

AGRONOMIC MANAGEMENT STRATEGIES FOR IMPROVING CROP ESTABLISHMENT, PHYSIOLOGY AND PRODUCTIVITY OF GRAIN LEGUMES: A REVIEW

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ABSTRACT

Grain legumes including green gram, black gram, chickpea, lentil, field pea, cowpea, pigeonpea, common bean and soybean are central to protein and nutritional security, cropping-system diversification and biological nitrogen fixation in Indian agriculture, yet their realized productivity remains well below attainable potential. This review synthesizes recent literature on two of the most consistently reported agronomic determinants of productivity time of planting and crop geometry and their downstream effects on crop establishment, physiological performance, resource use efficiency and yield across major grain legumes. Evidence indicates that timely sowing consistently improves germination, nodulation and canopy development, while delayed sowing depresses growth and yield through moisture and thermal stress during critical growth stages. Crop geometry studies show a broadly conserved density–competition trade-off, in which closer spacing raises biomass per unit area but reduces per-plant yield attributes, while wider spacing has the opposite effect; the position of the optimum shifts with species and growth habit. Climate-smart practices, conservation agriculture, and emerging tools such as crop simulation models, phenotyping and remote sensing are reviewed for their potential to translate these findings into site-specific management recommendations. Key research gaps include the scarcity of multi-legume, multi-location trials that test sowing time and geometry simultaneously, limited canopy-architecture models incorporating growth habit, and insufficient farm-level economic validation of precision-agriculture tools. Realizing the productivity potential of grain legumes will require multi-environment agronomic trials integrated with climate-smart and precision-agriculture frameworks, translated into practical, region-specific recommendations for growers and extension agencies.

KEYWORDS: Grain legumes; Crop geometry; Sowing time; Climate-smart agriculture; Resource use efficiency; Nitrogen fixation; Precision agriculture

1. INTRODUCTION

India is the largest producer and consumer of grain legumes (pulses) globally, and these crops occupy a central place in the country's food and nutritional security, supplying affordable dietary protein while contributing biologically fixed nitrogen to cropping systems and reducing dependence on synthetic fertilizers (Peoples *et al.*, 2021; (Singh and Kumar 2025; Mckechnie *et al.*, 2024; Parihar *et al.*, 2006). Despite this strategic importance, national productivity of most grain legumes remains substantially below their genetic yield potential, a gap widely attributed to sub-optimal agronomic management, increasing climate variability, and the persistence of crop-specific rather than broadly applicable management recommendations (Nair *et al.*, 2019)

Among agronomic interventions, time of planting and crop geometry are consistently identified as primary determinants of growth, physiological efficiency and yield formation across legume species. Time of planting governs the synchrony between phenologically sensitive growth stages germination, nodulation, flowering and pod filling and the prevailing thermal and moisture regime, while crop geometry regulates intra-specific competition for light, water, nutrients and space, thereby shaping canopy architecture and resource use efficiency (Kumar *et al.*, 2025; Kordrostami *et al.*, 2026). As shown in figure 1. Although these two levers have been investigated intensively within single-crop trials, the broader principles that transcend individual legume species remain only partially synthesized, limiting the transferability of findings and slowing the development of climate-resilient management guidelines suited to Indian growing conditions

Given the pace of recent agronomic research on grain legumes and the persistent yield gap in Indian production

systems, a consolidated, practice-oriented review is warranted (Kaur & Kaur (2025); Choudhary et al. (2025). This review synthesizes evidence across major grain legumes on crop establishment strategies, crop geometry, physiological responses, resource use efficiency, climate-smart management and emerging precision-agriculture tools, with the aim of identifying practical management recommendations and priority research needs Nair et al. (2019). Recent AI-enabled agricultural research also highlights data-driven decision-making, resource optimization, and technology-supported sustainable farm management (Singh and Kaur, 2025; Geetanjali and Singh, 2025).

