



REVIEW ARTICLE

Physiological and phenological response of pulses to sowing windows: A review

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Abstract

Selection of an appropriate sowing window is a low-cost management decision that regulates the thermal, photoperiod and soil-moisture environmental conditions experienced by pulse crops. This review evaluated how sowing time affects phenology, crop establishment, growth, nodulation, stress exposure, yield formation and grain quality in major pulses. A preferred reporting items for systematic reviews and meta-analyses (PRISMA) aligned search of Google Scholar, Web of Science (WoS), Scopus and CAB abstracts covered peer-reviewed studies published during 1990–2026. Of the 258 records identified, 197 remained after duplicate removal, 150 full-text articles were assessed and 63 studies met the inclusion criteria. Sowing within a locally suitable window improves crop establishment, thermal-use efficiency, biomass accumulation, pod set and seed filling by aligning critical growth stages with favourable temperature and soil-moisture conditions. In contrast, sowing too early or delaying sowing can alter crop duration and increase exposure to heat stress, drought, waterlogging, pests and diseases. Responses vary among species and genotypes because thermal thresholds, photoperiod sensitivity and stress tolerance differ. Therefore, optimum sowing recommendations cannot be based on a universal calendar date. Integrating thermal-time indices, rainfall probability, soil-moisture conditions, weather forecasts and cultivar duration can support crop-, genotype- and region-specific sowing decisions. Such adaptive scheduling offers a practical approach to reducing avoidable stress exposure, improving yield stability and strengthening the climate resilience of rainfed and irrigated pulse-production systems.

Keywords: climate resilience; growth; legumes; phenology; sowing windows; thermal indices; yield response

Introduction

Pulses are central to food and nutritional security because their edible seeds provide protein, complex carbohydrates, minerals and dietary fibre, while biological nitrogen (N) fixation supports soil fertility and reduces dependence on mineral N. The global harvested area under pulses reached about 91 Mha in 2024 (1) and India produced an estimated 25.68 million t in 2024–25 (2). Despite this scale, pulse yields remain highly variable because a large proportion of production occurs under rainfed conditions where rainfall onset, soil-water storage and terminal heat are difficult to predict. Sowing time determines the temperature, photoperiod and moisture regime encountered at each developmental stage and therefore controls emergence, vegetative duration, flowering, pod development, seed filling and maturity (3, 4). Phenological responses can be reported consistently using the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) decimal scale, which describes germination, leaf and shoot development, inflorescence emergence and flowering, pod development, seed ripening and senescence (5). Relating sowing windows to BBCH stages is especially useful because it identifies the precise stage at which heat, drought, waterlogging, pests or diseases act, rather than describing stress only by calendar date.

Moisture availability at sowing is particularly important in rainfed pulse production, where irregular rainfall and unpredictable soil moisture can cause poor establishment and uneven crop stand (6). Rainfall-based probability analysis and crop-growth modelling are increasingly being utilised to identify reliable sowing windows under changing climatic conditions. Pulse genotypes differ widely in stress tolerance, photoperiod sensitivity and temperature requirements; therefore, genotype × environment interactions complicate sowing-time decisions (7, 8). Late sowing may increase exposure to heat stress, drought, pests and diseases, resulting in substantial yield penalties, whereas excessively early sowing may increase the risk of unfavourable rainfall or temperature during flowering and pod development. Whereas early sowing increases probability of encountering rainfall during flowering and pod development stages. Timely sowing often promotes greater canopy formation, nodulation, biomass buildup and photosynthetic efficiency. The objective of this review was to synthesise evidence from chickpea, lentil, mung bean, black gram, pigeon pea and field pea; quantify the effects of early, optimum and late sowing on phenological and physiological responses; explain the underlying thermal and moisture mechanisms; and identify practical, climate-responsive criteria for crop-, genotype- and region-specific sowing recommendations. Unlike previous crop-specific or location-specific

summaries, this review integrates phenological stages, thermal indices, physiological mechanisms, stress exposure and regional evidence across major grain pulses to develop crop-, genotype- and region-specific sowing recommendations under increasing climate variability.

Methodology and literature search strategy

A structured literature search was conducted in Google Scholar, Web of Science (WoS), Scopus and CAB abstracts for studies published from 1 January 1990 to 31 May 2026. Search strings combined crop names with the terms “sowing window”, “sowing date”, “phenology”, “growing degree days”, “accumulated growing degree days”, “photothermal units”, “heat-use efficiency”, “heat stress”, “drought stress”, “nodulation”, “yield” and “pulse productivity” using AND and OR operators. Peer-reviewed English-language field studies and empirical reviews that reported defined sowing dates and at least one phenological, physiological, stress or yield response were eligible. Duplicate records, conference abstracts, opinion articles, studies without sufficient methodological information and papers unrelated to pulse sowing windows were excluded were excluded, as summarised in Table 1. The search identified 258 records; 61 duplicates were removed, 197 titles and abstracts were screened, 150 full texts were assessed and 63 studies were included in the qualitative synthesis. The selection and reporting process followed the PRISMA 2020 framework (9). The screening sequence is presented in Fig. 1 and the eligibility rules are summarised in Table 1. The review was restricted to major grain pulses with broad cultivation and comparable grain-production objectives in principal Indian and South Asian pulse systems. Regionally concentrated and multipurpose legumes, including cowpea, horse gram, faba bean, lablab bean, French bean and cluster bean, were excluded because they are frequently cultivated for vegetable, fodder, forage, dual-purpose or industrial uses, making their production objectives and harvest criteria less directly comparable with those of the major grain pulses reviewed.

Agro-climatic factors governing optimal sowing windows

Photoperiod and temperature requirements of major pulses

Temperature determines the rate of development, whereas photoperiod modifies the transition from vegetative to reproductive growth. Their interaction therefore determines whether flowering and seed filling coincide with favourable weather. Chickpea and lentil are cool-season pulses with quantitative long-day responses; excessive temperature during reproduction accelerates flowering and maturity and increases terminal-heat risk (3, 10). Temperature

acts as a developmental accelerator by modifying the rate of crop growth. In contrast, photoperiod serves as the main stimulant for the transition from vegetative to reproductive growth (11). Mung bean and black gram are warm-season, predominantly short-day crops that establish best under warm soils but lose reproductive duration when planting is delayed into hotter or drier periods (6, 12, 13).

In pulse crops, temperature and photoperiod work together to determine phenology and yield stability. To explain stage-specific temperature requirements, researchers quantify thermal requirements using growing degree days and photothermal units across pulse species and photoperiod sensitivity whether short-day, long-day or day-neutral further influences flowering time and seasonal adaptability (14). Chickpeas are cool-season pulses that need temperatures between 20 and 30 °C. They have a quantitative long-day response and breeding has increased photoperiod variation, allowing for early maturity and adaptation to shorter growing seasons (15).

Pigeon pea is generally a quantitative short-day crop with strong maturity-group differences. Medium- and long-duration genotypes require sufficient vegetative time before day length favours flowering, whereas short-duration cultivars provide greater flexibility post-rainy and winter production systems (14, 15). Field pea is adapted to cool conditions and is particularly sensitive to heat during flowering and seed filling; timely sowing is therefore needed to complete reproduction before high-temperature episodes (10, 16, 17). Crop-wise thermal and phenological responses are compared in Table 2.

