



Closing Indonesia's Sugar Yield Gap: Reconstructing Farm-to-Mill Productivity from Historical Highs toward a Competitive, Digital, and Climate-Resilient Sugarcane System

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ARTICLE INFO

Keywords: Indonesia, Sugarcane, Sugar Yield Gap, Sugar Productivity, Ratoon Management, Irrigation, Precision Agriculture, Milling Recovery, Smallholder Farming, Sugar Self-Sufficiency

Received : 3 July

Revised : 24 August

Accepted: 26 September

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ABSTRACT

Indonesia's sugar industry faces a persistent productivity gap between contemporary performance and the much higher yields historically reported for Java. This qualitative literature review synthesises recent peer-reviewed evidence published mainly during 2020–2026 to explain that gap through an integrated farm-to-mill perspective. Rather than equating productivity with cane tonnage, the review conceptualises realised sugar yield per hectare as the combined outcome of cane biomass yield, recoverable sucrose concentration, post-harvest quality retention and factory recovery. Evidence across agronomy, genetics, water and soil management, ratoon systems, crop protection, mechanisation, digital agriculture, logistics and farm institutions indicates that losses accumulate across the value chain. Key constraints include weak varietal adaptation, uneven planting-material quality, water stress, inefficient nutrient use, ratoon decline, disease pressure, machinery-induced compaction, delayed cut-to-crush times, variable milling performance, credit constraints and fragmented farmer–mill coordination. Remote sensing, machine learning, precision irrigation, controlled traffic, improved breeding and integrated nutrient management can raise productivity, but their effects depend on sequencing and institutional capacity. The review proposes an integrated transformation architecture in which foundational agronomy precedes operational integration, digitalization and frontier innovation. Sustainable gains in Indonesia's sugar yield therefore require coordinated improvements across farms, logistics, mills and enabling institutions rather than a single technology or headline productivity target.

INTRODUCTION

Sugarcane occupies an unusual position in Indonesia's agricultural and industrial economy. It is simultaneously a smallholder crop, an industrial feedstock, a source of household income, an input into food manufacturing, and potentially an increasingly important component of a broader sugar-ethanol-bioenergy system. Yet, despite its strategic importance, domestic productivity has repeatedly been identified as a major constraint on the competitiveness of the Indonesian sugar industry. Recent government reporting indicates that Indonesia produced approximately 39.07 million tonnes of sugarcane and 2.67 million tonnes of sugar in 2025, with average cane productivity of about 69.35 t ha⁻¹. These figures illustrate improvement but also highlight the importance of distinguishing tonnes of cane per hectare from tonnes of recoverable sugar per hectare, two indicators that are frequently conflated in public discussions (Directorate General of Estate Crops, 2026).

Historical accounts of Java show that the sugar industry once achieved exceptionally high output per unit of land, including sugar yields reported near 14.7 t ha⁻¹ around 1930. This historical observation is useful as a signal of latent productivity potential, but it should be treated as a heuristic frontier rather than as a directly comparable national target because contemporary Indonesia operates under very different agronomic, institutional and environmental conditions (Tegegn and Dhont, 2023).

The comparability problem is substantial. Colonial Java and contemporary Indonesia differ in production geography, land selection, labour organization, irrigation access, varietal composition, milling configuration, farm structure, environmental standards and social institutions. Historical research confirms that Java was an internationally important and technically efficient sugar-producing region before the disruptions beginning in the 1930s, yet that performance emerged from a specific production system whose institutional arrangements cannot simply be reproduced today (Tegegn and Dhont, 2023).

The relevant research question is therefore not whether Indonesia should mechanically "return" to a single historical productivity number. It is which biological, agronomic, technological, logistical, economic and institutional capabilities generated high productivity in the past, which constraints now prevent comparable efficiency, and which modern equivalents could sustainably raise recoverable sugar yield under current conditions. This reframing shifts the analysis from historical nostalgia to productivity-system reconstruction.

