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Effect of Sowing Time and Plant Density on Growth and Yield of Crops: A Review

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ABSTRACT

Sowing time and plant density are two of the most fundamental, low-cost agronomic decisions a farmer makes, yet their combined influence on crop growth and final yield is frequently underestimated relative to inputs such as fertilizer or irrigation. This review synthesizes recent experimental evidence on the effects of sowing time and plant density, individually and in interaction, on the growth and yield of a diverse range of field, fibre, pulse and specialty crops, including wheat, rice, maize, cotton, soybean, lentil, guar and roselle. Across crops, delayed sowing consistently shortened the vegetative growth period, reduced light and thermal resource capture, and lowered yield-forming components: cotton lint yield fell by roughly 21% and soybean seed yield by 29.1% when sowing was delayed beyond the optimal window, while wheat, rice, lentil and roselle each showed a similar pattern of yield decline with sowing delay, mediated through reduced tillering, panicle number, pod number or flowering duration. Plant density effects followed a more universal inverted-U response: yield per unit area typically peaked at an intermediate, crop- and environment-specific optimum density, with cotton lint yield 13% higher at moderate density than at high density, while maize yield gains from increased density depended on simultaneous optimization of row spacing and nutrient supply. Importantly, sowing time and plant density did not act independently: in wheat, sowing date consistently overrode the effect of density, and yield losses from late sowing could not be fully compensated by adjusting seeding rate; in cotton and soybean, the optimal density shifted depending on sowing date, with moderate-to-high density favoured under late sowing and lower density favoured under early sowing. These findings indicate that sowing time and plant density recommendations cannot be developed in isolation, and that agronomic guidance must specify density targets conditional on realistic sowing windows, and vice versa, to achieve consistent yield gains across seasons and environments.

INTRODUCTION

Among the many decisions a farmer makes across a cropping season, few are as consequential, and as inexpensive to optimize, as the choice of sowing date and plant population density. Unlike fertilizer, irrigation or crop protection inputs, sowing time and seeding rate require no additional purchased inputs, yet field experiments across a wide range of crops consistently show that suboptimal timing or density can reduce yield by 20% or more relative to well-managed treatments (Khan et al., 2017; Seo et al., 2024). Sowing time determines the environmental window — temperature, day length, radiation and moisture — within which a crop completes its developmental phases, while plant density determines the intensity of intra-specific competition for light, water and nutrients within the crop canopy. Both factors are, in principle, freely adjustable by the farmer at planting, making them a uniquely accessible lever for yield improvement relative to genetic or input-based interventions.

Despite their practical accessibility, sowing time and plant density are frequently treated as secondary considerations relative to variety choice or fertilizer programme, and are often set according to convention or convenience rather than evidence-based optimization for local conditions. This is a significant gap, because the evidence reviewed here shows that the interaction between sowing time and plant density is often as important as either factor alone: the optimal density for a given crop is frequently conditional on the sowing date actually achieved, and vice versa, meaning that generic, single-factor recommendations can under-perform relative to date-density combinations tailored to realistic on-farm conditions.

This review synthesizes recent field-based evidence on the effects of sowing time and plant density on crop growth and yield, drawing on studies spanning cereals (wheat, rice, maize), a fibre crop (cotton), legumes and pulses (soybean, lentil, guar), and a specialty crop (roselle). The review addresses four questions: (i) what physiological mechanisms link sowing time and plant density to yield formation; (ii) how does delayed or off-optimal sowing affect growth and yield across crop types; (iii) how does plant density affect growth and yield, and why does an optimum density typically exist; and (iv) how do sowing time and plant density interact, and what does this imply for agronomic recommendations. The review closes with practical implications for crop management and directions for future research.

PHYSIOLOGICAL BASIS OF SOWING TIME AND PLANT DENSITY EFFECTS

Sowing Time: Resource Capture and Developmental Timing

Sowing time influences yield primarily by determining the environmental conditions — temperature, photoperiod and solar radiation — that a crop experiences during each developmental phase, from germination through vegetative growth, flowering and grain or fruit filling. Delayed sowing generally compresses the length of the vegetative growth period available before the onset of reproductive development, particularly in photoperiod- or temperature-sensitive species, reducing the time available for leaf area development, canopy closure and radiation interception. In wheat, radiation use efficiency and the total amount of intercepted photosynthetically active radiation are both sensitive to sowing date, since earlier sowing allows the crop to establish a larger canopy before the period of peak seasonal radiation. In cotton, early-sown plants produced taller stems, more nodes, more leaves and more fruiting sites than late-sown plants, translating directly into a 26% lint yield advantage, an effect attributed to the longer cropping season available for resource capture and utilization under early sowing (Khan et al., 2017).