Thermal units as a basis for optimum sowing window

Thermal metrics, including growing degree days (GDD), accumulated growing degree days (AGDD), heliothermal units (HTU) and photothermal units (PTU), are commonly used to quantify the heat accumulation required for crop growth and development. The corresponding equations are presented below. Changing the sowing date affects the thermal conditions experienced during various developmental stages, which may help or hinder alignment with optimal temperatures because each crop variety has unique thermal accumulation requirements for reaching flowering and maturity (12).

i. Growing degree days (°C d)

$$GDD = \left[\frac{T_{max} + T_{min}}{2} \right] - T_b \quad (1)$$

Table 1. Criteria for inclusion and exclusion strategy for selecting an adequate review paper

Criteria	Inclusion	Exclusion
Study focus	Studies evaluating pulse crops alone (e.g., blackgram, chickpea, mung bean, pigeon pea) under varied sowing windows.	Studies unrelated to pulse crops or sowing window management.
Publication year	Articles published between 1990 and 2026	Publications before 1990
Study type	Original research, field experiments and review articles based on empirical evidence	Conference abstracts, editorials, opinion papers and non-data-based chapters
Language	Publications written in English	Publications in other languages
Access	Full-text articles available through open or institutional access	Articles available only as abstracts, with no full-text access
Crop relevance	Studies conducted on major pulse crops of agricultural importance.	Studies restricted to non-legume model plants without direct agricultural relevance
Parameters assessed	Studies reporting optimum sowing windows, phenological (GDD, maturity) and physiological (yield, biomass) responses.	Studies focusing solely on biotic stress or unrelated outcomes
Experimental details	Studies providing specific sowing dates, thermal unit data or phenotypic outcomes.	Studies with uncharacterised sowing protocols or insufficient methodology.

GDD: Growing degree days.

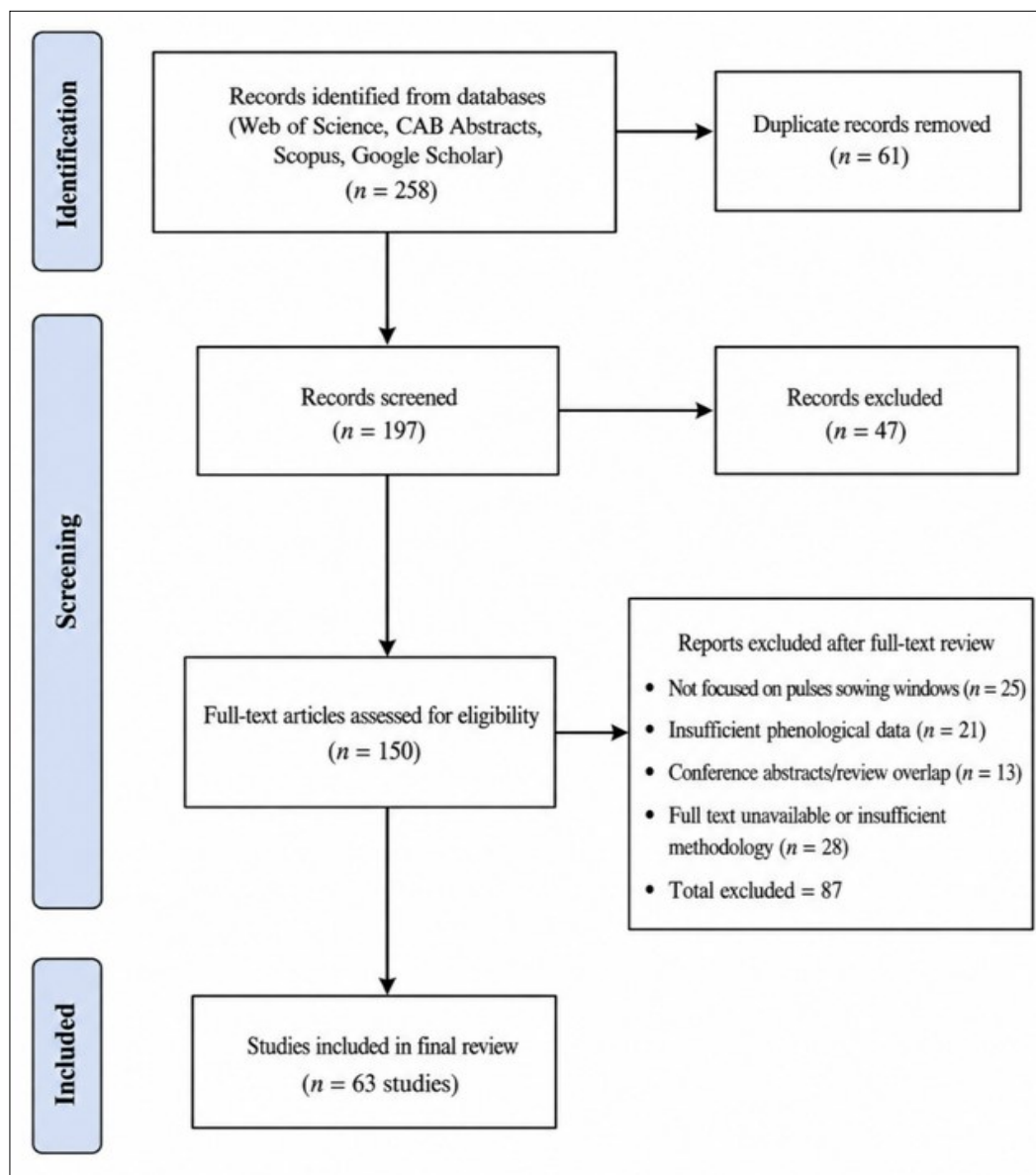


Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram.

Table 2. Thermal requirements and yield response of pulse crops across sowing windows

Crop	Sowing window	Days to maturity	AGDD (°C d)	HTU (°C d h)	PTU (°C d h)	HUE [kg ha ⁻¹ (°C d) ⁻¹]	Reported yield (kg ha ⁻¹)	Reference
Mung bean	1 st March (Early)	73	1496.1	11545.8	19599.3	0.50	762	(12)
	20 th March (Optimal)	70	1502.0	11903.0	20050.0	0.71	1086	
	30 th March (Late)	67	1549.6	12109.4	20609.8	0.48	745	
Field pea	13 th November (Early)	95	1800.0	9800.0	12500.0	3.88	6990	(39)
	28 th November (Optimal)	90	1850.0	10100.0	12850.0	4.64	8580	
	13 th December (Late)	85	1700.0	9100.0	11900.0	2.85	4850	
Pigeon pea	June 1 st FN (Early)	180	3209.0	16540.0	38430.0	0.48	1539	(15)
	June 2 nd FN (Optimal)	175	3075.0	15901.0	36898.0	0.50	1535	
	July 1 st FN (Late)	165	2943.0	15081.0	35320.0	0.47	1385	
Black gram	July 2 nd FN (Latest)	160	2877.0	14893.0	34526.0	0.42	1191	(55)
	39 th SW (Pre-monsoon)	75	1185.0	6966.0	9200.0	0.52	616	
	41 st SW (Optimal)	73	1158.0	6729.0	9000.0	0.52	601	
Chickpea	43 rd SW (Late)	70	1074.0	5985.0	8600.0	0.44	469	(57)
	10 th November (Early)	120	1931.0	1586.0	2040.0	1.04	2000	
	20 th November (Optimal)	115	1850.0	1500.0	1950.0	1.08	2200	
Mung bean	28 th SMW	72	1108.0	3763.0	14993.0	0.86	953	(62)
	29 th SMW	73	1025.0	3561.0	13875.0	0.77	789	
	30 th SMW	75	992.0	3932.0	13384.0	0.70	694	

AGDD: accumulated growing degree days; HTU: heliothermal units; PTU: Photothermal units; HUE: Heat-use efficiency; SMW: standard meteorological week.