A second conceptual problem concerns the definition of productivity itself. Sugarcane productivity is frequently reported as tonnes of cane harvested per hectare, yet sugar mills and national food systems ultimately require recoverable sugar. A field may produce a large quantity of biomass but still generate disappointing sugar output when stalk sucrose content is low, harvesting occurs outside the optimum maturity window, delivery to the mill is delayed, deterioration occurs after cutting, or factory extraction is inefficient. Research on commercial sugarcane yield gaps therefore increasingly combines crop modelling and field diagnosis rather than treating biomass yield as the sole performance indicator (Gasparotto et al., 2022).

The analytical proposition of this review is consequently expressed as a farm-to-mill identity rather than as a field-only productivity measure. The relationship is summarized in Equation (1), which separates biological production from quality retention and industrial recovery.

$$Y_s = Y_c \times S_r \times R_h \times R_m \quad (1)$$

In Equation (1), Y_s denotes realized sugar yield (t sugar ha⁻¹), Y_c denotes cane biomass yield (t cane ha⁻¹), S_r is the recoverable sucrose fraction, R_h is the fraction of recoverable sugar retained between harvest and milling, and R_m is the factory recovery fraction. The multiplicative form is analytically important because weakness at any stage reduces the value created by improvements elsewhere. A substantial increase in cane biomass, for example, will not translate proportionally into marketable sugar if sucrose concentration deteriorates during delayed transport or if factory recovery remains low.

The contemporary scientific literature strongly supports a multidimensional explanation of sugarcane productivity. Genetic improvement determines attainable yield and sugar concentration; genotype × environment interaction influences how varieties perform under different water regimes; irrigation and drought exposure affect canopy development and stalk growth; nutrient management determines biomass formation and environmental efficiency; repeated ratooning can progressively lower yields; pests and diseases reduce both biomass and sugar accumulation; heavy machinery may increase operational efficiency while simultaneously compacting soils; and post-harvest delays reduce sucrose recovery (Natarajan et al., 2020; Mohanraj et al., 2021; Dlamini and Zhou, 2022; Misra et al., 2022; Lu et al., 2024; Bao et al., 2024; Mehdi et al., 2024).

Recent technological developments expand the range of possible interventions. Satellite imagery and machine-learning algorithms can forecast sugarcane yield months before harvesting, UAV systems can detect spatial variation within fields, hyperspectral sensors can identify disease before visual symptoms become apparent, and precision management can allocate water, fertilizer, machinery, and harvesting capacity more efficiently (Canata et al., 2021; Luciano et al., 2021; Shendryk et al., 2021; Bao et al., 2024; Som-ard et al., 2024a).

Indonesia also faces an institutional productivity problem. Empirical studies among Indonesian sugarcane farmers show that technical efficiency varies considerably and is influenced by irrigation, training, seed variety, partnerships, financing, land conditions, farmer characteristics, and organizational participation. Credit constraints are associated with weaker productivity and technical efficiency, while partnerships and irrigation can materially influence outcomes (Rosidah et al., 2023; Maharani et al., 2024; Santosa et al., 2024).

Against this background, this article asks: **How can Indonesia close its sugar-yield gap through an integrated farm-to-mill productivity transformation?** Supporting questions examine the respective contributions of genetics, water, soil fertility, ratoon management, mechanization, digital agriculture, harvest logistics, milling, farmer efficiency, financing, and institutional coordination.

The article pursues four principal objectives. First, it develops a clearer conceptual distinction between cane yield and realized sugar yield. Second, it synthesizes post-2020 evidence on the principal biological, agronomic, technological

and institutional causes of sugarcane productivity gaps. Third, it assesses which lessons from major producing systems are conditionally transferable to Indonesia. Fourth, it develops an integrated and sequenced farm-to-mill transformation architecture. The article's contribution is therefore not another single-factor explanation of low productivity, but a framework that connects field performance, post-harvest retention, mill recovery and enabling institutions within one analytical system.

