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Seed Cane Selection, Planting Density, and Ratoon Management for High-Yield Sugarcane Cultivation

Zhaoyang Song [1,2]
1 Yiwu Feifan Agricultural Development Co. Ltd., Yiwu, 322002, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: 275911488@qq.com
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Abstract This review examines the biological connections among sugarcane cultivation practices based on English-language journal articles published in recent years. Evidence from propagation studies, field experiments, physiological investigations, and breeding research is analyzed according to experimental scale and the harvest cycles evaluated. Seed cane quality is assessed in terms of varietal identity, sanitary status, bud viability, and establishment capacity rather than stalk appearance alone. Planting density is evaluated by examining changes from planted buds or transplanted seedlings to surviving millable stalks, with attention to the compensatory relationship between stalk number and individual stalk mass. Ratoon performance is analyzed in relation to retained buds, root function, harvest injury, field traffic, crop residues, and nutrient availability. A case analysis draws on a published bud-chip transplanting experiment in India, together with studies on sugarcane establishment and ratoon cultivation in Brazil. These experiments show that the highest initial planting input, the greatest early tiller population, and the best economic returns do not necessarily occur together. This study aims to provide practical references for sugarcane growers, agricultural extension specialists, and plant breeders.

Keywords Sugarcane cultivation; Seed cane selection; Planting density; Ratoon management; Cane yield; Agronomic practices

1 Introduction

Sugarcane is an important crop for sugar production, bioenergy, and agricultural industries in tropical and subtropical regions. Its production differs from that of many annual crops because a single planting can support several harvests. The first crop develops from planted stem sections, while subsequent ratoon crops grow from buds retained in the underground stools after harvesting. This biological characteristic reduces the need for repeated planting but also makes productivity dependent on the condition of the remaining plant structures. A successful first harvest does not necessarily indicate that the crop will remain productive in later seasons. Xu et al. (2021) described ratooning ability as a complex characteristic influenced by genetic background, plant physiology, and environmental conditions. Their findings suggest that sugarcane productivity should be evaluated across successive harvests rather than through plant-cane yield alone. The crop also has an important role in biomass production, as stalks and harvesting residues can provide raw materials for industrial and energy applications. However, removing crop residues may affect soil conditions and future plant growth. Carvalho et al. (2019) found that sugarcane yield responses to straw removal varied among production environments in Brazil. Such variation highlights the importance of balancing immediate economic benefits with the maintenance of long-term field productivity. High-yield cultivation should therefore consider harvested cane mass, recoverable sugar, production costs, and the capacity of the crop to maintain satisfactory performance during subsequent ratoon cycles.

Achieving high sugarcane yields requires careful management of crop establishment, plant population, and postharvest regeneration. Seed cane selection determines the initial quality of planting materials, including bud viability, physiological condition, and sanitary status. Healthy planting materials generally provide a better foundation for uniform emergence and early growth, although their performance also depends on soil moisture, temperature, and planting practices. Planting density influences how individual plants occupy the available growing space and compete for light, water, and nutrients. A sparse population may leave productive land

underused, whereas excessive density can increase competition and restrict individual stalk development. The relationship between planting density and yield is therefore not necessarily linear. Costa et al. (2023) examined sugarcane responses to planting density across plant-cane and ratoon cycles, demonstrating the importance of considering crop performance beyond the initial harvest. Almeida et al. (2024) further showed that the planting density associated with greater productivity did not necessarily provide the most favorable economic return. These findings indicate that increasing planting material inputs cannot automatically be regarded as an effective strategy for improving profitability. Ratoon management introduces another challenge because the crop must regenerate from structures affected by previous growth and harvesting operations. Damage to underground buds, soil compaction, inadequate nutrient supply, and unfavorable moisture conditions may restrict regrowth. Effective management consequently requires coordination among planting material quality, population establishment, and the protection of productive stools throughout successive harvest cycles.

Environmental conditions and varietal characteristics further complicate the selection of suitable cultivation practices. Sugarcane varieties differ in tillering ability, stalk development, growth duration, and capacity for ratoon regeneration. A planting arrangement that performs well with one variety may not produce the same response with another. Soil properties, rainfall distribution, irrigation availability, and harvesting systems can also influence the effectiveness of management decisions. Ellsworth and White (2022) investigated row spacing under the relatively water-abundant conditions of Louisiana and found that differences in soil water storage did not necessarily indicate inadequate water availability for plant growth. Their observations illustrate why management recommendations developed under one set of environmental conditions should not be transferred directly to contrasting production regions. Similar caution is necessary when evaluating improved propagation techniques. Pre-sprouted seedlings and conventional stem cuttings differ not only in planting material requirements but also in nursery preparation, root development, establishment costs, and field handling. Differences in crop performance may therefore reflect several interacting factors rather than a single treatment effect. Understanding these relationships requires attention to the biological processes connecting early establishment with later yield formation. It is equally important to distinguish planted bud numbers, emerged shoots, surviving tillers, and harvestable stalks. These measurements represent different stages of crop development and cannot be used interchangeably when explaining yield responses.