Delayed sowing can also expose the crop to unfavourable conditions during critical, yield-determining growth stages. In soybean, delaying sowing from 25 June to 25 July in southern South Korea reduced yield by 29.1%, an effect linked to a shortened vegetative period and earlier, more constrained flowering under the compressed remaining growing season, alongside a 19.9% reduction in 100-seed weight as the crop was forced to complete seed filling under increasingly unfavourable late-season conditions (Seo et al., 2024). In lentil, delaying sowing beyond the optimal end-of-April to mid-May window reduced the time to flowering and podding, biomass accumulation and plant height, and lowered grain yield primarily through reductions in the number of pods and seeds per plant rather than through seed weight (Maphosa et al., 2023) — illustrating that the specific yield component affected by sowing delay is crop-dependent, even though the general direction of the effect (yield decline with delay) is broadly consistent.

Plant Density: Intra-Specific Competition and the Optimum-Density Principle

Plant density affects yield through a fundamentally different mechanism: rather than altering the external environment, density alters the internal competitive environment among neighbouring plants within the crop canopy. As density increases, individual plants compete more intensely for light, water and nutrients, typically reducing the yield-forming capacity of each individual plant — fewer branches, smaller reproductive structures, lower biomass per plant — even as the number of plants per unit area rises. Total yield per unit area is the net outcome of these two opposing trends, which is why yield-density relationships across crops typically follow an inverted-U or asymptotic curve: yield rises with increasing density up to an optimum, beyond which further increases in density cause per-plant yield losses to outweigh the gain from additional plant numbers, and total yield plateaus or declines.

This pattern was directly demonstrated in cotton, where moderate plant population density produced 13% higher lint yield than high density and 6% higher yield than low density, with the yield advantage at moderate density attributed to higher reproductive-organ nitrogen concentration and enhanced leaf net photosynthetic capacity relative to the high-density treatment, where mutual shading reduced photosynthetic efficiency in the lower canopy (Khan et al., 2017). In maize, increasing planting density raises leaf area index and the interception of photosynthetically active radiation, promoting plant growth and biomass accumulation, but this benefit is realized fully only when density is co-optimized with row spacing and nutrient supply: in an integrated cultivation trial in Northeast China, planting density contributed 16.05% to overall yield gain, second only to fertilizer management at 23.85%, with the combination of factors substantially outperforming any single adjustment (Piao et al., 2022).

Crop Growth Habit as a Modifier of Timing and Density Sensitivity

The magnitude of a crop's response to sowing time and density is not uniform across species, and much of this variation traces back to differences in growth habit, particularly tillering or branching capacity and the determinacy of flowering. Cereals capable of substantial tillering, such as wheat, have some inherent ability to compensate for low plant density by producing additional tillers per plant, partially buffering yield against sub-optimal establishment; this compensatory capacity helps explain why wheat trials found a genuine density optimum (400–500 seeds m^{-2}) that tolerated some deviation without catastrophic yield loss, provided sowing date was on target (Chen et al., 2025). Maize, by contrast, has markedly limited tillering ability, a short flowering window and a monoecious flower structure separating male and female reproductive organs, which together sharply constrain its capacity to compensate for poor stand establishment; this is precisely why maize yield is described as unusually sensitive to changes in plant population relative to other cereals, and why intra-row spacing must be more precisely managed for this crop than for tillering cereals (Hamoda & Dabbour, 2025).

Indeterminate crops with extended flowering periods, such as cotton, present a different pattern again: because reproductive structures continue to be initiated over an extended period, both sowing time and density influence not just the total number of fruiting sites but also their timing and distribution across the canopy, which is why cotton's optimal density was found to shift depending on sowing date — a moderate density suited early sowing, while a higher density became advantageous specifically when late sowing shortened the effective fruiting period and required more simultaneous fruiting sites per unit area to compensate (Khan et al., 2017). These growth-habit differences imply that sowing-time and density sensitivity cannot be extrapolated directly from one crop to another, even within the same broad category (e.g., cereals), and that agronomic recommendations must be grounded in the specific developmental biology of the target crop rather than generic cropping principles.