LITERATURE REVIEW

From Cane Yield to Realized Sugar Yield

Yield-gap analysis distinguishes potential yield, water-limited yield, and actual farm yield. Applied to sugarcane, this approach allows analysts to identify fields in which large productivity gaps occur and to diagnose whether they arise from establishment failure, nutrient limitations, pests, water shortages, or management constraints. Gasparotto et al. (2022), for example, demonstrated that combining crop simulation with field-level measurements can identify both the magnitude and causes of productivity gaps in commercial sugarcane operations. For the Indonesian sugar industry, however, a second level of decomposition is needed. The economically relevant outcome is not simply tonnes of stalk biomass but tonnes of sugar extracted from each hectare. Sugar yield therefore depends partly on crop yield and partly on technological quality. Research on varietal improvement demonstrates that breeding can increase sucrose concentration, juice quality and purity even when biomass effects are considered separately (Zhao et al., 2022). Harvest timing also changes Brix, sucrose, fiber and processing characteristics, illustrating why harvesting decisions form an integral component of productivity rather than merely a logistical activity (Tischler et al., 2021).

Post-harvest deterioration adds another layer. Once sugarcane is cut, biological and microbial processes begin reducing recoverable sucrose. Delayed transport and crushing can increase invert sugars, dextran formation and processing difficulties, reducing factory recovery. Misra et al. (2022) therefore emphasize minimizing delays between harvest and milling as a critical sugar-preservation strategy.

This distinction has important analytical and managerial consequences. Raising tonnes of cane per hectare while leaving sucrose concentration, transport performance or extraction efficiency unchanged may produce only modest gains in realized sugar yield. Conversely, better maturity-based harvesting, shorter cut-to-crush intervals and stronger factory recovery can increase sugar output even before major biological yield gains are achieved. The relevant performance frontier is therefore recoverable sugar per unit of land, supported by diagnostic indicators for each stage of the chain.

Genetics, Varieties and the Productivity Frontier

Sugarcane is genetically complex, highly polyploid and characterized by relatively long breeding cycles. Nevertheless, varietal improvement remains one of the most fundamental determinants of attainable productivity. Modern breeding increasingly integrates conventional crossing with molecular markers, genomic

tools, high-throughput phenotyping, gene editing, remote sensing and artificial intelligence (Lu et al., 2024).

Evidence from China shows that successive generations of improved commercial varieties have increased sucrose concentration, juice sugar and purity, demonstrating that genetic gain can directly improve the conversion of land into recoverable sugar (Zhao et al., 2022). Physiological evidence likewise shows meaningful genotypic variation in traits associated with transpiration efficiency and yield under irrigated and rainfed conditions (Natarajan et al., 2021).

The breeding objective for Indonesia should therefore not be defined as “high cane yield” alone. Desired cultivars require multiple traits: high biomass production, high recoverable sucrose, disease resistance, tolerance to water deficit or excess water, ratooning ability and compatibility with local harvesting conditions. Recent reviews of sugarcane breeding and crop improvement also emphasize that modern varietal portfolios should combine genetic gain with clear adaptation to regional production environments and management systems (Desalegn et al., 2023; Lu et al., 2024).

Water, Drought and Climate Resilience

Water availability is among the most important constraints on sugarcane productivity. Experiments across irrigation regimes show substantial reductions in cane yield under rainfed or water-deficit conditions, although genotypes vary in their response (Natarajan et al., 2020). Research involving commercial and Erianthus-introgressed germplasm similarly demonstrates that drought changes dry-matter partitioning and can reduce both cane and sugar yield (Mohanraj et al., 2021).

The timing of water stress also matters. Research in Guangxi indicates particularly high vulnerability during stem elongation, when crop water requirements are substantial and drought can materially affect yield (Qin et al., 2023). Climate simulation studies further suggest that increasing temperatures can raise crop water requirements while depressing yields in some production environments (Verma et al., 2023; Guhan et al., 2024).

Water policy should consequently focus not only on increasing irrigated area but also on irrigation efficiency. Genotypic selection for water-use efficiency, deficit-irrigation strategies, soil-moisture monitoring and improved drainage in waterlogged locations all have a role to play. Recent field studies further indicate that differences in genotype-level water-use efficiency and deficit-irrigation responses can be translated into higher recoverable sugar per unit of water when agronomy and variety choice are coordinated (Natarajan et al., 2021; Khonghintaiong et al., 2024; Barbosa et al., 2024).