2. BOTANICAL TAXONOMY AND AGRO-ECOLOGICAL DIVERSITY OF CULTIVATED GRAIN LEGUMES

Most cultivated grain legumes belong to the family Fabaceae, subfamily Papilionoideae, and share several agronomically important characteristics, including a well-developed taproot system with symbiotic root nodules, predominantly C₃ photosynthetic metabolism, and growth habits ranging from indeterminate to determinate (Makungu *et al.*, 2026). Crop duration varies considerably among species, ranging from short-duration crops such as green gram (*Vigna radiata*), black gram (*Vigna mungo*) and cowpea (*Vigna unguiculata*) (55–90 days), to medium-duration crops such as chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), field pea (*Pisum sativum*) and common bean (*Phaseolus vulgaris*) (90–120 days), and long-duration crops such as pigeonpea (*Cajanus cajan*) (150–270 days) and soybean (*Glycine max*) (90–140 days) (Richards *et al.*, 2022; Richards *et al.*, 2023; Pratap *et al.*, 2019). This wide developmental diversity indicates that agronomic recommendations developed for one legume species cannot be directly extrapolated to another because of differences in growth duration, phenology, canopy architecture and resource-use efficiency. Nevertheless, the fundamental physiological processes governing crop growth—including light interception, water and nutrient uptake, photosynthesis and biological nitrogen fixation through *Rhizobium/Bradyrhizobium* symbiosis—remain largely conserved across grain legumes (Peoples *et al.*, 2021; Kaur and Kaur, 2025). The major cultivated grain legumes, their botanical classification, growth duration and agro-ecological adaptation are presented in **Table 1**.

Table 1. Performance of Botanical and Agro-Ecological Attributes of Major Grain Legumes

Crop	Botanical name	Typical crop duration	Growth habit	Major adaptation zone
Green gram	<i>Vigna radiata</i>	55–90 days	Indeterminate, erect to semi-spreading	Tropical/subtropical, warm <i>kharif</i> season
Black gram	<i>Vigna mungo</i>	70–90 days	Indeterminate, semi-spreading	Tropical/subtropical
Chickpea	<i>Cicer arietinum</i>	90–120 days	Determinate to semi-determinate	Cool, semi-arid <i>rabi</i> /winter season
Lentil	<i>Lens culinaris</i>	100–120 days	Indeterminate, prostrate	Cool temperate to subtropical
Field pea	<i>Pisum sativum</i>	90–100 days	Indeterminate, climbing	Temperate, cool season
Cowpea	<i>Vigna unguiculata</i>	60–90 days	Indeterminate, erect to trailing	Warm semi-arid to arid
Pigeonpea	<i>Cajanus cajan</i>	150–270 days	Semi-woody shrub, perennial-like annual	Semi-arid tropics
Common bean	<i>Phaseolus vulgaris</i>	70–100 days	Determinate (bush) or indeterminate (climbing)	Temperate to subtropical highlands
Soybean	<i>Glycine max</i>	90–140 days	Determinate to indeterminate	Temperate to subtropical