EFFECT OF SOWING TIME ON GROWTH AND YIELD OF CROPS

Cereal Crops: Wheat and Rice

In wheat, a multi-site, multi-year field trial across three ecological zones of Shandong Province, China, testing four sowing dates from early October to early November, found that yield in each zone initially increased and then decreased as sowing was progressively delayed, with the specific optimal date differing by ecological zone; sowing date also shifted grain quality traits, including protein content and gluten strength, indicating that sowing time recommendations for wheat must be both environment-specific and jointly optimized for yield and quality rather than yield alone (Chen et al., 2025). This finding illustrates an important nuance: the sowing-time response is not always a simple monotonic decline with delay, but can be a genuine optimum curve in which both excessively early and excessively late sowing reduce performance.

In rice, transplanting age — a direct analogue of sowing/establishment timing under transplanted systems — strongly influenced growth and yield. Under rainfed conditions in the Guinea Savannah zone of Ghana, testing five transplanting ages from 14 to 42 days after sowing, the maximum grain yield of 7,810 kg ha^{-1} was achieved specifically at 21 days after planting, with both earlier and later transplanting ages producing lower yields (Yussif et al., 2026). Complementary evidence from mechanically transplanted rice in China found that delaying transplantation reduced tiller occurrence, dry matter weight per tiller, leaf area index, crop growth rate and photosynthetic potential, ultimately decreasing the number of effective panicles, filled grains per panicle and grain yield relative to timely, artificially transplanted controls (Liu et al., 2015). Together, these studies confirm that both direct-sown/transplanted timing and seedling age at transplanting are critical, tightly-bounded determinants of rice yield potential.

Fibre and Oilseed Crops: Cotton and Soybean

Cotton lint yield showed a pronounced sensitivity to sowing date, with early-sown plants producing 23%, 32%, 55% and 77% greater stem height, node number, leaf number and fruit number, respectively, than late-sown plants, and a corresponding 26% higher lint yield under early sowing, an advantage attributed primarily to the longer cropping season available for resource capture (Khan et al., 2017). In soybean, two independent studies in different environments confirmed the general pattern of yield decline with sowing delay: in southern South Korea, delaying sowing by one month (25 June to 25 July) reduced yield by 29.1% (Seo et al., 2024), while in North-Eastern Poland, sowing date was found to significantly affect the time from sowing to seedling emergence, growing season length, morphological development and final seed yield of soybean under regional climatic conditions (Fordoński et al., 2023). The consistency of this pattern across contrasting geographies — East Asia and Northern Europe — underscores that the sowing-date sensitivity of soybean yield is a robust, widely generalizable agronomic finding rather than a site-specific artifact.

Pulse and Specialty Crops: Lentil, Guar and Roselle

In lentil, phenotyping of eight varieties across four sowing times and multiple site-years in New South Wales, Australia, established that both earlier and later sowing than the optimal end-of-April to mid-May window reduced grain yield, primarily via reductions in pod number and seed number per plant, with seed weight comparatively unaffected (Maphosa et al., 2023). In guar, a two-year field trial testing four sowing dates found that seed sowings at the earliest tested dates (21 or 26 May, depending on year) produced the highest grain yield of the two ecotypes examined, with yield declining as sowing was progressively delayed toward late June and early July (Mahdipour-Afra et al., 2021). In roselle, sowing at six 10-day intervals from early May to late June showed that the earliest sowing date (6 May) produced the tallest plants, thickest stems, most leaves, most calyces per plant and highest calyx yield per hectare, with each of these traits declining progressively as sowing was delayed (Khattak et al., 2016).

Table 1. Effect of sowing time on the growth and yield of selected crops, based on field experiments reviewed.