Soil Health, Nutrient Management and Circularity

Sugarcane is a high-biomass crop with substantial nutrient requirements. Yet higher fertilizer application does not automatically imply higher productivity. Research from China demonstrates that excessive nitrogen can generate large reactive-nitrogen losses without corresponding yield benefits; substantially reduced nitrogen rates maintained yields while reducing environmental losses in field experiments (Yang et al., 2024).

Similar evidence emerges from fertilization studies in Brazil, where alternative organo-mineral formulations and inhibitors altered ammonia volatilization, nitrous-oxide emissions and crop performance (Oliveira et al., 2023). Integrated nutrient management combining inorganic fertilizers with organic sources can increase yield, profitability and soil-resource sustainability, although results depend on soil and management context (Arefin et al., 2022).

Long-term sustainability additionally creates opportunities to integrate by-products and biological inputs. Sugarcane/soybean intercropping has demonstrated the potential to improve system productivity while lowering the carbon footprint of nutrient use, and integrated nutrient management can raise both productivity and cane quality when nutrient application is aligned with crop demand (Wang et al., 2020; Arefin et al., 2022). Recent work on trash management, rhizosphere biology and bio-organic fertilizers also suggests that soil-biological strategies can complement mineral nutrition in more sustainable intensification pathways (Shukla et al., 2022; Chen et al., 2025).

Future nutrient efficiency may increasingly combine agronomy with genetics. Recent synthesis identifies substantial scope for improving nutrient-use efficiency through root traits, transport mechanisms and stress-tolerance pathways, while biochar-based and organo-mineral fertilizer strategies show promise for improving nutrient activation and soil physical condition under sugarcane systems (Krishnapriya et al., 2026; Zhu et al., 2025).

Ratoon Management and Field Longevity

Sugarcane is commonly ratooned because regrowth reduces replanting costs. However, repeated ratooning can generate declining yields when plant populations deteriorate, root systems weaken, soil conditions worsen, pests or diseases accumulate, or harvesting damages stools.

Long-term commercial evidence demonstrates that ratoon yield decline interacts strongly with soil type and harvest season (Dlamini and Zhou, 2022). Indonesian evidence similarly indicates meaningful differences between plant cane and ratoon production systems and suggests that field rejuvenation decisions have significant implications for productivity (Ridwan et al., 2022; Ariyanto et al., 2023).

Ratoon decline is also biologically connected to the soil microbiome. Consecutive ratooning can modify rhizosphere bacterial community structure, with possible consequences for nutrient cycling and plant health (Khan et al., 2022). Trash management and *Trichoderma* application have been associated with improvements in photosynthesis, soil carbon and ratoon productivity under particular production conditions (Shukla et al., 2022).

The evidence therefore supports a shift from fixed replanting rules toward field-specific ratoon economics. A ratoon should be retained when its expected net return and yield trajectory remain competitive with renewal, rather than simply because replanting is costly. Combining yield histories with stand density, disease status, soil condition and predicted sugar content would make renewal decisions more evidence-based and reduce avoidable productivity decline.

Pest, Disease and Biological Productivity Losses

Sugarcane smut is a globally important disease capable of reducing crop productivity and profitability. Resistant varieties remain one of the most effective

control options, but complex sugarcane genetics makes resistance breeding challenging (Bhuiyan et al., 2021).

Climate change may alter pest and disease pressure, reinforcing the importance of integrated adaptation rather than stand-alone pesticide strategies (Msomba et al., 2024). Modern sensing can materially improve surveillance, as hyperspectral imaging and deep-learning approaches are increasingly capable of detecting sugarcane smut and mosaic symptoms at early stages before severe field losses occur (Bao et al., 2024).

Mehdi et al. (2024) emphasize that sugarcane yield and sucrose accumulation arise from interacting environmental, physiological and biological processes. This reinforces the argument that disease management should be incorporated into overall productivity architecture rather than treated as a separate plant-protection issue.

Mechanization and the Soil-Compaction Trade-off

Mechanization is essential where rural labor is scarce or expensive, but sugarcane harvesting involves unusually heavy machinery. This produces a central trade-off: mechanization can raise labor productivity while degrading the soil resource that supports future ratoons.