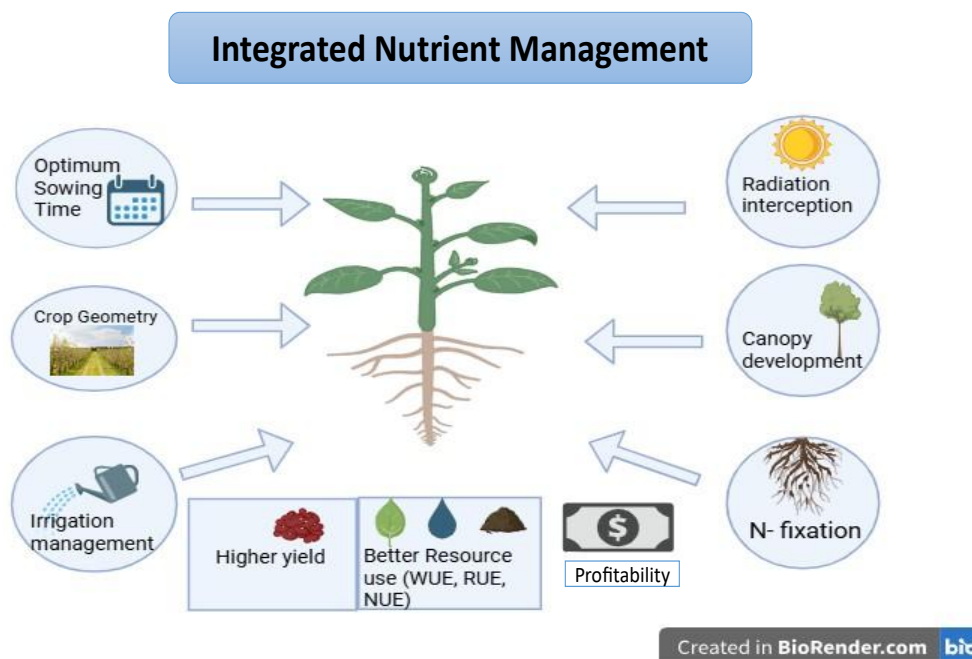


Fig 1: Performance of Integrated nutrient management in legume crops

3. AGRONOMIC DETERMINANTS OF CROP ESTABLISHMENT: PHENOLOGICAL SYNCHRONY AND SPATIAL ARCHITECTURE

Crop geometry, encompassing row spacing, intra-row spacing, plant population and spatial arrangement, is a fundamental agronomic factor governing crop establishment, canopy development and resource-use efficiency in grain legumes (Bedoussac *et al.*, 2015; Singh *et al.*, 2016). Appropriate crop geometry determines the timing of canopy closure and regulates inter-plant competition for solar radiation, soil moisture, nutrients and growing space, thereby influencing biomass accumulation and reproductive development (Ahmed *et al.*, 2024; Ali *et al.*, 2021; Ramesh *et al.*, 2024).

Closer row spacing generally accelerates canopy closure, increases leaf area index and enhances dry matter production per unit area; however, excessive plant density intensifies competition for available resources, often reducing branching, pods per plant, seeds per pod and individual seed weight (Dutta *et al.*, 2022; Ismail and hall., 2000; Goswami, V., 2023). Conversely, wider spacing promotes greater light penetration, root proliferation and branching, resulting in improved yield attributes per plant, although excessive spacing may reduce overall productivity because of suboptimal land utilization (Ahmed *et al.*, 2021; Patgiri *et al.*, 2023; Rank *et al.*, 2026; Muchira *et al.*, 2018).

The optimum crop geometry varies considerably among grain legume species because of differences in growth habit, canopy architecture and duration (Sandhu *et al.*, 2025; Sawarkar *et al.*, 2026). In mungbean and black gram, moderate spacing has consistently produced the highest seed yield by balancing plant population with reproductive efficiency (Basuchaudhuri *et al.* 2022; Patgiri *et al.*, 2023). In chickpea and cowpea, wider spacing enhances branching, pod formation and light interception in spreading and indeterminate genotypes (Kumar *et al.*, 2025; Karabidas *et al.*, 2022; Seraglio *et al.*, 2025) whereas pigeonpea requires substantially wider row spacing to accommodate its prolonged growth duration and extensive canopy development. Similarly, soybean and common bean exhibit improved radiation interception and canopy photosynthesis under narrower row spacing until an optimum population threshold is reached, beyond which lodging, mutual shading and disease incidence may reduce productivity (Nleya *et al.*, 2020; Bakure, B., 2025; Kouam and Tsague 2020).

In cereal–legume intercropping systems, crop spatial arrangement further determines the degree of complementarity and competition between component crops (Seraglio *et al.*, 2026; Ullah *et al.*, 2021). Interaction indices such as the Land Equivalent Ratio (LER) and Competitive Ratio (CR) provide useful measures for evaluating the efficiency of different spatial arrangements and resource partitioning (Kammoun *et al.*, 2021; Silwal *et al.*, 2026). Despite substantial progress, comparative studies integrating canopy architecture, growth habit and genotype-specific responses across multiple grain legume species remain limited (Lisciani *et al.*, 2024). Consequently, species-specific recommendations based on canopy ideotype and phenological synchrony are essential for maximizing productivity and resource-use efficiency under diverse agro-ecological conditions (Singh *et al.*, 2025; Sinky *et al.*, 2024).