EFFECT OF PLANT DENSITY ON GROWTH AND YIELD OF CROPS

Cereal Crops: Maize

Maize yield responds strongly to plant density, but the magnitude and even direction of the response depend on co-management of row spacing and nutrient supply. In an integrated field trial in Northeast China comparing an optimum cultivation mode against treatments omitting fertilization, density or wide-narrow row spacing individually, planting density contributed 16.05% to total yield gain — the second-largest single contribution after fertilizer management (23.85%) — by increasing nitrogen accumulation and transport in leaves and stems via a higher leaf area index and greater dry matter accumulation around anthesis (Piao et al., 2022). A separate study on hybrid and intra-row spacing effects emphasized that because maize has limited tillering ability, a short flowering period and a monoecious flower structure, its yield is unusually sensitive to changes in plant population compared with other cereal crops, meaning that intra-row spacing recommendations must be periodically reassessed as breeding continues to produce increasingly density-tolerant hybrids (Hamoda & Dabbour, 2025). Overly narrow spacing was found to deplete soil nutrients and moisture before maturity and intensify competition for light, while excessively wide spacing wasted available resources and promoted weed growth, reinforcing the existence of a genuine density optimum rather than a simple more-is-better relationship

Fibre and Legume Crops: Cotton and Soybean

Cotton lint yield followed a clear inverted-U relationship with plant population density: moderate density (D2) produced 13% higher lint yield than high density (D3) and 6% higher yield than low density (D1), with the moderate-density advantage explained by improved nitrogen status in reproductive organs and higher leaf net photosynthetic capacity relative to the high-density treatment, where increased mutual shading reduced photosynthetic efficiency, particularly in the lower canopy (Khan et al., 2017). Figure 2 illustrates this relationship using the reported relative lint yield values across the three density treatments In soybean, the density response was more strongly conditioned by sowing date than in cotton. In a two-year trial in Southern Xinjiang, China, testing two sowing dates and three planting densities, the highest seed yield was achieved specifically at the combination of early sowing (S1) with the lowest tested density (D1), while high density did not improve yield under early sowing and instead increased plant height, main-stem internode length and petiole length — morphological changes associated with shade-avoidance responses rather than

Table 1: summarizes the optimal sowing windows identified and the reported consequences of sowing delay across the crops reviewed *Table 2. Effect of plant population density on the growth and yield of selected crops, based on field experiments reviewed.*

Crop	Optimal sowing window	Effect of delayed / off-optimal sowing	Source
Wheat	Region-specific; e.g., early-to-mid October in Shandong ecological zones	Yield first increased then decreased as sowing was progressively delayed; quality (protein, gluten) also shifted with sowing date	Chen et al. (2025)
Rice (transplanted)	21 days after sowing (seedling age) under rainfed Guinea Savannah conditions	Delaying transplantation reduced tiller occurrence, dry matter accumulation, effective panicles, filled grains per panicle and grain yield	Yussif et al. (2026); Liu et al. (2015)
Cotton	Early sowing (S1) preferred over late sowing (S2)	Late-sown plants were 23–77% smaller in stem height, node, leaf and fruit number; lint yield 26% lower than early sowing	Khan et al. (2017)
Soybean (South Korea)	25 June (avoid sowing after mid-July for early-maturing types)	Yield fell by 29.1% and 100-seed weight by 19.9% when sowing was delayed from 25 June to 25 July	Seo et al. (2024)
Soybean (Poland)	Region-specific optimal window under North-Eastern European conditions	Sowing date significantly affected growth, development and final seed yield	Fordoński et al. (2023)
Lentil	End of April to mid-May in southern/central-western New South Wales	Sowing earlier or later than optimum decreased grain yield, mainly via reduced pods and seeds per plant	Maphosa et al. (2023)
Guar	Late May (21–26 May) in semi-arid conditions	Highest grain yield recorded at earliest sowing dates; yield declined with progressively later sowing	Mahdipour-Afra et al. (2021)
Roselle	Early sowing (6 May) in sub-tropical semi-arid conditions	Plant height, stem diameter, leaf number, calyx number and calyx yield all declined progressively as sowing was delayed at 10-day intervals	Khattak et al. (2016)

yield gain (Xu et al., 2024). This finding is a useful counter-example to the assumption that higher density is always compensatory: for soybean under favourable, early-sown conditions, lower density combined with good canopy architecture outperformed higher density.