Numerical analysis shows that harvesting vehicles can transmit substantial stress deep into the soil profile and reduce porosity (Jimenez et al., 2021). Controlled-traffic experiments indicate that permanent traffic lanes and automatic steering can protect the crop row from some physical degradation (Esteban et al., 2020; Luz et al., 2023).

More recent research identifies transportation operations involving tractors and trailers as particularly important sources of compaction and subsequent yield loss. Field evidence from mechanized harvesting indicates that the tractor-trailer set can be the critical operation for soil degradation and that repeated traffic can restrict root development and reduce yield in subsequent cycles (Delmond et al., 2024; Esteban et al., 2024).

Mechanization should therefore not be treated simply as the replacement of labour with machinery. Field geometry, row spacing, tyre configuration, soil moisture, controlled-traffic lanes, harvest scheduling and service-provider business models must be designed as an integrated operating system. Without that systems perspective, gains in labour productivity can be offset by compaction, stool damage and shorter ratoon longevity.

METHODOLOGY

This study adopts a qualitative, integrative literature review (QLR) designed to synthesize mechanisms and relationships across disciplinary boundaries rather than to estimate a pooled effect size. The approach is appropriate because the productivity problem spans agronomy, genetics, plant physiology, soil science, water management, agricultural engineering, remote sensing, supply-chain management, agricultural economics, economic history and institutional analysis. Consistent with contemporary guidance on literature-review design, the objective is conceptual integration and framework development rather than exhaustive enumeration of all available studies (Paul and Criado, 2020).

Literature identification was purposive and iterative, with priority given to peer-reviewed journal articles published from January 2020 to September 2026. Search combinations included sugarcane, sugar yield, yield gap, sucrose, ratoon decline, irrigation, drought, nitrogen, soil, mechanized harvesting, soil compaction, remote sensing, artificial intelligence, machine learning, post-harvest deterioration, supply chain, technical efficiency, Indonesia and Thailand. Earlier evidence was used only when required to interpret the historical productivity benchmark; the analytical core of the review remains anchored in recent literature.

Study selection emphasized direct relevance to the farm-to-mill productivity problem, methodological transparency, publication in established peer-reviewed outlets and the usefulness of the reported mechanisms for Indonesian conditions. Indonesia-specific empirical studies were prioritized for farmer efficiency, credit, partnerships and institutional constraints, while evidence from Brazil, Australia, China, Thailand, India, Southern Africa and other producing regions was used to examine mechanisms that may be transferable across production systems.

Evidence was coded into nine thematic domains: genetic productivity; water and climate; soil and nutrient management; ratoon dynamics; pests and diseases; mechanization; precision and digital agriculture; harvest-logistics-milling performance; and institutional efficiency. Within each domain, findings were compared for convergence, divergence and causal mechanism. The synthesis then examined interactions among domains, particularly where an intervention at one stage could amplify or constrain outcomes elsewhere in the farm-to-mill chain.

International findings were interpreted through the principle of conditional transferability rather than assumed to apply mechanically to Indonesia. Evidence was considered more transferable when the underlying production constraint, farm structure or environmental mechanism resembled Indonesian conditions, and less transferable when outcomes depended strongly on distinct land tenure, capital intensity, climate, field scale or industrial organization. This distinction is especially important when translating mechanization, precision-agriculture and irrigation evidence from large commercial systems to smallholder-dominated landscapes.

The review is intentionally qualitative and does not claim exhaustive coverage, formal risk-of-bias scoring or statistical aggregation; accordingly, no PRISMA flow counts are reported. Its principal limitation is that the evidence base is heterogeneous in geography, scale and research design. Analytical robustness is instead pursued through explicit thematic coding, triangulation across disciplines and cautious interpretation of transferability. Historical evidence is treated as contextual evidence of a productivity frontier and organizational capability, not as a prescription for reproducing colonial institutions (Tegegn and Dhont, 2023).

RESULTS

Finding 1: Indonesia Does Not Have One Sugar Yield Gap but Four Interlocking Gaps

The literature indicates that the phrase “low sugarcane productivity” conceals several distinct problems. At minimum, four interlocking performance gaps should be distinguished. The first is a biomass gap, represented by tonnes of cane produced per hectare. The second is a quality gap, represented by sucrose concentration and

recoverable sugar content. The third is a retention gap, representing losses between harvest and processing. The fourth is an extraction gap, representing the ability of the mill to recover sugar contained in delivered cane.