where, $T_{\max}$ denotes daily maximum temperature

$T_{\min}$ denotes daily minimum temperature

T_b denotes crop-specific base temperature

ii. Accumulated growing degree days ($^{\circ}\text{C d}$)

$$\text{AGDD} = \sum \text{GDD} \quad (2)$$

where, GDD denotes growing degree days

iii. Heliothermal units ($^{\circ}\text{C d h}$)

$$\text{HTU} = \sum (\text{GDD} \times \text{bright sunshine hours}) \quad (3)$$

iv. Photothermal units ($^{\circ}\text{C d h}$)

$$\text{PTU} = \sum (\text{GDD} \times \text{day length}) \quad (4)$$

v. Heat-use efficiency [$\text{kg ha}^{-1} (^{\circ}\text{C d})^{-1}$]

$$\text{HUE} = \frac{\text{Grain yield}}{\text{AGDD}} \quad (5)$$

In black gram, heat use efficiency (HUE) was strongly influenced by sowing time, with pre-monsoon sowing during the 39th standard meteorological week (late September) recording the highest HUE of $0.153 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1}$, followed by monsoon sowing during the 41st standard week with $0.151 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1}$, whereas post-monsoon sowing during the 43rd standard week recorded the lowest HUE of $0.143 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1}$. The greater HUE under early sowing was associated with a higher grain yield of 885 kg ha^{-1} because thermal accumulation coincided with adequate soil moisture, optimum temperature conditions and a longer reproductive period, thereby enabling more efficient conversion of accumulated heat units into biomass and seed yield. Among the evaluated varieties, CO 5 recorded the highest HUE of $0.156 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1}$, indicating its superior ability to utilise accumulated thermal energy for yield production (13). Late sowing shortened vegetative and reproductive development and reduced seed and stover yields, whereas BARI Chola-11 maintained comparatively greater resilience under the adverse sowing window. Depending on genotype, accumulated GDD at physiological maturity declined from $2142.9\text{--}2664.7 ^{\circ}\text{C days}$ under the 20th November sowing to $1897.8\text{--}1923.2 ^{\circ}\text{C days}$ under the 10th December sowing (18).

Sowing time markedly altered crop duration, thermal accumulation and grain yield in pulse crops. Late sowing on 30th March shortened maturity to 67 days and recorded the highest GDD ($1549.61 ^{\circ}\text{C day}$), HTU ($12,109.40 ^{\circ}\text{C day h}$) and PTU ($20,609.8 ^{\circ}\text{C day h}$), whereas sowing on 1st March required 73 days and accumulated $1496.13 ^{\circ}\text{C day}$, $11,545.80 ^{\circ}\text{C day h}$ and $19,599.3 ^{\circ}\text{C day h}$, respectively. However, the highest thermal accumulation did not produce the greatest yield. Sowing on 20th March recorded the maximum grain yield of $1086.5 \text{ kg ha}^{-1}$, together with higher HUE ($0.710 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1}$) and PTUE ($0.054 \text{ kg ha}^{-1} ^{\circ}\text{C}^{-1} \text{ day}^{-1} \text{ h}^{-1}$), indicating that synchronisation of reproductive development with favourable temperature and moisture conditions is more important than thermal accumulation alone (12, 19).

Late sowing generally accelerates flowering and maturity, compresses the reproductive and seed-filling phases and may reduce yield and seed quality through heat stress, while excessively early sowing can prolong vegetative development under cooler conditions (20, 21). Thermal requirements also vary among genotypes; for example, Phule Durva required approximately $2161 ^{\circ}\text{C day}$ to complete its development, demonstrating the need to align

genotype-specific thermal thresholds with suitable sowing windows (22). Under climate change, sowing dates may therefore be adjusted using short-term temperature forecasts and accumulated GDD targets, provided that adequate soil moisture is available and damaging heat is avoided during flowering to maturity, corresponding approximately to BBCH 60–89. Comparative thermal responses are presented in Table 2.

Influence of rainfall pattern and soil moisture

In rainfed systems, the effective sowing window begins only after rainfall has sufficiently wetted the seed zone for uniform germination and early root development. Monsoon onset and withdrawal, weekly rainfall probability, soil-water storage, dry-spell duration and terminal drought risk therefore determine crop establishment and growth duration (23, 24). Delayed monsoon onset may cause poor establishment and expose mung bean and black gram to mid-season or terminal moisture stress, whereas sowing into persistently wet soil may increase waterlogging and seedling mortality (25).

The favourable season varies with crop and location: chickpea, lentil and field pea generally benefit from post-rainy sowing using stored soil moisture, while mung bean and black gram perform better when sowing follows reliable early-season rainfall and flowering occurs before terminal drought. In rainfed mung bean, late-September sowing received 409.0 mm rainfall with a more favourable distribution than mid-October and late-October sowings, which received 461.0 and 404.4 mm, respectively, demonstrating that rainfall distribution is more important than seasonal rainfall total alone (26). Representative crop-season combinations and their climatic basis are summarised in Table 3, while the effects of sowing time on crop establishment, growth and yield are presented in Fig. 2.

Influence of sowing windows on phenological development

Germination and seedling establishment

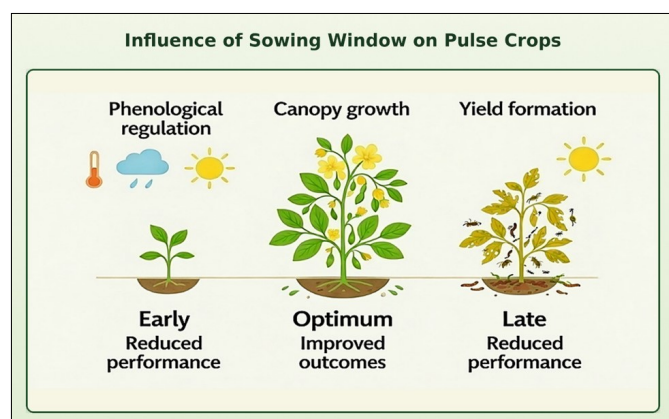
Sowing windows regulates germination and seedling establishment through its effects on soil temperature and soil moisture. Early sowing of soybeans can delay germination, with reports indicating that emergence may require 11.5 days compared to 7.4 days under the warmer conditions associated with late sowing. Elevated temperatures accelerate metabolic activity, which can reduce emergence time by several days, though early sowing often mitigates moisture deficits common in late sowing (26). The recommended sowing windows, such as 15th–25th March for lentils and mung bean, promote uniform emergence by avoiding chilling delays and moisture deficits common in late sowing, underscoring the significance of optimal sowing period (25, 27, 28). Since late sowing increases susceptibility to evaporative loss and intermittent dryness, resulting in uneven plant stands and decreased seedling vigour, moisture availability during the imbibition phase is a crucial factor in effective establishment. On the other hand, radicle emergence and initial growth are facilitated by early seeding under ideal moisture conditions (16, 23). Zero-tillage seeding between the 40th and 45th standard meteorological weeks (29) improves the early growth of black gram and mung bean, resulting in increased initial biomass and yield potential (22).

The time of sowing had a significant effect on the initial germination and establishment of black gram crops. Sowing prior to the monsoon period during the 39th Standard Week (24th–30th September) created the most advantageous thermal conditions for instant and uniform seed germination, ultimately leading to a more robust crop establishment. Conversely, crops planted during the 41st

Table 3. Regional variations in optimum sowing time and yield response of pulses

Region	Crop	Recommended sowing window	Agroclimatic basis	Yield Response	Reference
Central India	Chickpea	Late October–November	Residual moisture; avoids terminal heat	Higher yield and HI	(57)
Semi-arid North India	Chickpea	Mid November	Avoids heat stress	Improves yield and physiological efficiency	(57)
Eastern India	Lentil	Mid-November	Favourable flowering temperature	Improved phenology and yield	(16, 22)
North India regions	Field Pea	Mid-November	Reduced rust; favourable reproductive climate	Higher pod and seed yield	(39, 42)
South-Central Bangladesh	Mung bean	Early March	Better thermal accumulation	Higher yield and HUE	(12, 28)
Tropical Dryland Regions	Mung bean	Late February–early March	Lower pest incidence	Improved yield and seed quality	(60)
Rainfed Tropics	Black gram	39 th Standard Week (Late September)	Better moisture use efficiency	Higher yield and nodulation	(44, 55)
Meghalaya (NE India)	Black gram	1 st Week of March	Favourable pre-monsoon conditions	Increased CGR, NAR and yield	(6)
Central Chhattisgarh, India	Black gram	Late July	Improved dry-matter accumulation and yield components	Improved seed yield	(49)
Semi-arid Tropics	Pigeon pea	Mid-June to early July	Synchronised flowering with rainfall	Higher biomass and yield	(15, 59)
Semi-arid Regions	Pigeon pea	2 nd Fortnight of June	Reduced drought and pest pressure	Improved yield and protein content	(51)
Sub-humid Tropical Regions	Soybean	Mid-April to Early May	Optimum vegetative and grain-filling temperature	Higher biomass and seed quality	(27, 32)
Eastern or Central India	Rice–Pulse Systems	40 th –42 nd SMW	Utilises residual soil moisture	Better establishment and yield stability	(24)

HI: harvest index; HUE: heat-use efficiency; CGR: crop growth rate; NAR: net assimilation rate; SMW: standard meteorological week; NE: Northeastern.