This study aims to examine the roles of seed cane selection, planting density, and ratoon management in high-yield sugarcane cultivation, with particular attention to their relationships across successive production cycles. A case analysis draws on published sugarcane planting experiments from India and Brazil to investigate how different establishment practices affect plant-cane and ratoon performance. By evaluating these management components together, this review seeks to provide a more comprehensive understanding of sugarcane yield formation than examining individual practices independently. It also seeks to explore how suitable combinations of management practices are influenced by genotype, environmental conditions, and production costs, rather than identifying a universally applicable planting standard. The findings are expected to provide a basis for selecting sugarcane varieties capable of maintaining economically satisfactory yields over multiple harvest cycles.

2 Seed Cane Selection and Crop Establishment

2.1 Characteristics and quality requirements of seed cane

Seed cane should be evaluated as living propagation material rather than as a quantity of stalk biomass. A useful quality assessment distinguishes varietal identity, sanitary status, viable buds, and physical condition. These categories should not substitute for one another. A correctly named cultivar may carry infection; an apparently healthy stalk may contain damaged buds; and high sprouting under favorable nursery conditions does not establish satisfactory performance after transport and field planting. The practical objective is to obtain a reliable population of suitable plants, not merely to purchase a prescribed mass of cane.

Sanitary assessment deserves particular attention because visual inspection has limits. Chakraborty et al. (2024) describe the diagnostic challenges associated with ratoon stunting disease, including the absence of reliably distinctive external symptoms. Their review supports combining clean-seed systems with appropriate pathogen

detection rather than certifying material through appearance alone. Records should identify the source nursery, multiplication history, sampling procedure, and tests performed. The expression pathogen-free should be reserved for the scope of the diagnostic evidence, not used as an unrestricted promise.

Bud number and sett size should be reported separately. A longer sett can contain more buds and reserves, but an experiment comparing sett lengths may also change the total bud population and planting mass. Without controlling those changes, it cannot isolate a reserve effect. Physiological age likewise needs a clear definition: chronological age, stalk position, and bud developmental stage are not interchangeable. For cultivar comparison, a practical assessment would record viable buds delivered, buds damaged during handling, and the proportion producing established shoots. This makes quality measurable at the point where it matters to the grower, while avoiding an unsupported universal age or sett-length recommendation.

Physiological quality can be lost after a seed lot has been inspected. Madala et al. (2023) noted that their material was handled carefully and that mechanical handling could damage pre-germinated buds. Thus, inspection at the nursery gate and inspection at planting answer different questions. Recording both would reveal whether poor establishment reflects the original material or the operation that delivered it. This distinction is especially important when comparing manually prepared experimental material with commercial planting.

2.2 Effects of seed cane selection on germination and early growth

Emergence is the first visible outcome of planting quality, but its timing and distribution matter alongside its final percentage. Two lots can eventually produce similar shoot numbers while differing in emergence spread and the length of unoccupied row segments. A useful establishment record would therefore include emergence over time, surviving stools, and gap distribution rather than one final count. Such a record can distinguish failure to sprout from death after emergence, which are different problems and need not require the same corrective action.

Madala et al. (2023) compared ungerminated and pre-germinated buds in greenhouse experiments and a small field experiment. Pre-germinated material produced neutral or favorable early responses, with some effects differing between experiments and cultivars. The study challenges the assumption that a bud beginning to grow before planting is necessarily unusable. It does not, however, demonstrate a mature-yield advantage or establish suitability for rough mechanical handling. Sprouting buds on source cane must also be distinguished from rooted seedlings deliberately raised in a nursery.

Plant health can influence population formation through less visible processes. Garcia et al. (2021) found that higher populations of the ratoon stunting pathogen in a susceptible genotype were associated with reduced sugar allocation to tillers and lower tiller development. Their results connect infection with source-sink relations rather than only with an externally shortened stalk. For seed selection, the implication is that apparently satisfactory parent-stalk growth cannot substitute for a healthy multiplication system. The broader inference remains conditional: pathogen effects observed in a susceptible genotype should not be assigned an identical magnitude across all cultivars, environments, or stages of infection.