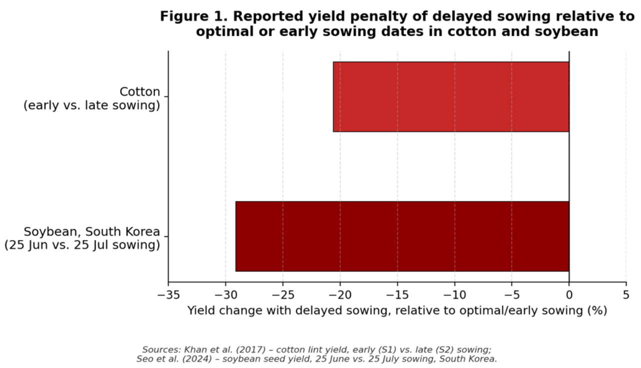

Figure 2: Reported yield penalty of delayed sowing relative to optimal or early sowing dates in cotton and soybean, based on data reported by Khan et al. (2017) and Seo et al. (2024).

Pulse and Specialty Crops: Guar and Roselle

In guar, grain yield was significantly affected by plant density across both years of a field trial testing three densities (13, 20 and 40 plants m^{-2}), with the lowest tested density of 13 plants m^{-2} combined with the earliest sowing dates producing the highest grain yield of 3,004.8 and 2,826.1 kg ha^{-1} in the two respective years, indicating that for this crop under the semi-arid conditions tested, wider spacing outperformed denser planting (Mahdipour-Afra et al., 2021). In roselle, the density response diverged depending on whether yield was measured on a per-plant or per-hectare basis: individual-plant traits including calyx number and calyx fresh and dry weight were all higher at the lowest tested density of 2 plants m^{-2}, reflecting reduced competition for each plant, yet total calyx yield per hectare was maximized at the highest tested density of 18 plants m^{-2}, because the much larger number of plants per unit area more than compensated for the lower yield contributed by each individual plant (Khattak et al., 2016). This roselle example is a particularly clear illustration of why yield-density relationships must always be interpreted at the appropriate spatial scale: per-plant and per-hectare yield responses to density can point in opposite directions.

Table 2. Effect of plant population density on the growth and yield of selected crops, based on field experiments reviewed.

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Table 2: summarizes the plant density response patterns reported across the crops reviewed

Crop	Density response pattern	Key findings	Source
Maize (Northeast China)	Optimum density combined with wide-narrow row spacing	Planting density contributed 16.05% to yield gain in an integrated cultivation package; increased density raised leaf area index and canopy nitrogen accumulation	Piao et al. (2022)
Corn / sweet corn (intra-row spacing)	Density-tolerant hybrids respond differently to narrow spacing	Optimal intra-row spacing maximizes light, water and nutrient capture; overly narrow spacing depletes resources and intensifies competition before maturity	Hamoda & Dabbour (2025)
Cotton	Inverted-U; moderate density (D2) optimal	Moderate density gave 13% higher lint yield than high density and 6% higher than low density, via improved reproductive-organ nitrogen status and photosynthetic capacity	Khan et al. (2017)
Soybean (Southern Xinjiang)	Lower density combined with earlier sowing favoured yield	Highest seed yield at the lowest density (D1) with early sowing (S1); higher density increased plant height, internode and petiole length but did not raise yield under early sowing	Xu et al. (2024)
Roselle	Yield per unit area highest at highest tested density despite lower yield per plant	Number of calyces, fresh and dry calyx weight per plant were higher at the lowest density (2 plants m^{-2}), but total calyx yield per hectare was maximized at the highest density (18 plants m^{-2})	Khattak et al. (2016)
Guar	Lower density favoured grain yield	Highest grain yield obtained at the lowest tested density (13 plants m^{-2}) rather than higher densities (20 or 40 plants m^{-2})	Mahdipour-Afra et al. (2021)

INTERACTION BETWEEN SOWING TIME AND PLANT DENSITY

A central finding across the literature reviewed is that sowing time and plant density rarely act independently; instead, the optimal density is frequently conditional on the sowing date achieved, and the yield penalty from delayed sowing is frequently, though not fully, moderated by density adjustment. In wheat, a four-factor field trial testing three sowing dates, five sowing densities and three fertilization models found that sowing date exerted the strongest influence on yield among all factors tested, consistently overriding the effects of both nutrition model and plant density; critically, yield losses due to late sowing could not be offset by increasing seed density, even though a density of 400–500 seeds m^{-2} was identified as broadly optimal across sowing dates. This finding carries an important practical implication: farmers who are forced into late sowing because of preceding crop harvest timing, weather delays or labour constraints cannot fully compensate for the resulting yield penalty simply by sowing more densely.