**Fig. 2.** Influence of sowing window on pulse crops.

Standard Week (8th–14th October) and the 43rd Standard Week (22nd–28th October) exhibited suboptimal early growth and weaker establishment, suggesting that postponed sowing negatively impacted the germination and initial vigour of black gram seedlings (13).

Biomass and leaf area development

Timely sowing increases leaf-area duration and dry-matter production by extending vegetative growth under favourable radiation and temperature. In chickpea, sowing during the first two weeks of November produced 22.54 g plant⁻¹ total dry matter at harvest. Delaying sowing to the first two weeks of December reduced total dry matter to 16.54 g plant⁻¹ and leaf and stem dry matter to 1.26 and 4.82 g plant⁻¹, respectively, indicating restricted canopy expansion (30). The delayed crop also produced less leaf and stem dry matter, indicating restricted canopy expansion. A larger leaf area and more biomass are produced by early sowing, which enhances photosynthesis and increases the possibility of better harvests. In summer soybean, sowing during the first standard meteorological week (1–7 January) produced greater total dry

matter and leaf-area development, whereas sowing during the seventh week (12–18 February) restricted canopy expansion and biomass accumulation (27). Similar patterns observed in mung bean and lentil indicate that appropriate sowing times lead to a greater leaf area index and more robust seedling establishment, while later sowing limits vegetative growth and canopy development (7, 30). Genotype and sowing window interactions add another layer of complexity, emphasising the need for variety-specific scheduling.

Vegetative growth duration

The duration of the vegetative stage in pulse crops is significantly affected by the time of sowing, with earlier plantings typically encouraging an extended growth period and improved canopy development. In soybean, planting in early January resulted in slower emergence and a longer vegetative phase, whereas sowing in late February reduced this phase due to quicker heat accumulation (31, 32). Late sowing typically reduces the overall duration of the crop cycle by accelerating developmental stages in warmer temperatures. The shifting of pigeon pea sowing from early November to early December substantially reduced the total crop duration. Early sowing around 1st November resulted in the longest crop cycle, extending up to about 339 days, whereas late sowing on 10th December reduced total duration to around 269 days, indicating a contraction of nearly 70 days. In another season, a similar shift shortened the crop duration from approximately 293 to 253 days, a reduction of about 40 days. An intermediate sowing time around 20th November produced a moderate crop duration while supporting superior yield performance (33). Similarly, delaying soybean sowing from 3 January to 14 February shortened physiological maturity from 115.0–90.5 days (25, 34).

Reproductive phase transitions: Flowering and pod set

Reproductive transitions in pulses are strongly influenced by sowing time. Early-sown crops generally reach flowering later and maintain

a longer flowering and pod-setting period, which can reduce exposure to heat and drought stress during seed filling (16). Crops sown in early November reached 50 % flowering at 55–60 days after sowing (DAS), in contrast to those sown in December, which reached 50 % flowering significantly earlier at 35–40 DAS due to their exposure to elevated temperatures and a reduced crop duration. Nonetheless, the crops sown earlier preserved a more extended flowering period (30–35 days) relative to the 15–20 days observed in late-sown crops, ultimately leading to enhanced pod formation and increased yield (35). Sowing at an earlier date (late June) resulted in 50 % flowering occurring between 32 and 35 days after sowing (DAS) and maturity being reached between 80 and 85 DAS in black gram. In black gram, late-June sowing reached 50 % flowering at 32–35 days after sowing (DAS) and maturity at 80–85 DAS, while mid-July sowing flowered at 25–28 DAS and matured at 65–70 DAS (36). Conversely, postponing sowing dates leads to a greater accumulation of heat units, which accelerates the transition to flowering and maturity. This abbreviated growth cycle results in a shorter seed-filling period, potentially compromising final crop production (18, 22).

Phenological plasticity and genotype x environment interactions

Phenological plasticity, the ability of crops to adjust developmental timing in response to environmental conditions like temperature and moisture, varies among genotypes and drives significant genotype and environment (G×E) interactions affecting growth and yield. Varieties vary in their heat unit requirements at crucial stages, which affects their ability to adjust to changes in sowing windows (37). Black gram phenological phases were frequently abbreviated. When pigeon peas were sown on May 15th, they required longer to reach 50 % flowering about 94–107 days, which gradually decreased when they were sown on June 15th (90 and 97 days) respectively. Days to physiological maturity showed a similar decline, with crops seeded on May 15th matured in around 134 days. Mung bean phenology was extremely sensitive to the timing of planting, sowing on March 20th showed an extended vegetative phase, whereas delaying sowing until May 5th expedited crop growth and reduced the time to maturity (8, 38).

Recent genetic studies show that phenological adaptation in pulses is controlled by several flowering-time and maturity loci rather than a single pathway. In lentil, distinct loci regulate component phases of early phenology, indicating that the emergence-to-flowering period can be modified without changing every developmental phase to the same extent (3). Environmental effects accounted for 78 % of total yield variation, while G×E interaction accounted for a further 13 %. Higher minimum temperatures during flowering and the reproductive period were associated with lower yields and substantial environmental variation was observed in flowering, maturity, reproductive duration, seed weight and yield (17). Chickpea genotypes differ in the duration and sensitivity of the photoperiod-responsive phase (11) and recent genotype–phenology analyses link flowering and maturity patterns with harvest index and grain-yield adaptation (8). Combining these genetic traits with thermal-time models should improve cultivar-specific sowing recommendations across environments.

Maturity period and seed filling

Seed-filling duration is a major link between sowing time and final seed weight. Field pea sown on 1st November required

approximately 145–160 days to mature, whereas 10th December sowing matured in 121–123 days; the degree of contraction differed among genotypes (39). Genotypic variation in maturity duration is pronounced; for instance, some genotypes maintain extended maturity periods under early sowing, which significantly contracts when planting is postponed, requiring around 160–165 days when sown on 1st November, but only 113–123 days when sown on 10th December. Other enhanced genotypes exhibited a similar trend, with maturity duration decreasing from roughly 145–150 days under early sowing to 112–124 days under late sowing. Conversely, local genotypes matured somewhat earlier, diminishing from approximately 125 days with early sowing to almost 117 days when sowing were postponed (39). A similar pattern, advancing soybean sowing from early January to mid-February shortened physiological maturity from approximately 115–90 days, representing a reduction of 20–25 days. These results clearly highlight that early sowing prolongs crop maturity, whereas late sowing accelerates crop completion across different pulse and legume crops (33). The cumulative influence of sowing windows on phenological duration, biomass accumulation and yield attributes of pulse crops is represented in Fig. 3.

Comparative effects of sowing windows on growth traits of representative pulse crops

Plant height, canopy development and branching

The time of sowing and the specific genotype significantly affect the height and canopy structure of pulse crops. Generally, planting earlier enhances plant height, leaf area expansion and branching due to an extended and more favourable vegetative period late-November sowing yields the tallest plants. In field pea, late-November sowing produced plants up to 64.97 cm at 60 DAS, compared with 49.71 cm under 13th December sowing (39, 40). In black gram, first-week-of-July sowing produced 36.8 cm plants compared with 32.0 cm after third-week-of-July sowing (6). Increased leaf area index (4.84) and effective canopy development resulting from early sowing have also been observed in field peas and mung bean, facilitating enhanced photosynthesis and dry matter accumulation (5.98 g plant⁻¹) (41, 42). In contrast, late sowing reduces the length of the vegetative phase, resulting in a lower LAI (2.47), fewer branches and less effective canopy formation and lowest dry matter production (2.6 g plant⁻¹) (42).