Early vigor should be interpreted through an explicit measurement plan. Shoot height, root development, and surviving plant number describe different dimensions of establishment. Combining them into an unspecified quality score can conceal a trade-off. Reporting each component preserves information needed to explain later field performance.

2.3 Seed cane preparation and planting techniques

Conventional setts, bud-chip settlings, and tissue-culture-derived plants represent different establishment systems, not simply different sizes of the same planting unit. Their evaluation should include multiplication, handling, field survival, and the subsequent crop. Salokhe (2021) developed a meristem-culture and acclimatization protocol for producing healthy seed cane. Such work demonstrates a propagation pathway, but commercial quality assurance must still address varietal fidelity, contamination during multiplication, and the health of plants after transfer outside protected conditions. Tissue culture is a technique within a sanitary system, not a replacement for that system.

Planting depth should similarly be interpreted in relation to material type. Tayade et al. (2021) compared tissue-culture plantlets and bud-chip settlings and obtained different preferred planting depths for the two materials under their experimental conditions. This is stronger evidence for matching placement to the planting unit than for imposing one depth across systems. A rooted plantlet and an unrooted sett encounter different establishment requirements, so a common label such as improved planting can hide important biological differences.

The appropriate economic denominator is the cost per successfully established, useful stool, followed by its contribution to harvests. Nursery labor, substrate, culling, transport, and replacement costs belong in that calculation even when field planting uses less cane biomass. Conversely, the opportunity value of stalks diverted from milling to conventional seed supply should not be ignored. Comparisons should document these inputs without assuming that either reduced planting mass or greater nursery sophistication guarantees a better outcome. Where treatment packages differ in several respects, their practical performance can still be compared, but the causal contribution of each component should remain unresolved until a suitable experiment separates it.

In the Coimbatore experiment, the preferred depths were 5 cm for tissue-culture plantlets and 2.5 cm for bud-chip settlings at the evaluated 120 by 60 cm arrangement (Tayade et al., 2021). These values identify the tested system, not a general depth standard. Their practical significance is that placement deserves separate calibration when a farm changes propagation material, even if its nominal planting density remains unchanged.

3 Planting Density and Sugarcane Yield Formation

3.1 Planting density and crop population development

Planting density is not one measurement. It may describe buds per metre of furrow, buds per square metre, transplants per hectare, or emerged stools. Later observations may count tillers or millable stalks. These quantities answer different questions, and none should be substituted silently for another. At a fixed number of buds per metre of row, narrowing the interrow distance increases buds per unit land area. A row-spacing comparison conducted in this way changes both geometry and initial density. Its outcome cannot be attributed to geometry alone.

The relevant population sequence is planting units, established stools, total shoots, and surviving harvestable stalks. Losses or compensation can occur between successive observations. Thus, an initially sparse treatment may partly compensate through more surviving stalks per stool, whereas a dense treatment may retain only a fraction of its early numerical advantage. This reasoning is consistent with the changing density responses across harvest cycles reported by Costa et al. (2023). Their results support following the same treatments beyond the plant crop rather than choosing a recommendation from one early population peak.

Genotype adds another level of variation. Dlamini et al. (2024) associated stalk population, stalk mass, and other structural traits with ratoon yield across variety trials. Their findings encourage selection for combinations of traits rather than treating prolific tillering as an adequate breeding objective by itself. For density experiments, this means that the cultivar is part of the treatment context. A design using only one genotype can identify a local response, but it cannot establish that weakly and strongly tillering cultivars need the same initial population. Reporting the final stalk population alongside initial density is therefore essential for interpretation.

For equally spaced single rows, buds per unit land area can be calculated by dividing buds per unit row length by interrow width, provided that both lengths use compatible units. For paired rows, the calculation must include both rows and the wider interval between pairs. This simple accounting should accompany treatment descriptions. Otherwise, nominally similar planting rates can represent quite different investments and starting populations.

3.2 Effects of planting density on canopy structure and resource utilization

The canopy connects plant arrangement with resource capture. Closer placement can shorten the distance that leaves must occupy before the ground is covered, but this does not mean that every additional leaf contributes equally to crop growth. Light intercepted by an already shaded leaf is not equivalent to light captured by an

exposed, photosynthetically active leaf. The useful question is how an arrangement changes resource capture and its distribution through time, not whether it produces the darkest-looking canopy on one observation date.

Gasparotto et al. (2020) synthesized interrow-spacing experiments across diverse climates and reported an overall yield advantage for narrower spacing, while recognizing constraints associated with mechanization and field traffic. Their synthesis supports considering row width as an agronomic lever, but it does not make the narrowest feasible row universally preferable. Harvest equipment, crop geometry, and the management of wheel tracks can alter the practical outcome. Light capture and operational compatibility must therefore be considered together rather than optimized independently.