In soybean, the interaction operated somewhat differently: increased planting density was found to partially compensate for yield loss associated with delayed sowing, since the short growing season and competition from winter crops such as wheat in Southern Xinjiang limit the window available for soybean cultivation, and a quantitative relationship between increased density and delayed sowing days was explicitly sought to guide compensatory management; nonetheless, the single highest-yielding treatment combination remained early sowing paired with lower density, with late sowing combined with low density producing the lowest yield of all treatments tested (Xu et al., 2024). In cotton, the interaction was more genuinely two-directional: moderate-to-high density specifically increased lint yield under late sowing, while under early sowing, moderate density alone (without the need for higher density) was sufficient to maximize yield; the authors concluded that both 'moderate density with later sowing' and 'lower density with earlier sowing' represent viable, alternative optimal strategies for lint yield, rather than there being a single universal optimum density independent of sowing date (Khan et al., 2017).

In rice, the interaction between transplanting age (an establishment-timing analogue of sowing date) and spacing (a density analogue) was also significant and non-additive: the highest above-ground biomass was recorded with young seedlings (14 days after planting) at close 20 × 20 cm spacing, whereas the highest actual grain yield was recorded at a different combination — 21 days after planting with the same close 20 × 20 cm spacing — demonstrating that the timing-density combination that maximizes vegetative biomass is not necessarily the same combination that maximizes final

Table 3

Crop	Nature of the sowing time × plant density interaction
Wheat	Sowing date exerted the strongest influence on yield, consistently overriding the effects of plant density and nutrition model; yield losses from late sowing could not be fully offset by increasing seeding density, although a density of 400–500 seeds m^{-2} was found optimal across sowing dates.
Soybean (Xinjiang)	An increase in planting density can partially compensate for yield loss caused by delayed sowing, but the highest yield overall was still achieved by combining early sowing with a lower planting density, since late sowing combined with low density produced the lowest yield of all treatments tested.
Cotton	Moderate-to-high density increased lint yield specifically under late sowing, while moderate density combined with earlier sowing was optimal; the authors concluded that a strategy of moderate density with later sowing, or lower density with earlier sowing, together represent the two viable optimal combinations for lint yield.
Rice	Significant interaction between transplanting age and spacing: the highest biomass occurred with young seedlings (14 days after planting) at close (20 × 20 cm) spacing, while the highest grain yield was achieved specifically at 21 days after planting combined with 20 × 20 cm spacing — a distinct optimum from either factor considered alone.

grain yield, and that both factors must be jointly, rather than separately, optimized (Yussif et al., 2026). Table 3 summarizes these interaction findings table 3

Table 3. Reported interactions between sowing time and plant density in selected crops.

Figure 1 complements Table 1 by directly comparing the magnitude of the yield penalty associated with delayed sowing in the two crops — cotton and soybean — for which comparable percentage yield reductions were explicitly reported, illustrating that sowing-time sensitivity, while universal in direction, varies substantially in magnitude across crops and environments

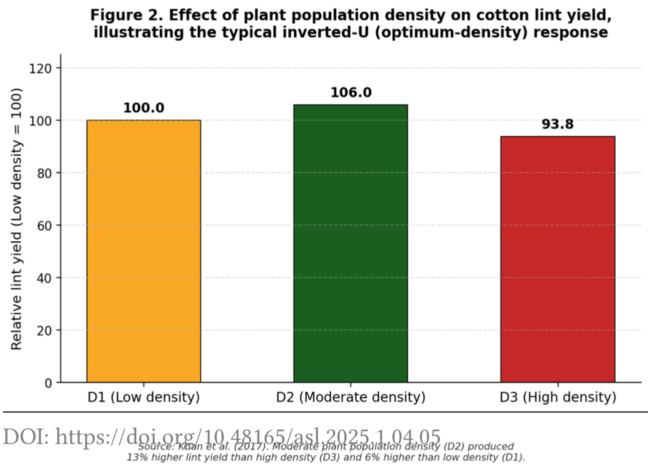

Figure 1: Effect of plant population density on cotton lint yield, illustrating the typical inverted-U (optimum-density) response, based on data reported by Khan et al. (2017).