4. PHYSIOLOGICAL AND BIOCHEMICAL RESPONSES TO AGRONOMIC MANIPULATION

4.1 Photosynthetic Efficiency, Chlorophyll Stability and Source-Sink Assimilate Partitioning

Timely crop establishment and optimum crop geometry exert a profound influence on photosynthetic efficiency, chlorophyll stability and assimilate partitioning in grain legumes (Jeuffroy *et al.*, 2015; Sheershika *et al.*, 2026). Sowing within the optimum planting window ensures synchronization of vegetative and reproductive

development with favourable environmental conditions, thereby maintaining higher chlorophyll content, photosynthetic rate and leaf area duration during flowering and pod filling (Diatta *et al.*, 2024; Jha *et al.*, 2023). Conversely, delayed sowing exposes plants to terminal heat and moisture stress, which accelerates chlorophyll degradation, leaf senescence and oxidative damage, ultimately reducing the duration of active photosynthesis and limiting assimilate availability for reproductive growth (Farooq *et al.*, 2017; Ahmed *et al.*, 2021; Somta *et al.*, 2022)

Crop geometry also regulates canopy architecture and light interception (Stoddard *et al.*, 2017; Udawat *et al.*, 2023). Moderate plant density improves radiation-use efficiency and canopy photosynthesis by minimizing mutual shading and optimizing light penetration, whereas excessively close spacing increases intra-specific competition, reducing photosynthetic efficiency on a per-plant basis despite a higher leaf area index (Sprent *et al.*, 1984; Rank *et al.*, 2026). Consequently, efficient source–sink translocation during pod development enhances pod filling, seed weight and harvest index, ultimately improving grain yield. The physiological responses of grain legumes to agronomic management (Kaur *et al.*, 2026; Stagnari *et al.*, 2017; Kumar *et al.*, 2026) are summarized in Table 2.

4.2 Crop Growth Rate, Relative Growth Rate and Dry-Matter Accumulation Dynamics

As shown in figure 2. Crop growth rate (CGR) and relative growth rate (RGR) integrate the combined influence of planting time and crop geometry on dry-matter accumulation over the growing season (Upadhyay *et al.*, 2023). Timely-sown crops under optimum geometry consistently record higher CGR during the vegetative-to-reproductive transition, translating into greater total biomass and, ultimately, higher harvest index and seed yield (Layek *et al.*, 2018; Pathak *et al.*, 2025). Delayed sowing or sub-optimal spacing truncates the period of maximal CGR, most consequentially when this coincides with the pod-filling stage, when assimilate demand from developing seeds is highest (Vaishna *et al.*, 2026; Ahmed *et al.*, 2023).

Table 2. Efficacy of Sowing Time on Growth and Physiological Parameters of Grain Legumes

Parameter	Effect	Major Findings	References
Germination and crop establishment	Delayed sowing reduces germination percentage and seedling vigour due to moisture and temperature stress	Timely sowing ensures optimum soil moisture and temperature for uniform emergence	Sandeep <i>et al.</i> , 2023
Plant height and vegetative growth	Delayed sowing restricts vegetative growth and stem elongation	Timely sowing enhances canopy development	Sharma <i>et al.</i> (2025)
Leaf area index and canopy development	Delayed sowing reduces LAI under environmental stress	Timely sowing increases leaf expansion and light interception	Laekemariam and worku (2013)
Dry matter accumulation and crop growth rate	Delayed sowing lowers biomass accumulation and CGR	Timely sowing under optimum geometry sustains higher CGR through pod filling	(Layek <i>et al.</i> , 2018).
Nodulation and nitrogen fixation	Delayed sowing reduces nodule number and biological nitrogen fixation efficiency	Favourable rhizobial activity under timely sowing increases nodulation	Singh <i>et al.</i> , 2013
Photosynthesis and chlorophyll dynamics	Late sowing accelerates senescence and shortens the photosynthetic period	Favourable sowing sustains higher chlorophyll content through flowering–pod filling	Ahmed <i>et al.</i> , 2021 Laekemariam and Worku (2013)
Stomatal conductance and water relations	Drought stress under delayed sowing reduces stomatal activity	Timely sowing maintains efficient gas exchange	Ali <i>et al.</i> (2021)
Seed filling duration and grain quality	Terminal stress shortens seed-filling duration	Favourable reproductive conditions under timely sowing improve seed yield and grain quality	Ali <i>et al.</i> (2021)