Water interpretation needs equal care. In Louisiana, Ellsworth and White (2022) observed spacing-related differences in soil water, but both arrangements could retain adequate plant-available water in the monitored soil profile. More stored water was not automatically evidence of greater crop water-use efficiency. A field comparison intended to explain density responses should therefore record rainfall or irrigation, rooting-zone water conditions, and crop growth together. Otherwise, reduced growth could be attributed to competition without demonstrating that water actually became limiting. The same logic applies to nutrients: a larger population changes potential demand, but a diagnosis of nutrient limitation requires evidence beyond plant number alone.

Canopy measurements are most informative when repeated through development. Leaf area, intercepted radiation, and biomass accumulation should be compared over the same intervals, with dead or senescent tissue distinguished from functional foliage. This would allow a proposed light-capture mechanism to be tested rather than inferred from final stalk yield. It would also separate faster canopy establishment from a genuine improvement in biomass production per unit radiation intercepted.

3.3 Optimization of planting density for high-yield production

Cane yield can be decomposed into harvestable stalk number per unit area and mean harvested stalk mass. This accounting identity explains why density responses must be examined through both components. A treatment may produce more stalks but smaller individual stalks, leaving total yield little changed. Another may improve stalk survival without greatly increasing early tillering. Reporting stalk counts, mass, and their variability allows these alternatives to be distinguished. It also prevents a visually impressive population from being mistaken for a demonstrated yield improvement.

Economic optimization introduces another comparison. Almeida et al. (2024) showed that productivity and economic-return measures could favor different planting densities. Their study should be read as a site-specific analysis, not as a transferable schedule of seed rates or prices. An economically useful experiment needs to account for additional planting material, associated labor, and any change in harvest or maintenance costs. Where yield differences are small and uncertain, a modest increase in input cost can alter the preferred decision without changing the biological ranking.

A defensible local recommendation would identify a response range rather than announce an exact optimum unsupported by the tested treatments. The range should be evaluated across contrasting seasons and at least the ratoon stages relevant to local replacement practice. Comparisons must also use equivalent land area, including alleys in paired or multiple-row systems. A convenient within-row count is not an area-based productivity measure. Ultimately, suitable density is the least costly arrangement that reliably supplies enough harvestable stalks under the relevant environment, without creating operational or resource constraints that undermine later crops. This definition makes the optimum conditional, measurable, and open to revision.

Sugar measurements complete the comparison. Brix records soluble solids and should not be reported as if it were identical to recoverable sugar. Dlamini et al. (2024) found relationships among quality and yield traits, but correlated indicators still retain different meanings. A density recommendation aimed at sugar production should therefore use a stated recovery measure and comparable harvest maturity, rather than relying on cane tonnage alone.

4 Ratoon Management and Sustained Sugarcane Productivity

4.1 Biological basis of ratoon growth and regeneration

Ratoon establishment begins with retained living structures rather than a newly supplied planting unit. Buds and associated underground tissues must support renewed shoot production after the aboveground crop is removed. This makes the condition at harvest biologically consequential. Xu et al. (2021) emphasize the multiple traits involved in ratooning ability, including the need to understand underground structures and their changing function. For management, the relevant unit is therefore the surviving stool and its environment, not the cut stalk considered in isolation.

Root function provides a useful mechanistic example. Pissolato et al. (2021) manipulated root-system size in young sugarcane plants grown in nutrient solution and found that retaining a larger root system supported stronger regrowth. The experiment establishes a relationship under controlled conditions; it does not provide a field coefficient for predicting yield loss from wheel damage. Pierre et al. (2019), meanwhile, found that reducing tillering did not automatically increase the root mass fraction in their screening study. Together, these observations argue against a simple assumption that fewer shoots always leave more resources for roots.

A practical consequence is that belowground condition should be examined when aboveground recovery is poor. Repeated shoot counts alone cannot distinguish dead buds, damaged roots, or an unfavorable soil environment. Field diagnosis should connect stool survival, root condition, and moisture with the timing of regrowth. For research, measurements taken before harvest and during early ratoon recovery would help identify whether a treatment protected existing structures or merely changed subsequent shoot growth. Without that distinction, a high ratoon population may be described correctly but explained incorrectly.

Carbohydrate reserves offer a further link between retained tissues and regeneration. In the nutrient-solution study, root-system size was examined alongside nonstructural carbohydrate status and subsequent shoot recovery (Pissolato et al., 2021). For field work, this suggests measuring reserve status and living-root capacity together. A large quantity of root tissue is not necessarily equivalent to a large quantity of physiologically active tissue, so mass alone remains an incomplete description.