Root growth and development

Root growth and development are essential for pulses to absorb water and nutrients. However, environmental factors that are influenced by sowing dates have an indirect impact on root vigour. Sowing during optimal periods allows enhanced root development, contributing to improved plant vigour and nutrient uptake. Sowing time also changes the duration available for root exploration. In field pea, early sowing promoted faster penetration and maximum rooting depths of 0.88–1.06 m in uncompacted soil, compared with 0.71–0.97 m under less favourable conditions; root-occupied soil volume increased by 10–40 % in the more favourable sowing treatment (43). Early sowing promoted faster root penetration and greater rooting depth throughout the vegetative stage, boosting soil exploration before flowering. The subsurface root elongation rate ranged from 3.9–18.8 × 10⁻² m MJ⁻¹ m², with early-sown crops exhibiting steadier root development due to extended exposure to mild soil temperatures. Additionally, when spring-sown peas were

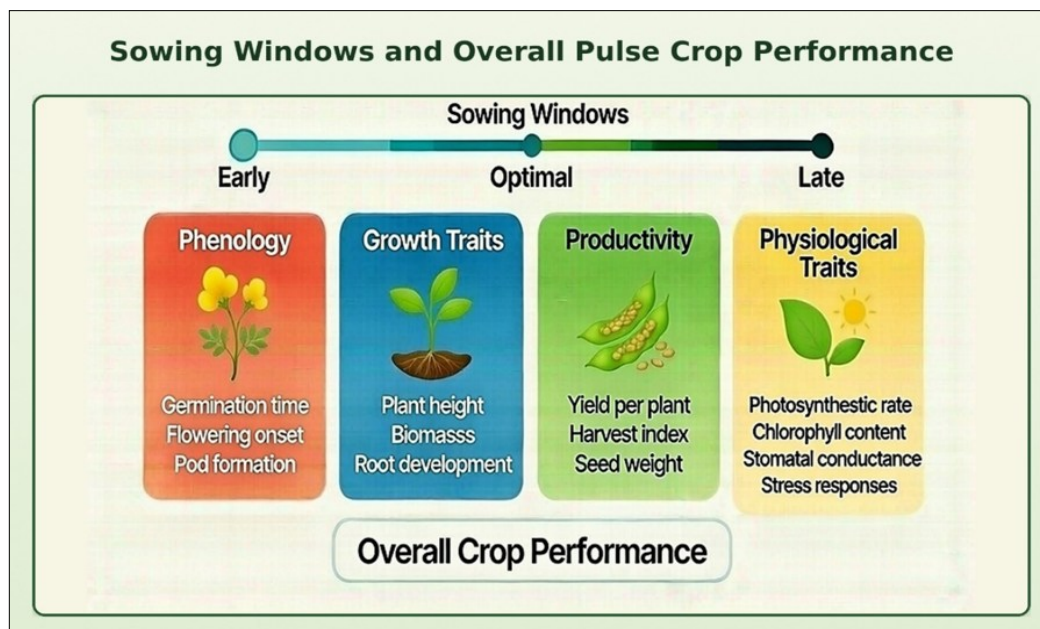


Fig. 3. Impact of sowing windows on crop performance traits in pulse crops.

compared to early fall sowing, the proportion of soil volume filled by roots rose by 10–40 %, indicating better lateral root multiplication. Early sowing extended the effective root growth time and resulted in deeper and more uniformly distributed root systems, whereas late sowing often reduced root extension due to rapid phenological development (43).

Nodulation and nitrogen fixation capacity

Pulses are well-known to fix atmospheric N symbiotically through root nodules. The relationship between sowing window and root nodulation dynamics in pulse crops is illustrated in Fig. 4, showing enhanced nodulation under early and optimum sowing conditions. Black gram sown on 8 July showed superior nodulation, with the variety Mash recording 35.7 nodules plant⁻¹ at 45 DAS and 61.7 nodules plant⁻¹ at 60 DAS. Delaying sowing to 8 August reduced nodulation to 32.9 and 49.9 nodules plant⁻¹ at 45 and 60 DAS, respectively, representing a 19 % reduction at 60 DAS. Among the early-sown cultivars, Mash 114 and Mash 338 recorded the highest nodule numbers of 59.3 and 56.0 nodules plant⁻¹, respectively, indicating that timely sowing favoured root nodulation in black

gram (44). Lentils that early sowing during the 1st week of November consistently produced more nodules than late sowing during the final week of November. Crops sown early exhibited a greater quantity of root nodules, in contrast to those sown later, which recorded merely 12.4–3.6 nodules per plant. This benefit associated with early sowing continued into the subsequent phases of growth. At 60–75 days after sowing (DAS), early-sown plants sustained a range of 23.2–27.2 nodules per plant, whereas late sowing led to diminished nodulation, with counts decreasing to 22.5–26.5 nodules per plant (45). Early sowing (15th July) is provided favourable soil conditions for root initiation and *rhizobia* colonisation, resulting in the highest nodule (29.3), whereas late-sown (5th August) crops suffered a marked decline in nodulation (12.0) (46). Black gram Pant U 31 sown during March 1st week exhibited greater nitrate reductase activity, indicating enhanced nitrate-assimilation capacity (47).

Productivity, yield components and grain quality in representative pulse crops

Pod and seed formation in pulses

The number of pods per plant and seeds per pod are major

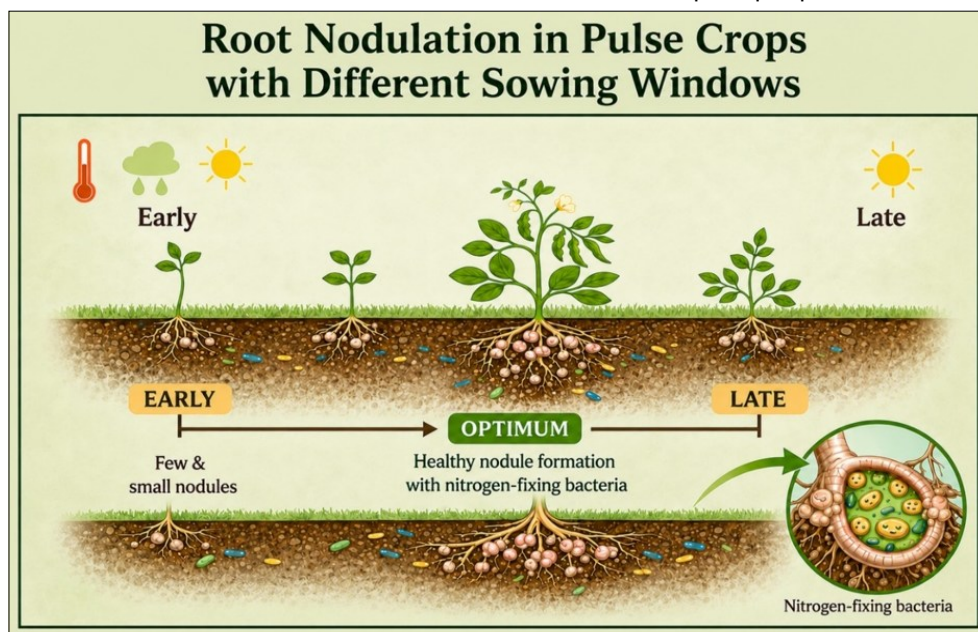


Fig. 4. Sowing window effects on root nodulation in pulse crops.

determinants of pulse-crop productivity and are strongly influenced by sowing time and genotype. Studies indicate that peas planted early typically yield over 20 pods per plant and experience improved seed set. Conversely, delaying the sowing process notably reduces both pod quantity and seed set due to a shorter vegetative growth period and increased exposure to high temperatures during flowering (33, 39, 42). A similar pattern is seen in black gram, where early planting, especially in short-duration varieties, results in a greater number of pods and seeds per pod compared to late sowing (39). Higher temperatures during the reproductive stage can lead to flower drop, which ultimately reduces seed set. These results highlight the importance of timely sowing to lessen heat stress and achieve better yields (38).