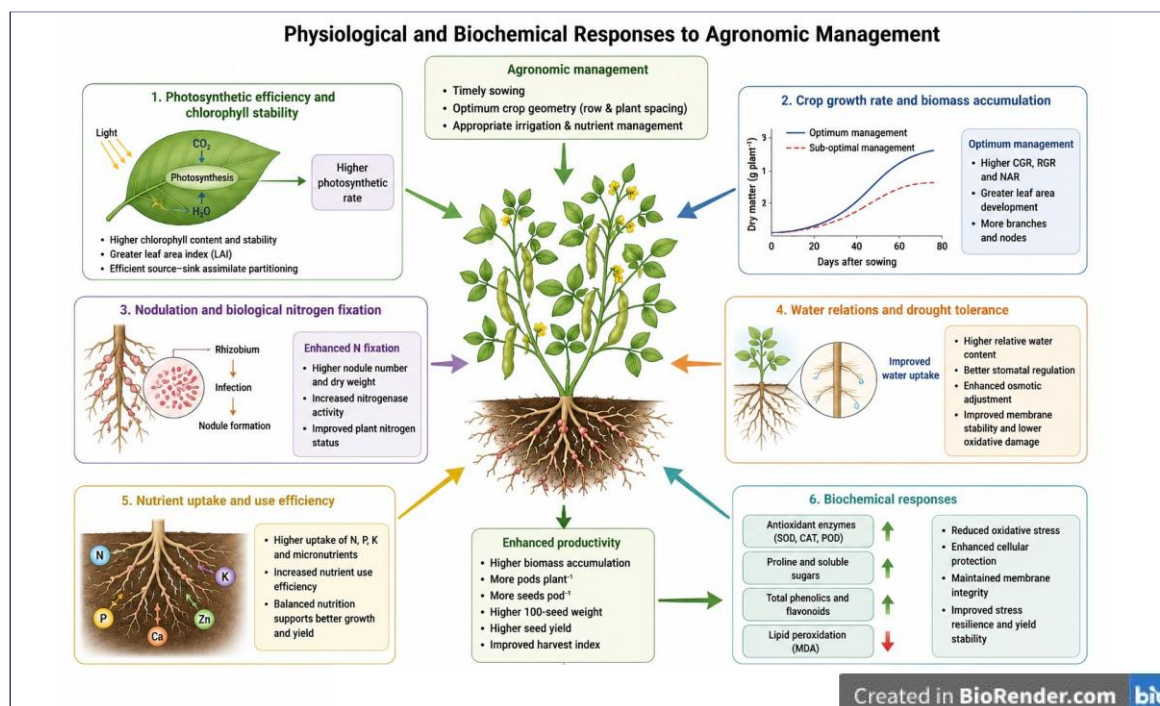


Fig 2. Performance of Physiological and Biochemical responses to Agronomical Management

5. RESOURCE USE EFFICIENCY: RADIATIVE, HYDRIC AND NUTRITIONAL DIMENSIONS

5.1 Radiation Interception and Radiation Use Efficiency across Canopy Architectures

Radiation use efficiency (RUE) in grain legumes is generally lower than in C_4 or non-leguminous C_3 cereals owing to the additional carbon cost of symbiotic nitrogen fixation, and is further constrained under water-deficit conditions that reduce both radiation interception and the efficiency of radiation conversion to biomass (Tesfaye *et al.*, 2006) (Choudhary *et al.*, 2025). Crop geometry and sowing time jointly determine the trajectory of leaf area development and hence the fraction of incident radiation intercepted during the critical reproductive period; sowing-date-driven differences in light interception and RUE have been documented for mungbean cultivars, with earlier, well-timed sowing sustaining higher RUE through to maturity (Feng Q *et al.*, 2024; Zustovi *et al.*, 2024).

5.2 Water Use Efficiency, Stomatal Regulation and Drought-Adaptation Mechanisms

Grain legumes face increasing exposure to intermittent and terminal drought as sowing windows narrow under climate variability (Gierlich *et al.*, 2026; Sadeque *et al.*, 2026). Improving water use efficiency (WUE) in this group requires an integrated view of agronomic practice planting time, geometry and supplemental irrigation scheduling alongside breeding for root architecture and stomatal regulation traits, since agronomic and genetic levers act on different components of the water-productivity equation (Kumar *et al.*, 2026; Parihar *et al.*, 2022). Supplemental irrigation timed to coincide with flowering and pod-development stages, rather than applied uniformly across the season, has consistently produced the largest marginal gain in seed yield per unit of water applied (Ghosh *et al.*, 2026). This indicates that WUE in grain legumes is more sensitive to the timing than to the total quantity of water received during the growing season.