4.2 Factors affecting ratoon growth and yield

Harvesting changes both the plant and the soil around it. Cutting injury, displacement of stools, and traffic close to the row can influence the environment inherited by the next crop. Aguilera Esteban et al. (2019) compared controlled traffic and row arrangements and found improvements in root-related and yield outcomes where traffic was managed. Their treatments show why geometry cannot be evaluated solely through plant competition: it can also change where heavy equipment passes relative to the crop.

Cutting height or depth is another context-dependent intervention. Yang et al. (2021) compared cutting at the soil surface and at two subsurface depths; the intermediate depth produced the strongest performance in their experiment. The appropriate interpretation is that cutting position can affect root development and ratoon productivity, not that one subsurface depth is safe or optimal everywhere. Equipment accuracy, soil conditions, cultivar, and the position of living buds must be considered before transferring the result. Da Silva Gírio et al. (2019) further showed that planting system and spacing influenced aspects of multi-row harvesting quality, reinforcing the need to assess establishment and harvesting as connected operations.

Crop age alone is an incomplete explanation of decline. Riajaya et al. (2022) reported different plant-to-first-ratoon patterns among varieties, illustrating that a uniform percentage reduction is not a sound expectation for every genotype. A low-yielding ratoon should therefore trigger diagnosis rather than automatic attribution to age. The observed decline may combine biological deterioration, weather, disease, harvest injury, or reduced resource availability. Separating these possibilities matters because renewing the crop is an expensive response when the actual limitation would remain after replanting.

The spatial pattern of injury can also explain why field means are misleading. In the controlled-traffic study, soil and root measurements distinguished the planting row, the trafficked interrow, and the intervening seedbed

(Aguilera Esteban et al., 2019). That design links the sampling position to the suspected mechanism. Comparable sampling is needed before recommending broad soil disturbance for a problem confined mainly to wheel tracks.

4.3 Agronomic practices for improving ratoon productivity

Postharvest management should begin with an assessment of what the harvest left behind. Permanent traffic lanes can protect the stool zone even while compaction becomes concentrated in the trafficked interrows. Aguilera Esteban et al. (2020) documented this spatial redistribution under automatic steering. Soil assessment should consequently distinguish wheel tracks from the seedbed; averaging both can conceal the benefit of protecting the zone occupied by the retained crop. Controlled traffic is best understood as limiting damaging contact with that zone, not eliminating machinery pressure from the field.

Residue management should also reflect spatial and environmental conditions. Melo et al. (2020) linked straw-management treatments with root and stalk responses, while Cherubin et al. (2021) found that high or total straw removal could degrade soil-health indicators across Brazilian experiments. Neither result supports treating all residues as surplus biomass. The management question is how much residue can be removed without compromising the particular soil and crop, rather than whether removal is inherently beneficial or harmful under every condition.

Nutrient and water management require diagnosis rather than routine escalation. Bhatt et al. (2021) examined potassium under contrasting water supply in a potassium-deficient setting, supporting attention to nutrient-water combinations. De Castro et al. (2022) showed that nitrogen timing and rate could be adjusted to harvest-season conditions. These findings favor synchronizing supply with recovery and demand instead of simply increasing fertilizer when ratoons weaken. Weed control and gap repair should likewise be assessed against stool survival and the remaining productive life of the field. Where a recommendation lacks direct evidence in the local system, a small, monitored comparison is preferable to assuming that a standard postharvest package will restore every declining ratoon.

The nitrogen experiments provide a concrete example of timing specificity: favorable application windows differed between fields harvested early and midway through the season (de Castro et al., 2022). A fixed number of days after harvest therefore cannot serve as a universal prescription. Likewise, the potassium study was conducted on deficient soil; its fertilizer response should inform diagnosis of comparable fields, not justify the same dose wherever a ratoon crop grows (Bhatt et al., 2021).

5 Case Analysis: Effects of Planting Practices on Sugarcane Yield and Ratoon Performance

5.1 Background and selection of the case study

Kumar (2020) provides the principal case because the experiment connects planting geometry, plant-crop performance, ratoon performance, and economics. Conducted at Pusa, Bihar, India, during 2013-2016, it evaluated bud-chip-raised seedlings under furrow-irrigated raised-bed planting. Planting distance and row spacing were examined within a plant-ratoon system. Its publication falls within the selected literature window even though the fieldwork preceded that window. The case is particularly useful because the treatment associated with the largest mean cane yield was not necessarily the treatment with the best benefit-cost ratio.