Seed size and test weight

Seed size, often measured by 1000-seed weight, varies with genotype, sowing date and growing circumstances. In peas, 1000-seed weight ranged from around 50 g to more than 120 g, with early sowings producing larger, heavier seeds (39, 42, 48). Black gram genotypes also displayed diversity, with 1000-seed weights generally between 40 and 50 g, frequently favouring early sowing (34). Field pea (*Pisum sativum*) 100 seed weight varied between 3 and 5 g in different settings, decreased by 6–16 % under heat stress (HSE-I/II vs. NHSE) and was greater in early-maturing genotypes. (38). In kharif black gram, test weight ranged from 36.4 to 38.8 g and declined by approximately 6 % between 8th July and 8th August sowing; Mash 114 retained the greatest test weight among the evaluated cultivars. Overall, late sowing reduced test weight by about 6 %, highlighting the importance of timely planting and suitable genotype selection for better seed quality (44).

Grain yield and biological yield

Grain yield integrates pod number, seeds per pod and seed size, but the optimum calendar date is strongly location- and genotype-dependent. In the environments represented by the cited pea studies, early- to mid-November sowing produced 530–1300 kg ha⁻¹ (39, 42). Black gram yields ranged from 0.8–2.5 t/ha, with early sowing and superior cultivars producing higher yields (6). Early sowing of black gram (*Vigna mungo* L.) during pre-monsoon or early kharif (around 8th July) results in higher grain yield (1.02–1.53 t ha⁻¹), which is 13–31 % greater than late August sowing. Late sowing consistently reduces yield, while improved varieties such as Mash 114, PU 31 and CO 5 perform best when sown early (44). Biological yield, the total above-ground biomass, exhibited similar tendencies, increasing with early sowing and high-yielding varieties as early sowings extend growing time for dry matter development (39). Timely sowing is therefore crucial for maximising black gram grain yield under rainfed conditions. (31, 44). In black gram, Timely sowing on 27th July produced a mean seed yield of 929 kg ha⁻¹ compared with 856 kg ha⁻¹ under late sowing on 11th August. The genotype IU-2021-3 recorded the highest mean yield of 1012 kg ha⁻¹, while its interaction with the 27th July sowing produced 1091 kg ha⁻¹ (49)

In summer mung bean, early-March sowing was superior to progressively later dates: yield declined from 917.5 kg ha⁻¹ on 20th February and 869.5 kg ha⁻¹ on 12th March to 720.5, 456.4 and 388.8 kg ha⁻¹ on 22nd March, 1st April and 11th April, respectively (50). Late sowing time significantly decreased the mung bean seed yield. In comparison to crops sown during the monsoon phase (41st standard week; mid-October) at 226 kg ha⁻¹ and the post-monsoon phase (43rd standard week has late October) at just 168 kg ha⁻¹, mung bean

planted during the pre-monsoon phase (39th standard week; late September) produced the highest seed yield of 308 kg ha⁻¹. These results clearly show that while late sowing in mid and late-October significantly reduced seed yield because of unfavourable weather conditions during the reproductive growth phase, early sowing in late September promoted superior crop establishment and yield maximisation. The timing of sowing had a major impact on black gram seed yield. Because of improved pod development, more seeds per pod and higher seed weight, planting during the 39th standard week (24th–30th September) produced the highest seed yield. Crops sown after the 41st Standard Week (8th–14th October) produced incredibly poor results and any delay in sowing beyond this period resulted in a gradual decline in yield. While late sowing led to excessive vegetative growth, insufficient flowering and decreased pod formation, which ultimately resulted in a lower grain yield, late-September sowing performed exceptionally well due to ideal temperatures and efficient soil moisture utilisation during the reproductive stage (26). Region-specific responses of pulse crops to sowing windows are presented in Table 3, highlighting the need for location-specific sowing recommendations

The three sowing dates examined (26), the sowing conducted on 28th November yielded the most substantial green seed production, measuring 8.58 t ha⁻¹, in contrast to 6.99 t ha⁻¹ recorded for 13th November and 4.85 t ha⁻¹ noted for 13th December. The yield superiority associated with the 28th November sowing was corroborated by enhanced yield attributes, which included the highest number of pods per plant (11.75), seeds per pod (8.54) and test seed weight (51.46 g). The postponement of sowing to mid-December resulted in a significant decline in all yield components, attributable to a reduced duration of vegetative growth and exposure to sub-optimal temperatures during reproductive development, culminating in a 43 % reduction in yield when compared to the optimal sowing window (39).

Harvest index variations

Harvest index (HI) expresses the proportion of total above-ground biomass recovered as economic yield. In black gram, HI typically varied between 25–29 %, with early sowings producing higher HI through improved partitioning to seed rather than vegetative components (34, 37). Field-pea studies reported values near 27–30 %, with late sowing reducing effective sink strength during seed filling (42). In black gram, HI ranged from 26.6–47.1 %. Earlier sowing during the first week of March or the 39th standard meteorological week produced a higher HI of 28.5–45.9 % than later sowing during the second week of March or the 43rd week, which produced an HI of 26.6–42.7 %, reflecting more favourable assimilate partitioning (6, 47)

The harvest index (HI) of chickpeas fluctuated between 47.3–56.3 % across various sowing periods in the central region of Bangladesh. Specifically, for the BARI Chola -5 variety, an early sowing on November 20th yielded a lower HI of 47.3 %, while a later sowing on December 10th achieved the highest HI of 56.3 %. This observation suggests an enhanced proportional distribution of biomass to grain when the crop duration is abbreviated. In the case of BARI Chola-11, the highest HI (43) was recorded for sowing on November 30th, whereas both the early (November 20th) and late sowing (December 10th) exhibited relatively lower HI figures at 47.8 % (18). Mung bean harvest index (HI) of varies from 30–45 %, contingent upon the timing of sowing. Early sowing, specifically from late June to early July, demonstrated a higher HI (38.0 % - 45.0 %)

compared to late sowing conducted from mid to late July, which registered an HI of 30.0–36.0 %. This discrepancy is attributed to improved synchronisation between vegetative growth and reproductive stages under optimal photothermal conditions (46).

Quality parameters (Protein content)

Pulses are valued for their high protein content but seed protein concentration varies with species, genotype, growing environment and sowing time. Pea protein levels ranged from roughly 23–27 %, with early planting and specific genotypes enhancing protein concentration (33, 42). Black gram had seed protein concentrations of approximately 20–22 %, with earlier sowing and superior cultivars generally maintaining higher protein yield (34). Late sowing commonly reduced protein yield because shortened phenology and reproductive stress lowered seed production.

Pigeon pea grain contains approximately 22 % protein, thereby playing a crucial role in ensuring food and nutritional security. Crops that are sown during the optimal timeframe (15th–30th June or the second fortnight of June) exhibit enhanced biomass production, improved pod formation and increased grain yield, which collectively promote a greater accumulation of seed protein in contrast to those sown later. Conversely, late sowing (October 1st–14th) subjects the crop to terminal moisture stress and a reduced grain-filling duration, resulting in diminished yield and inferior assimilate translocation to seeds, which ultimately culminates in a reduction in protein accumulation within the grains. Early sowing facilitates favourable temperature conditions, sufficient rainfall and an extended reproductive period, which promotes superior nitrogen fixation, photosynthate generation and protein synthesis in the developing seeds (51). The protein content of soybean seeds fluctuated across different sowing periods. Early sowing (mid-April) yielded lower protein levels (35.2 %–35.8 %), while later sowing (early May) resulted in higher protein concentrations (36.3–37.5 %) due to increased N accumulation within a shorter yet warmer grain-filling period. The average protein concentration increased from 35.6 % under early sowing to 37.0 % under late sowing, suggesting that later sowing increased soybean seed-protein concentration in the cited environment (32).