5.3 Nutrient Use Efficiency, Symbiotic Nodulation and Rhizosphere Microbial Interactions

Biological nitrogen fixation (BNF) through the legume-rhizobium symbiosis is the defining nutrient-acquisition trait of grain legumes, reducing dependence on synthetic nitrogen while improving soil fertility for succeeding cereals (Dudeja *et al.*, 2012; Gohil *et al.*, 2017). Nodule initiation, development and nitrogenase activity are highly sensitive to soil moisture, temperature and rhizosphere microbial interactions; multipartite interactions among legumes, rhizobia and other rhizosphere microorganisms can alter rhizobial fitness during nodulation and influence the efficiency of fixation under field conditions (Sinharoy *et al.*, 2024) (Choudhary *et al.*, 2025). Because crop geometry and planting time influence root-zone microclimate and moisture availability, they indirectly modulate nodulation intensity and, consequently, nitrogen and other nutrient use efficiencies a linkage that remains under-quantified relative to the extensive literature on nodulation genetics (Karaman *et al.*, 2026; Asiamah *et al.*, 2025). As depicts in table 3.

Table 3. Effect of Crop Geometry on Growth, Physiological and Yield Attributes of Grain Legumes

Parameter	Effect	Major Findings	References
Plant population and canopy development	Closer spacing raises biomass per unit area but intensifies competition; wider spacing favours per-	Optimum spacing balances plant population with efficient resource use	Basuchaudhuri <i>et al.</i> , 2022

Parameter	Effect	Major Findings	References
	plant yield but under-utilizes resources		
Leaf area index and light interception	Dense canopies reduce light penetration; very wide spacing lowers total radiation interception	Moderate spacing maximizes interception of photosynthetically active radiation and RUE	Tobiasz-Salach <i>et al.</i> , 2023
Root growth and nutrient uptake	Close spacing restricts root expansion; wider spacing promotes extensive root growth	Optimum spacing improves nutrient and water uptake	Tobiasz-Salach <i>et al.</i> , 2023
Nodulation	Crowding stress under dense spacing reduces nodulation	Optimum spacing enhances nodulation and nitrogen fixation	Peoples <i>et al.</i> , 2026
Aeration and disease incidence	Dense spacing increases humidity and disease risk	Adequate spacing maintains aeration and reduces disease incidence	Patgiri <i>et al.</i> , 2023
Yield attributes (pods per plant, seeds per pod, 1000-seed weight)	Interplant competition under close spacing reduces pods per plant and seed weight	Optimum spacing maximizes yield attributes	Da Silva <i>et al.</i> , 2025
Seed yield	Yield declines under both very close spacing (competition) and very wide spacing (under-utilization)	Maximum yield is recorded under moderate, optimum spacing	Da Silva <i>et al.</i> , 2025 Banotra <i>et al.</i> (2023);

6. YIELD FORMATION, HARVEST INDEX DYNAMICS AND ECONOMIC PERFORMANCE METRICS

Seed yield in grain legumes is the outcome of biomass accumulation and its partitioning to reproductive sinks, summarized by harvest index (Jha *et al.*, 2024; Rao *et al.*, 2023). Timely planting combined with optimum crop geometry consistently improves biological yield, harvest index and seed yield by sustaining photosynthesis and assimilate translocation through the reproductive phase; the same combination has also been linked to higher net returns and benefit-cost ratios, since yield gains generally outweigh the marginal cost of optimizing sowing time or seed rate (Yali *et al.*, 2026; Marthe *et al.*, 2024). Conversely, delayed sowing and sub-optimal geometry depress profitability through moisture stress, poorer canopy development and lower seed yield, even where cultivation costs remain similar across treatments (Banotra *et al.* (2023)). Adjustment of planting time and crop geometry therefore remains one of the most cost-effective levers for improving both productivity and profitability across grain legumes (Kumar *et al.*, 2023; Gogoi *et al.*, 2024).