The case does not compare every component named in the present review. It evaluates the deployment of a particular planting material, not a factorial contrast between infected and pathogen-tested seed cane. Nor does it independently randomize a complete set of postharvest management practices. Its contribution is narrower and more useful than such an expanded claim: it allows the consequences of an initial spatial decision to be followed into a subsequent crop. Any explanation involving seed health or root protection must therefore remain an interpretation unless directly measured.

Two Brazilian studies broaden the comparison without being pooled statistically with the Indian experiment. Otto et al. (2022) followed conventional establishment and pre-sprouted seedlings through plant cane and two ratoons in experiments established in different seasons. De Souza et al. (2022) examined planting arrangements and

planting-material systems during the third, fourth, and fifth ratoons. These studies represent different environments, treatments, and stages of crop persistence. Their role here is to test whether the practical lesson from one experiment remains plausible when the establishment system and observation horizon change, not to manufacture a single cross-country effect estimate.

The Brazilian establishment comparison also makes the planting unit explicit. Conventional treatments used billets at 12-15 buds per metre, whereas pre-sprouted seedlings were placed at 0.5 m intervals within 1.5 m rows (Otto et al., 2022). These treatments cannot be compared by counting planting units as though each represented the same biological investment. Their value lies in comparing complete establishment alternatives through later harvests, while documenting the different material and operations needed to produce them.

5.2 Comparative analysis of planting treatments and crop performance

In Kumar's experiment, the 30 cm planting distance produced mean cane yields of 81.7 t/ha for plant cane and 74.6 t/ha for ratoon cane. Differences between 30 and 45 cm were not statistically significant, while the 45 cm distance produced the higher benefit-cost ratio. A 90 cm row spacing performed strongly for several production and economic measures. Sucrose content was not significantly affected by the tested spacing factors (Kumar, 2020). These are reported treatment effects, not a basis for assigning an unreported advantage to a particular interaction between row and within-row spacing.

The economic interpretation follows directly from the separation of outcomes. A numerically larger yield does not establish that its additional planting input paid for itself. Conversely, a higher benefit-cost ratio does not necessarily mean the greatest absolute net return. A grower choosing among these treatments would need to decide which financial criterion matters and recalculate it using the relevant costs and prices. The historical comparison remains evidence about trade-offs, but its monetary values should not be presented as current farm budgets.

Otto et al. (2022) offer a contrasting result. Conventional billet planting and pre-sprouted seedlings differed in establishment inputs and early development, yet harvestable population, stalk yield, and recoverable-sugar concentration were similar across the evaluated crop cycles and establishment seasons. In later ratoons, de Souza et al. (2022) likewise found no significant yield or quality response to the planting arrangements and seedling systems they compared. These studies do not invalidate the Indian results. They show that changing planting practice does not guarantee a lasting production difference. Statistical non-significance also should not be rewritten as proof that treatments are exactly equivalent; the size of uncertainty remains relevant to any practical decision.

5.3 Implications for integrated sugarcane management

The combined lesson is to separate three questions: whether establishment changes, whether a yield difference persists, and whether the change is worth its cost. The answers can differ within the same experiment. For a planting technology, reduced seed-cane mass may be valuable even when mature yield is unchanged, provided that nursery and transplanting costs do not offset the saving. A visually stronger early population may offer little additional income when later compensation narrows the difference. These are economic and biological interpretations of the comparison, not new measured outcomes.

The evidence also suggests a more informative approach to local verification. A conventional system and its proposed replacement should be compared under documented seed health, comparable land area, and clearly stated fertilizer and water management. Establishment losses should be recorded before remedial gap filling. Subsequent harvests should retain the identity of the original plots so that mortality, repair, and yield can be followed. This would make it possible to distinguish a durable planting advantage from an early advantage maintained only through additional intervention.

Transfer remains conditional. The Indian geometry should not be copied directly into a mechanized Brazilian field whose machinery requires different traffic lanes, nor should Brazilian null responses be treated as a reason to

ignore seed quality elsewhere. The cases support testing the whole establishment-to-ratoon sequence and retaining non-significant results in the interpretation. They do not demonstrate a universally superior propagation method, a universal seed rate, or a proven synergistic interaction among seed sanitation, density, and ratoon care. Their strongest contribution is a disciplined way to decide what a planting result actually supports (Figure 1).