Stress response associated with sowing time

Heat stress during flowering, fertilisation and pod development stages adversely impacts pulses by promoting early flowering and shortening reproductive periods, leading to decreased seed set and yield penalties (37, 38, 52). The principal abiotic and biotic stress reactions of leguminous crops linked to variations in planting schedules are diagrammatically illustrated in Fig. 5. For example, pea (*Pisum sativum* L.) plants challenged to high temperatures exhibited substantial reductions in grain-filling time and seed weight due to decreased photosynthesis and faster senescence (38, 53). Manipulation of the sowing window to avoid peak high-temperature times has been demonstrated efficient in limiting heat stress effects, hence boosting yield (6).

Drought stress at critical growth stages

Drought during flowering and pod filling reduces pulse yield by limiting photosynthesis and the remobilisation of assimilates to developing seeds. A deep root system is an important drought-tolerance characteristic of pigeon pea; however, late sowing may increase exposure to dry spells during reproduction (54). Timely sowing can improve drought avoidance by coordinating crop water demand with soil-moisture availability (42, 55). Reproductive-stage drought reduces photosynthate production and translocation, resulting in fewer pods and filled seeds. Lentil yield declined by up to 28 % in drier environments because moisture limitation reduced grain number and weight (41).

In the case of extra-short-duration pigeon pea planted within the conventional rainy-season timeframe (late May to mid-June), drought stress typically aligns with phenological phases, contingent upon rainfall distribution. For crops sown on 30 May and 16 June, moisture stress experienced during the flowering phase (55–75 DAS in 1991; 55–80 DAS) led to the most significant yield decline (40–55 % and 15–40 %), whereas stress prior to flowering (35–60 DAS) resulted in a yield decrease of 10–40 % and stress during pod-filling (from 75 DAS to maturity) caused only a 15–20 % reduction in yield. Extended drought conditions persisting from pre-flowering to flowering or from flowering to pod-filling induced a drastic yield reduction, with grain

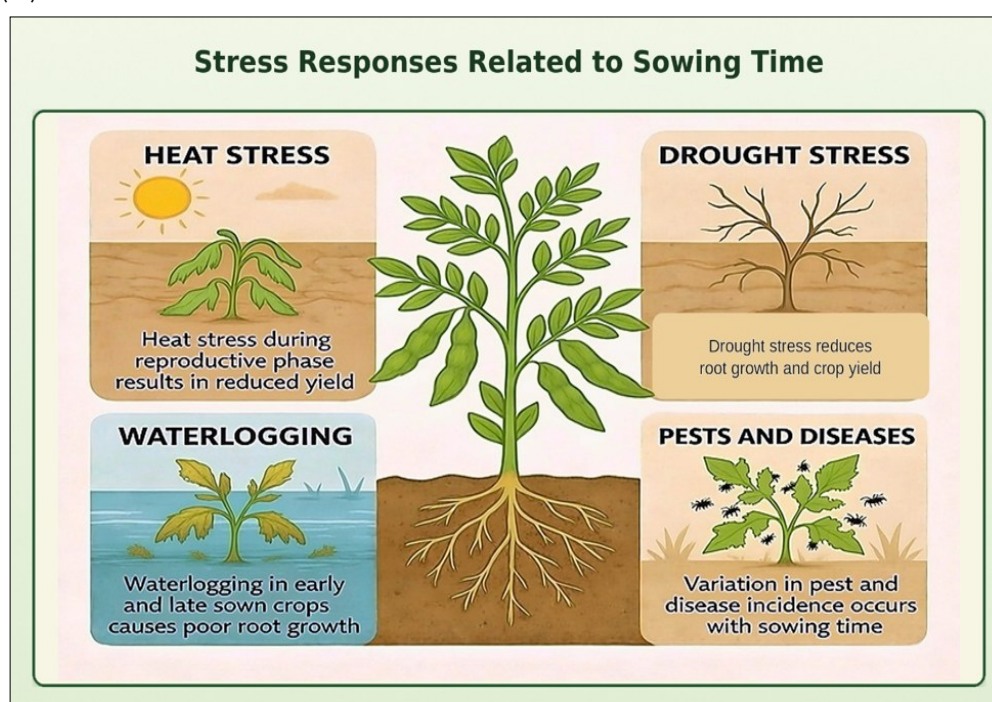


Fig. 5. Sowing-time-dependent stress responses in pulse crops.

yield diminishing to approximately 39 % of that observed in fully irrigated crops. These findings suggest that in pigeon pea typically sown during the rainy season, drought occurring during the flowering phase represents the most critical and detrimental stress interval due to its substantial adverse effects on dry-matter accumulation, flower retention and grain formation (56). The sensitivity of different growth stages of pulse crops to major abiotic stresses under varying sowing windows is summarised in Table 4, indicating that flowering and pod filling are the most vulnerable stages.

Impact of waterlogging in early and late sown crops

Waterlogging detrimentally impacts pulses, especially during germination and early vegetative stages, through oxygen deficiency causing poor seedling establishment and root function (44, 57). The cultivation of pigeon pea during the rainy season (June to July) frequently results in the exposure of crops to waterlogging during their initial growth phase, whereas late sowing exacerbates drought and thermal stress during the critical stages of flowering and pod development. In pigeon pea, waterlogging imposed at 20 and 40 DAS reduced plant survival by 40–50 % and 40–80 %, respectively, indicating greater sensitivity when waterlogging occurred at the later crop stage (58).

Variation in pest and disease incidence with sowing time

Pest and disease incidence changes with sowing time because crop-susceptible stages overlap differently with pest population peaks and weather conditions favourable for infection (6). Early sowing has been associated with reduced pest infestation and disease pressure, improving overall crop health and economic returns. Conversely, late sowing often coincides with peak pest activity, exacerbating damage and yield losses.

In pigeon pea, the time of sowing significantly influences the incidence of insect pests and the overall yield across four distinct sowing dates (10th June, 20th June, 10th July and 10th August). The early sowing on 10th June permitted the crop to evade significant pest pressures, including *Maruca vitrata*, *Helicoverpa armigera*, *Clavigralla gibbosa* and *Empoasca kerri*, culminating in the lowest recorded infestation levels. During the early sowing phase, *M. vitrata* manifested later (100–130 DAS) with an average of 22.6–28.2 webs per plant, whereas the late sowing on 10th August documented the highest infestation levels (35–36 webs per plant at 100 DAS). Likewise, *H. armigera* was virtually absent in the early sowing but exhibited a peak population of 0.60 larvae per plant in the late

sowing on 10th August. The extent of pod damage inflicted by *M. vitrata* escalated from 12.8 % (10th June) to 31.9 % (10th August), while damage attributed to *H. armigera* increased from 1.85–5.90 %; similarly, the prevalence of sucking pests (*E. kerri* and *C. gibbosa*) also intensified under late sowing conditions. Conversely, damage caused by the pod fly (*Melanagromyza obtusa*) was more pronounced in the early sowing (29.4 %) and subsequently diminished to 21.05 % in late sowing. Consequently, the grain yield was maximised under the 10th June sowing (1219 kg ha⁻¹) and minimised in the 10th August sowing (747 kg ha⁻¹), thereby substantiating the notion that optimal sowing time constitutes an effective eco-friendly approach to pest management (59). In summer mung bean, the early sowing performed on 15th February and the late sowing on 8th March corresponded with higher infestations of major sucking pests, including whitefly (*Bemisia tabaci*), leafhopper (*Empoasca kerni*) and thrips (*Thrips spp.*), as well as increased damage from pod borer (*Helicoverpa armigera*). Conversely, the crop sown during the final week of February (26th February) witnessed comparatively diminished populations of these pests and minimal pod borer damage, which ultimately resulted in enhanced yield outcomes (60).