7. CLIMATE-SMART AGRONOMY AND CONSERVATION AGRICULTURE INTERVENTIONS

Rising temperatures, erratic rainfall and increasing moisture stress are altering the reliability of traditional planting windows for grain legumes, with cascading effects on crop establishment, physiological processes and yield stability (Das *et al.*, 2025). Climate-smart management responses include shifting sowing windows in line with seasonal forecasts, adopting stress-tolerant cultivars, and integrating supplemental irrigation with in-season decision support (Mukherjee *et al.*, 2025; De Ron *et al.*, 2015). Conservation agriculture comprising reduced tillage, residue retention and diversified rotations that include a grain legume has been shown to enhance soil organic carbon fractions and crop productivity in intensively cultivated systems such as the Indo-Gangetic Plains, indicating that legume inclusion under conservation agriculture delivers co-benefits for both productivity and soil carbon sequestration (Mishra *et al.*, 2024; Lawn, 2008). These findings position grain legumes as a dual-purpose lever for climate adaptation, through flexible and resilient agronomic management, and climate mitigation, through reduced-tillage carbon storage and lower reliance on synthetic nitrogen (Dave *et al.*, 2024; Lee *et al.*, 2024). Agricultural systems in Northeast India also provide recent evidence of the vulnerability of crop production to climate change and the importance of adaptive management strategies (Bhattacharjee *et al.*, 2024). Shown in figure 3.