PRACTICAL AND AGRONOMIC IMPLICATIONS

The evidence synthesized in this review points toward several practical implications for crop management and extension recommendations:

- Sowing time should be treated as a primary, not secondary, yield-determining decision: the magnitude of yield loss from delayed sowing (20–30% in the crops with quantified data) is comparable to, or exceeds, typical yield responses to many fertilizer or variety interventions, yet requires no additional input cost to optimize.
- Plant density recommendations should be presented as a range bracketing a genuine optimum, not a single 'higher is better' target, since several crops reviewed here (soybean under early sowing, guar, and roselle on a per-plant basis) showed yield penalties, not gains, at the highest tested densities.
- Density and sowing-date recommendations should be issued jointly rather than independently wherever field evidence permits, since the optimal density in cotton and soybean specifically depended on the sowing date achieved, and a density recommendation calibrated for early sowing may be sub-optimal if farmers are, in practice, sowing later due to logistical constraints.
- Where late sowing is unavoidable due to prior crop rotation, weather or labour constraints, agronomic advice should be realistic about the limits of density-based compensation: in wheat, density adjustment could not fully offset the yield penalty of late sowing, and farmers should not be led to expect that simply increasing seeding rate will resolve the yield loss associated with a late sowing date.
- Because the specific yield-forming component affected by sowing time or density differs by crop — pod number in lentil, seed weight in soybean, panicle number in rice, calyx number in roselle — crop-specific rather than generic agronomic guidance is needed, even though the general direction of the sowing-time and density effects is broadly consistent across crops.

There is also an important economic dimension to these agronomic choices that extends beyond the biological yield response reported in most trials. Plant density is directly linked to seed cost, since higher target densities require proportionally more seed, which is a significant expense for hybrid seed of crops such as maize and cotton; the finding that moderate, rather than maximal, density often maximizes yield therefore carries a favourable economic corollary, since it implies that the yield-maximizing density is frequently also more seed-cost-efficient than pushing density to its upper tested limit. Conversely, where late sowing is unavoidable and compensatory density increases are only partially effective, as found in wheat, farmers face a genuine economic trade-off: additional seed expenditure to raise density will not fully recover the yield lost to delayed sowing, meaning that on-time sowing should be prioritized operationally — through timely land preparation, machinery scheduling and seed availability — ahead of compensatory input-based strategies applied after a delay has already occurred

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Several gaps and challenges emerge from this review. First, most of the density-optimum evidence reviewed derives from a limited number of density treatments (typically three), which constrains precise identification of the true optimum and may understate the sharpness or breadth of the yield plateau around it; future trials would benefit from finer-resolution density gradients, particularly around the levels identified as locally optimal. Second, while several studies (wheat, soybean, cotton, rice) explicitly tested sowing time × density interactions, others (lentil, guar, roselle, maize) examined the two factors either separately or without a full factorial design, limiting direct comparability of interaction strength across the full set of crops reviewed; expanding factorial trials to these crops would strengthen cross-crop synthesis. Third, almost all the evidence reviewed derives from single- or few-site, few-year field trials; given that optimal sowing dates and densities are inherently site- and season-specific, longer-term, multi-environment trials, combined with crop simulation modelling, would help generalize recommendations across the wider range of soils and climates farmers actually encounter. Finally, as breeding continues to produce cultivars specifically selected for density tolerance, sowing-date flexibility or accelerated development, historical sowing-time and density recommendations will require periodic re-validation against current genotypes rather than being treated as fixed agronomic constants.

CONCLUSION

Sowing time and plant density are two of the most accessible and cost-effective levers available to farmers for influencing crop growth and yield, and the evidence reviewed here confirms that both exert substantial, often crop-specific effects. Delayed sowing consistently reduced yield across the crops examined, by margins as large as 21–29% in cotton and soybean, primarily through shortened vegetative growth periods, reduced light and thermal resource capture, and diminished yield-forming components such as tiller, panicle, pod or calyx number. Plant density effects followed a more universal inverted-U pattern, with yield typically maximized at an intermediate, crop-specific optimum rather than at either extreme, though the precise optimum, and even whether higher or lower density was favoured, varied by crop and by the sowing date under which density was evaluated. Critically, sowing time and plant density interacted significantly in wheat, soybean, cotton and rice, meaning that density recommendations calibrated without reference to realistic sowing dates — and vice versa — risk underperforming relative to jointly optimized management. Future agronomic guidance should therefore present sowing-time and density recommendations as an integrated, conditional package rather than as two independent single-factor targets, supported by expanded, higher-resolution, multi-environment factorial trials across the wider range of crops for which such integrated evidence remains limited.

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