------------------|------------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|
|                      | 2022–2023        |                |       | 2023–2024      |                |       | Pooled data    |                |       |
|                      | V <sub>1</sub>   | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  |
| D <sub>1</sub>       | 87.0             | 85.3           | 86.1  | 89.0           | 87.0           | 88.0  | 88.0           | 86.1           | 87.0  |
| D <sub>2</sub>       | 85.3             | 85.0           | 85.1  | 87.0           | 86.3           | 86.6  | 86.1           | 85.6           | 85.9  |
| D <sub>3</sub>       | 84.0             | 84.3           | 84.1  | 85.3           | 85.3           | 85.3  | 84.6           | 84.8           | 84.7  |
| D <sub>4</sub>       | 82.0             | 82.3           | 82.1  | 84.3           | 84.3           | 84.3  | 83.1           | 83.3           | 83.2  |
| D <sub>5</sub>       | 81.6             | 80.6           | 81.1  | 82.3           | 82.6           | 82.5  | 82.0           | 81.6           | 81.8  |
| D <sub>6</sub>       | 80.3             | 80.3           | 80.3  | 81.6           | 80.6           | 81.1  | 81.0           | 80.5           | 80.7  |
| Mean                 | 83.3             | 83.0           | 83.1  | 84.9           | 84.3           | 84.6  | 84.1           | 83.6           | 83.9  |
|                      | V                | D              | V × D | V              | D              | V × D | V              | D              | V × D |
| SEM±                 | 0.27             | 0.47           | 0.66  | 0.21           | 0.70           | 0.92  | 0.23           | 0.54           | 0.74  |
| CD ( <i>p</i> =0.05) | NS               | 1.38           | NS    | NS             | 2.02           | NS    | NS             | 1.61           | NS    |

V, Variety; D, Sowing window; NS, Non-significant. Treatment details are given under Materials and Methods.

Table 6 Effect of sowing dates on seed yield/plant in soybean genotypes JS 335 and DSb 21

| Treatment            | Seed yield/plant (g) |                |       |                |                |       |                |                |       |
|----------------------|----------------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|
|                      | 2022–2023            |                |       | 2023–2024      |                |       | Pooled data    |                |       |
|                      | V <sub>1</sub>       | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  | V <sub>1</sub> | V <sub>2</sub> | Mean  |
| D <sub>1</sub>       | 10.7                 | 10.4           | 10.6  | 10.5           | 10.2           | 10.4  | 10.6           | 10.3           | 10.5  |
| D <sub>2</sub>       | 10.7                 | 10.4           | 10.6  | 10.5           | 10.2           | 10.3  | 10.6           | 10.3           | 10.4  |
| D <sub>3</sub>       | 8.3                  | 8.8            | 8.5   | 8.2            | 8.5            | 8.3   | 8.2            | 8.7            | 8.4   |
| D <sub>4</sub>       | 6.3                  | 6.7            | 6.5   | 6.0            | 6.6            | 6.3   | 6.1            | 6.7            | 6.4   |
| D <sub>5</sub>       | 6.2                  | 6.7            | 6.4   | 5.9            | 6.5            | 6.2   | 6.0            | 6.6            | 6.3   |
| D <sub>6</sub>       | 6.0                  | 6.4            | 6.2   | 5.7            | 6.2            | 6.0   | 5.8            | 6.3            | 6.1   |
| Mean                 | 8.0                  | 8.2            | 8.1   | 7.8            | 8.0            | 7.9   | 7.9            | 8.1            | 8.0   |
|                      | V                    | D              | V × D | V              | D              | V × D | V              | D              | V × D |
| SEM±                 | 0.13                 | 0.39           | 0.52  | 0.12           | 0.38           | 0.50  | 0.13           | 0.38           | 0.51  |
| CD ( <i>p</i> =0.05) | NS                   | 1.16           | NS    | NS             | 1.11           | NS    | NS             | 1.13           | NS    |

V, Variety; D, Sowing window; NS, Non-significant. Treatment details are given under Materials and Methods.

**Days to maturity:** Days to maturity was significantly affected by sowing windows, while genotypic differences and their interaction with sowing dates were found to be non-significant (Table 5). Among the genotypes, JS 335 took slightly more days to reach maturity (~84 days) compared to DSB 21 (~83–84 days) across both years and pooled analysis. Among the sowing windows, D<sub>1</sub> recorded the maximum duration to maturity (about 86–88 days), whereas D<sub>6</sub> resulted in the shortest duration (approximately 80–81 days). A clear reduction in days to maturity was observed with delay in sowing.

The longer duration under early sowing may be attributed to favourable environmental conditions that support prolonged vegetative and reproductive phases. In contrast, delayed sowing exposed the crop to higher temperatures during later growth stages, which accelerated physiological processes and hastened maturity. These findings are in agreement with Islami and Sugito (2012) and Divito *et al.* (2016) who reported earlier maturity under higher temperature conditions in soybean.

**Seed yield:** Seed yield was significantly influenced by sowing windows, while genotypic differences and their interaction with sowing dates were found to be non-significant. Among the genotypes, DSB 21 recorded slightly higher seed yield/plant (8.2, 8.0 and 8.1 g) compared to JS 335 (8.0, 7.8 and 7.9 g) respectively in 2022–23, 2023–24 and in pooled data. Among the sowing windows, D<sub>1</sub> recorded the highest seed yield/plant and seed yield/plot (10.6, 10.4 and 10.5 g and 2.4, 2.3 and 2.3 kg) and the lowest was recorded in D<sub>6</sub> (6.2, 6.0 and 6.1 g and (1.0, 1.0 and 1.0 kg) in 2022–23, 2023–24 and in pooled data, respectively (Table 6 and Supplementary Table 1).

A clear declining trend in seed yield was observed with delay in sowing. The superior yield under early sowing is attributable to permissive microclimatic conditions that

facilitated extended vegetative and reproductive durations, optimised canopy architecture, and enhanced assimilate translocation efficiency toward reproductive sinks. Conversely, late sowing subjected the crop to elevated thermal stress and a compressed ontogenetic window, resulting in diminished source sink dynamics, reduced biomass partitioning, and impaired seed set. As a result, yield reductions of 10–40% are commonly reported, although the magnitude varies with genotype and environment (Etsushi and Tomoki 2020). These findings unequivocally demonstrated that early sowing establishes an optimal phenological niche for maximising seed productivity under off-season cropping systems. The results corroborate Oad *et al.* (2002), Neenu *et al.* (2017) and Osagie *et al.* (2024) who emphasised that physiological yield potential is governed by assimilate availability and its allocation efficiency to developing seeds.

The sowing window critically governed the growth, phenology, seed yield, and quality of off-season soybean. Genotypes JS 335 and DSB 21 exhibited comparable adaptability across sowing regimes, with no significant differential response. Sowing during the first fortnight of November (D<sub>1</sub>) consistently optimised morpho-phenological traits, extended reproductive duration, maximised sink capacity, and enhanced seed quality. Conversely, delayed sowing induced thermal stress and phenological compression, leading to substantial yield reduction. Thus, D<sub>1</sub> represents the most agronomically viable and physiologically favourable window for off-season seed production in North Eastern Dry Zone of Karnataka region, ensuring superior crop performance and resource-use efficiency.

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