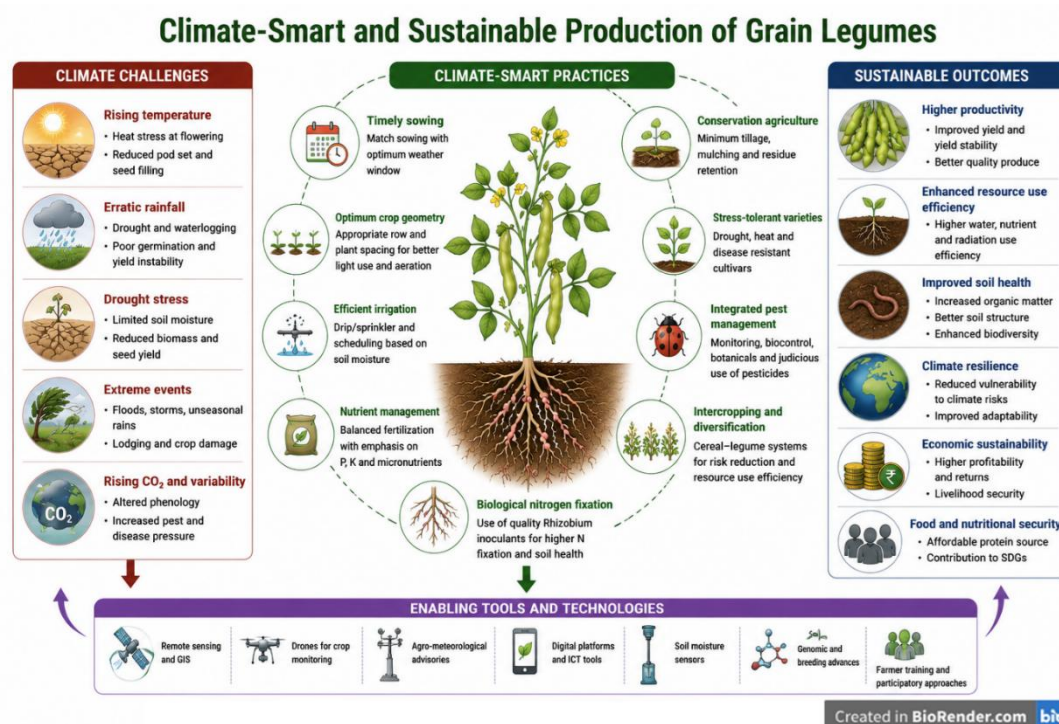


Fig 3: Performance of Climate-smart and sustainable production of grain legumes

8. EMERGING DIGITAL AND PRECISION-AGRICULTURE TECHNOLOGIES IN LEGUME PRODUCTION

Crop simulation models such as DSSAT and APSIM are increasingly used to translate the understanding of sowing time and crop geometry into site-specific management recommendations under future climate scenarios, including the identification of heat-tolerant genotype-management combinations for chickpea, pigeonpea, lentil and black gram under simulated warming (Jayadharshan *et al.*, 2025; Munier-jolain *et al.*, 1998). Complementing these process-based models, high-throughput and precision phenotyping platforms combining proximal and remote sensors with machine-learning analytics now allow non-destructive, field-scale estimation of plant height, canopy cover, leaf area index and stress indices, supporting both breeding and in season crop management decisions (Visakh *et al.*, 2024; Ntshalintshali *et al.*, 2025). These methods align with recent studies that highlight the importance of precision and smart farming in enhancing the monitoring, planning, and efficient use of agricultural resources (Geetanjali and Singh, 2025).

Wider adoption of these tools in Indian grain legume systems will depend on the availability of location-specific calibration data and on simplifying decision-support outputs into forms accessible to extension personnel and farmers, since most current applications remain confined to research settings rather than routine field advisory use (Adusei *et al.*, 2023; Neha *et al.*, 2024). AI-driven agricultural systems also enable data-driven forecasting and decision-support tools to enhance farm management and resource-use efficiency (Singh and Kaur, 2025; Taqvi, 2025).

9. AGRONOMIC IMPLICATIONS AND EXTENSION-ORIENTED RECOMMENDATIONS

Translating the evidence reviewed above into field practice, the following implications are relevant for grain legume growers, extension agencies and policymakers:

- 1) **Sowing windows:** Align sowing with region- and species-specific optimum dates identified through local trials, rather than relying on uniform calendar-based practice. (Ali *et al.*, 2021; Silwal *et al.*, 2026)
- 2) **Crop geometry:** Adopt species- and cultivar-specific optimum plant population moderate spacing for mungbean and black gram, wider spacing for chickpea, cowpea and pigeonpea rather than a single uniform recommendation. (Basuchaudhuri *et al.*, 2022; Patgiri *et al.*, 2023; Kordrostami *et al.*, 2026).
- 3) **Water management:** Prioritize protective and supplemental irrigation at flowering and pod-development stages under erratic rainfall, since WUE responds more to irrigation timing than to total water applied.
- 4) **Climate adaptation:** Encourage conservation agriculture, residue retention and legume-inclusive rotations in rainfed tracts to buffer moisture stress and build soil carbon. (Mishra *et al.*, 2024; Mukherjee *et al.*, 2025)
- 5) **Extension delivery:** Simplify crop-simulation and phenotyping outputs into decision aids usable by extension workers and farmers with limited technical infrastructure. (Marteau-Bazouni *et al.*, 2024)

10. CONCLUSION

Across grain legumes, time of planting and crop geometry emerge as high-leverage agronomic interventions that jointly regulate crop establishment, canopy architecture, resource use efficiency and, ultimately, productivity and profitability. While the direction of these effects is broadly conserved delayed establishment is almost universally

penalized, and a density competition trade-off governs the crop-geometry response the precise optimum for each species is modulated by growth habit, photoperiod sensitivity and regional climate, so recommendations cannot simply be transferred from one legume to another without local validation. Realizing the productivity potential of grain legumes under an increasingly variable climate will depend on embedding these agronomic principles within climate-smart and conservation agriculture frameworks, and on translating crop simulation modelling, phenotyping and remote sensing into practical, farmer-accessible tools. Future work combining multi-legume, multi-environment field trials with these digital tools, alongside farm-level economic validation, offers the clearest path toward closing the yield gap and strengthening the contribution of grain legumes to India's food and nutritional security.

AUTHOR CONTRIBUTIONS

Sharmila: Conceptualization, literature collection, review of relevant scientific literature, and drafting of the manuscript.

Baljinder Singh: Supervision, critical evaluation of the manuscript, and scientific guidance throughout the review process.

Kanik Kumar Bansal: Conceptualization, organization of the review, critical revision, and overall coordination of the manuscript.

Sagar: Literature search, compilation of relevant information, and contribution to manuscript preparation.

Sahil: Literature review, data and information compilation, and critical reading of the manuscript.

Mohit Kumar: Literature collection, interpretation of relevant findings, and assistance in manuscript preparation. All authors contributed to the development and preparation of the manuscript, critically reviewed the content, and approved the final version for submission.

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