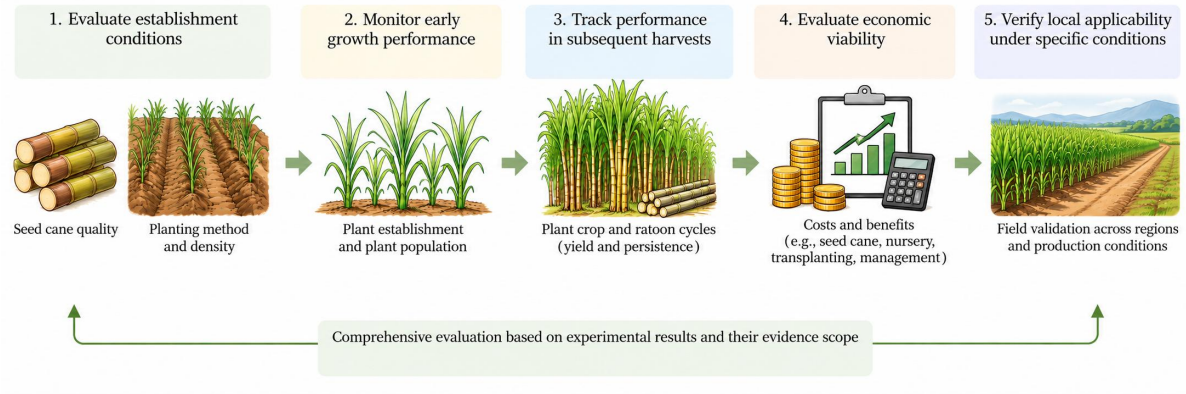


Figure 1 Integrated evaluation framework for sugarcane establishment and ratoon management

Image caption: The proposed framework consists of five steps: (1) Evaluating establishment conditions, including seed cane quality, planting methods, and planting density; (2) Monitoring early growth performance through plant establishment and population development; (3) Tracking crop performance across plant crop and ratoon cycles, with particular attention to yield and productivity persistence; (4) Assessing economic viability by comparing production benefits with costs associated with seed cane, nursery production, transplanting, and management; and (5) Conducting field validation under different regional and production conditions to determine the applicability of management practices. The framework emphasizes comprehensive evaluation based on experimental results and their evidential scope rather than assuming that a particular propagation method, planting density, or management combination is universally superior

6 Integrated Management Strategies for High-Yield Sugarcane Cultivation

6.1 Interactions among seed cane quality, planting density, and ratoon management

Integration should begin with a causal sequence rather than a list of preferred inputs. Verified planting material enters a defined spatial arrangement; establishment determines the distribution of stools; crop growth and harvesting determine the structures retained; and postharvest conditions influence their recovery. An improvement at one stage can be lost at another. This framework makes the survival of useful stools the connection between decisions, without assuming that all positive single-factor responses will multiply when combined.

Root and shoot traits underline the need for caution. The controlled studies of Pierre et al. (2019) and Pissolato et al. (2021) show that belowground capacity and aboveground growth cannot be represented by a simple rule that more shoots are always better or fewer shoots always strengthen roots. An integrated field experiment should therefore measure both population development and the condition of retained structures. Final yield alone cannot reveal where a benefit originated or why it disappeared.

A genuine test of interaction would vary seed quality, initial population, and a defined ratoon-management intervention independently, with sufficient replication across environments. Until such evidence exists, the present synthesis supports coordinated decision-making but not a numerical claim of three-way synergy. The distinction matters: a coherent management explanation can guide an experiment without being presented as an already verified treatment effect.

6.2 Development of site-specific agronomic management strategies

Site-specific management should identify the dominant limitation before adjusting inputs. A field with low viable-bud delivery poses a different problem from one with adequate establishment but repeated harvest injury. Where both occur, correcting only density can obscure the cause of continued failure. Useful records should therefore connect the seed lot, planting operation, establishment pattern, harvest conditions, and ratoon recovery. The purpose is not to collect every available measurement, but to retain the information needed to distinguish competing explanations.

Genotype selection belongs in this process. Dlamini and Zhou (2024) modeled yield potential and ratooning ability over successive crops and identified varietal differences. Their work supports considering both absolute yield and persistence when selecting varieties. A slowly declining but consistently low-yielding variety need not be preferable to a productive variety with a somewhat steeper decline. The choice should depend on cumulative sugar output, the expected replacement interval, and the environment in which the comparison was made.

A practical recommendation should include an operating range and a condition for reassessment. Density could be reconsidered when viable establishment changes; residue removal could be reconsidered when soil condition deteriorates; and continued ratooning could be reconsidered when the expected return falls below that of renewal. These are proposed decision rules, not fixed thresholds validated by the cited studies. Their value is that each recommendation is linked to an observable condition rather than to an inflexible calendar.