In the context of mung bean cultivation, the timing of sowing exerts a significant influence on the incidence and severity of Mung bean yellow mosaic virus (MYMV) and cercospora leaf spot (CLS) across six distinct sowing dates (January 15th, February 1st, February 15th, March 1st, March 15th, April 1st). The initiation of sowing on January 15 resulted marked reduction in MYMV incidence (ranging from 6.54–13.28 %) and severity (assigning a score of 1 across various cultivars), whereas the later sowing on April 1st recorded the highest incidence (ranging from 21.96–40.94 %) (61). Similarly, CLS severity remained minimal (score of 1) for sowings conducted between January 15th and February 1st, but escalated to scores ranging from 3–5 for the April 1st sowing. As a result, the grain yield reached its zenith under the March 1st sowing (up to 2131 kg ha⁻¹) and was at its nadir in the April 1 sowing (681 kg ha⁻¹), thereby substantiating the conclusion that optimal sowing timing mitigates disease severity and fosters environmentally sustainable management practices (61–63).

In field pea cultivation, the time of sowing significantly affects the severity of rust (*Uromyces sp.*) across five distinct sowing dates (October 15th, October 30th, November 14th, November 29th, December 13th). Early sowing on October 15th exhibited the lowest

Table 4. Growth-stage-specific effects of abiotic and biotic stresses in pulses

Stress type	Sensitive growth stage	Impact	Crops	Sowing-window implication	References
Heat stress	Flowering and pod filling	Flower abortion, pollen impairment, reduced seed set and 100-seed weight	Pea, Lentil, Chickpea	Sowing that completes reproduction before peak heat reduces yield loss	(33, 38, 39, 20)
Drought	Pod filling	Lower photosynthesis, pod retention, seed filling and grain weight	Pigeon pea, black gram	Pigeon pea drought at flowering reduced yield by 40–55 % in the cited study	(54, 63)
Waterlogging	Germination and early vegetative	Poor establishment, root damage	Pulses (general)	Early rainy-season sowing requires adequate drainage; survival declined by up to 80 %	(6, 38, 58)
Insect-pest pressure	Flowering to pod development	Pod damage and yield reduction	Pigeon pea, Mung bean	Late sowing increased several borers and sucking pests, although pod-fly response differed	(41, 59, 60)
Disease incidence	Vegetative to reproductive	MYMV: mosaic and stunting; Cercospora: necrotic lesions and defoliation; rust: pustules and loss of green leaf area	Mung bean, Field pea	Timely sowing reduced disease pressure while maintaining a favourable yield environment	(41, 42, 61)

MYMV: mung bean yellow mosaic virus.

severity levels (ranging from 3–8 %), while the latest sowing on December 13th ascended to peak severity levels of 65–75 % across seasonal variations. The mid-late sowings (from November 14th to November 29th) recorded intermediate severity levels (ranging from 30–65 %). The yield was maximised in the November 14th sowing (ranging from 1035–1050 kg ha⁻¹) but experienced a decline in the December 13th sowing (ranging from 800–850 kg ha⁻¹) (14).

Oxidative stress and antioxidant responses

Abiotic stresses related to improper sowing windows, including heat and drought, can lead to oxidative stress by increasing reactive oxygen species (ROS) production in pulses. (38). Proper adjustment of sowing time combined with nutrient management enhances antioxidative capacity and plant resilience. In chickpea, sowing time influenced physiological responses to temperature-induced water deficit and heat stress across three sowing dates: 15 October, 15 November and 15 December. Late sowing on 15 December exposed the reproductive phase to a maximum temperature of 28.9 °C and resulted in the lowest leaf water potential (-0.35 MPa), osmotic potential (-0.87 MPa), relative water content (61.5 %), chlorophyll content (3.516 mg g⁻¹ DW), pods plant⁻¹ (43.5), test weight (13.47 g) and seed yield (1890 kg ha⁻¹), together with the highest RSI of 11.03 %. Sowing on 15 October or 15 November maintained higher relative water content, chlorophyll content, pod number and seed yield, confirming the physiological and yield benefits of timely sowing under semi-arid conditions (44).

The reviewed studies do not support a single universal “early sowing” rule. Pre-monsoon black gram benefited from better moisture use, whereas some chickpea treatments produced a greater proportional harvest index after moderate delay because total crop duration was shortened. These findings are not contradictory when biomass and grain allocation are separated: a delayed crop can have a higher HI but lower biomass and yield. Differences in rainfall distribution, cultivar duration, photoperiod response, soil-water storage and the temperature reached during BBCH 60–89 explain much of the regional variation.

Accordingly, AGDD or PTU should not be used as stand-alone predictors. The same accumulated thermal total may produce different yields when heat is concentrated during flowering, when moisture is limiting or when pest pressure coincides with pod development. Future studies should report BBCH stage, daily weather, soil water, genotype duration, nodulation, pest and disease observations and both biomass and grain yield. Multi-location experiments linked with crop simulation and seasonal forecasts are needed to convert calendar dates into probability-based, variety-specific sowing recommendations.

Critical synthesis, climate-change implications and research priorities

Explaining conflicting findings

The evidence does not support a universal assumption that earlier sowing always maximises pulse productivity. Early or pre-monsoon sowing generally improved yield, nodulation and heat-use efficiency in black gram and mung bean (12, 13, 44). However, an increase in harvest index under a shortened crop cycle should not be interpreted as a yield advantage because late sowing may reduce biomass, reproductive duration and grain yield (18, 30). Variation among studies reflects cultivar duration, photoperiod sensitivity, rainfall distribution, soil-water availability and the criterion used to define optimum performance (3, 17). Therefore, calendar dates should not be transferred directly among regions without

considering thermal, photoperiod and soil-moisture conditions.

Mechanistic interpretation and climate adaptation

Sowing date determines the temperature and water conditions experienced by leaves, flowers, nodules and developing seeds. Supra-optimal reproductive temperatures impair pollen function and fertilisation, accelerate respiration and senescence and consequently reduce pod set and seed filling (38, 53). Drought reduces canopy photosynthesis, assimilate supply and flower retention, whereas waterlogging-induced oxygen deficiency restricts root metabolism and crop survival (58). Climate change may therefore shift suitable sowing windows differently among environments. APSIM simulations for south-central Bangladesh identified 15–25th March as the current optimum mung bean window, while projected warming favoured advancement towards early March (28). This is a location-specific adaptation rather than a universal recommendation. Climate adaptation should combine seasonal forecasts, soil-moisture thresholds, thermal-time monitoring, stress-tolerant cultivars and locally validated crop models.

Knowledge gaps and future research priorities

Future studies should prioritise multi-location and multi-year genotype × sowing-window experiments using standardised phenological stages, thermal indices and soil-water measurements. Greater attention is required for underrepresented pulses, including cowpea, horse gram, faba bean, lablab bean, French bean and cluster bean. Studies should measure pollen function, photosynthesis, carbohydrate remobilisation, root architecture, nodule activity and biological nitrogen fixation alongside yield and grain quality. Decision Support System for Agrotechnology Transfer (DSSAT), Agricultural Production Systems sIMulator (APSIM) and climate-model ensembles require independent validation across cultivars and environments. Remote sensing and artificial intelligence may support real-time monitoring, but should complement physiological measurements and field validation. These approaches should ultimately produce farmer-usable advisories that report suitable sowing ranges, climatic risks and contingency options.

Conclusion

Sowing window is a practical and climate-responsive determinant of pulse phenology, stress exposure and yield stability. A locally suitable window aligns germination, vegetative growth, flowering and seed filling with favourable temperature, soil moisture and photoperiod, thereby supporting canopy development, nodulation, assimilate production and seed formation. Late sowing commonly accelerates phenological development and shortens seed filling, while excessively early sowing may expose crops to low temperature, waterlogging or unfavourable rainfall. The response is not universal because pulse species and cultivars differ in thermal requirements, photoperiod sensitivity, rooting, nodulation and stress tolerance. Sowing recommendations should therefore integrate cultivar duration with rainfall probability, soil-water availability and thermal-time information. Multi-location experiments and crop models that explicitly evaluate genotype × environment × management interactions are needed to refine region-specific recommendations and sustain pulse productivity under increasing climate variability.

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Authors' contributions

GRP prepared the initial draft of the manuscript. SS and MJ conceived the review and provided scientific guidance. TS, BBS and VS critically reviewed, edited and revised the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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Declaration of artificial intelligence (AI) and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve the layout and visual presentation of the figures. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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