The financial comparison should include the opportunity cost of renewal and the timing of returns. A further ratoon avoids immediate replanting expenditure but may produce less than a successful replacement crop. Renewal, however, does not guarantee success and may expose the farm to establishment risk. Comparing these alternatives under a common time horizon prevents either a low current cost or an optimistic first-harvest forecast from dominating the decision without justification.

6.3 Challenges and future research directions

Improved observation can make these decisions more precise. Barbosa Júnior et al. (2021) showed that the timing and spatial resolution of UAV imagery influenced sugarcane-gap detection, with earlier and lower flights improving accuracy in their conditions. Images should nevertheless be checked against field observations. A mapped gap identifies an absence of canopy, not its cause, and later canopy overlap can hide missing stools. The appropriate use is targeted inspection and repeated monitoring rather than automatic diagnosis.

Prediction methods offer complementary opportunities. Todd et al. (2021) explored ratoon-yield prediction using breeding data, while Islam et al. (2023) investigated genomic prediction of ratooning ability. Their approaches can help connect early information with later outcomes, but predictive performance is specific to the data and validation design. Testing new years, sites, and genetic material is essential before a model is used to justify replacing prolonged field evaluation.

Future experiments should combine these tools with stronger agronomic designs. Common measurements should include viable planting units, spatial gaps, harvestable stalks, recoverable sugar, harvest damage, and actual management expenditure across cycles. Trials should report uncertainty and failed treatment responses as carefully as successful ones. The next useful advance is not necessarily another nominally higher-yielding package; it may be a reliable explanation of when a simpler, less costly system achieves comparable production without shortening the productive life of the field.

The genomic study evaluated 432 clones across plant cane and two ratoons, with prediction accuracies of 0.21-0.36 for the investigated ratooning traits (Islam et al., 2023). Such results justify further development, not replacement of phenotyping. An important next test is whether prediction remains useful when management or genetic background changes, rather than only when validation samples resemble the training population.

7 Conclusions

Seed cane selection, planting density, and ratoon management should be understood as connected decisions governing establishment, population development, and the persistence of productive stools. Their integration does not mean maximizing each input or assuming that favorable responses will combine automatically. It means locating the biological or operational constraint, selecting an intervention capable of addressing it, and checking whether the benefit survives into harvest and subsequent regrowth. The appropriate management unit is the continuing plant-ratoon system rather than an isolated planting operation or one favorable harvest.

For seed cane, quality must remain broader than appearance and narrower than an unqualified promise of freedom from disease. Varietal identity, tested sanitary status, bud viability, physical integrity, and successful establishment

should be documented separately. Nursery methods can improve the organization of propagation, but their value depends on field survival and the complete cost of producing usable plants. A reduction in planting biomass is an input saving, not by itself evidence of increased yield. The strongest comparison follows planting material from its source through establishment and into the harvests for which it was intended.

For density, the essential distinction is between the population planted and the population harvested. Buds, transplants, stools, tillers, and millable stalks should never be treated as interchangeable measures. More initial units can create a larger early population without proportionately increasing the final crop. Recommendations therefore need to explain the balance between stalk number, individual stalk mass, spatial distribution, and operating costs. Row geometry also determines how a crop can be managed and harvested. An arrangement that performs well biologically but is incompatible with local machinery is not a complete production solution.

For ratoons, the harvest should be regarded as both the end of one crop and an intervention in the next. Protecting living buds, useful roots, and the stool zone gives postharvest management a viable starting point. Subsequent water, nutrient, residue, and weed management should respond to the condition actually retained. Increasing fertilizer cannot be assumed to repair physical damage or replace missing stools. Nor should crop age alone determine renewal. The decision to continue ratooning should reflect expected future output, the cost of maintaining the field, and the realistic performance of a replacement crop under the same constraints.

The case analysis highlights a particularly important lesson for interpretation: the largest numerical yield, the most favorable statistically supported comparison, and the best financial result can identify different treatments. These differences are not contradictions. They reflect different questions. A sound recommendation must state which outcome it seeks to improve and what uncertainty remains. Non-significant comparisons should be retained, not discarded as uninformative, while a lack of significance should not be inflated into proof of exact equivalence. Economic calculations should be updated for the intended production setting rather than transferred from an earlier experiment as current forecasts.

The most informative future studies will connect reliable planting-material records with repeated observations of the same field populations. Independent treatment factors, appropriate replication, documented repair operations, and comparable harvest maturity will improve causal interpretation. Remote sensing and prediction models can support that work, provided that their outputs remain tied to field measurements and are tested beyond the datasets used to develop them. Transparent reporting of null responses, uncertainty, costs, and operational difficulties will make results more transferable than a recommendation supported only by its best-performing treatment.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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