Figure 1 translates this finding into a farm-to-mill productivity chain. The figure should be read as a multiplicative rather than additive model because productivity losses at one stage reduce the value created by improvements elsewhere. This explains why interventions focused only on cane tonnage may fail to generate proportional growth in national sugar output.



Figure 1. Farm-to-Mill Decomposition of Realized Sugar Yield

Source: Author synthesis based on Gasparotto et al. (2022), Misra et al. (2022), Tischler et al. (2021), Zhao et al. (2022) and Teixeira et al. (2023).

The implication is substantial. A field yielding 80 tonnes of cane per hectare can generate less recoverable sugar than a 70-tonne field if sucrose concentration, post-harvest retention or mill recovery is sufficiently lower. Productivity monitoring should therefore treat recoverable sugar per hectare as the strategic outcome while retaining cane yield, sucrose content, cut-to-crush losses and recovery as diagnostic indicators for identifying where the gap originates.

4.2 Finding 2: Genetics Determines the Ceiling, but Management Determines How Much of It Is Realized

Genetic potential establishes the biological ceiling available to farmers. Modern breeding can improve yield, sugar concentration, disease resistance, water-use characteristics, ratooning ability and harvest suitability. Yet realized performance depends on whether the chosen genotype is matched with local environment and management conditions. This helps explain why varietal recommendations should be location-specific and empirically validated under real production conditions (Desalegn et al., 2023; Lu et al., 2024).

This means that Indonesia requires geographically differentiated varietal portfolios rather than a narrow nationwide strategy based on a limited number of cultivars. Varieties for irrigated East Java need not be identical to those best suited to drier or newly expanded production regions. Breeding programs should also incorporate factory-relevant traits because high biomass accompanied by weak sucrose concentration may not improve industrial competitiveness.

Aerial phenotyping, remote sensing and smart breeding can accelerate this process. UAV-derived vegetation indices and thermal characteristics can help identify high-performing and drought-resilient genotypes earlier in breeding programs, while genomic and information technologies may shorten selection cycles (Shailesh et al., 2024; Lu et al., 2024).

Finding 3: Water Management Is Both an Agronomic and an Efficiency Problem

Water shortages reduce canopy development, stalk elongation and biomass accumulation, especially when drought coincides with critical growth stages. Natarajan et al. (2020) documented substantial yield reductions under rainfed relative to fully irrigated conditions, while Qin et al. (2023) identified the stem-extension phase as particularly sensitive to drought.

Indonesia's productivity strategy should therefore not be framed simply as an expansion of irrigation infrastructure. The economically relevant objective is higher and more stable sugar output per unit of water. Evidence on genotypic variation and deficit irrigation indicates that limited water can be managed more strategically when variety choice, soil-moisture monitoring, irrigation scheduling and drainage are coordinated (Khonghintaisong et al., 2024; Barbosa et al., 2024).

This issue is increasingly important under climate change. Crop simulations suggest that warming may increase crop water requirements and depress yields, depending on location and management conditions, while variety-specific modelling indicates that climate effects can differ substantially across genotypes and production environments (Qin et al., 2023; Guhan et al., 2024; Verma et al., 2023).

Finding 4: High Fertilizer Use Is Not Equivalent to High Productivity

A recurring lesson from recent international research is that poor nutrient management can simultaneously reduce profitability and increase environmental pressure. Yang et al. (2024) found that substantial reductions in nitrogen input could maintain high sugarcane yields while sharply reducing reactive-nitrogen losses in a high-input production system. Oliveira et al. (2023) similarly show that fertilizer formulations alter both crop performance and emissions.

For Indonesia, nutrient policy should consequently move from generalized recommendations toward soil testing and site-specific nutrient management. Organic resources—including filter cake, compost, trash and other mill by-products—may become part of a circular nutrient strategy where agronomically appropriate. Arefin et al. (2022), Shukla et al. (2022), Zhu et al. (2025) and Chen et al. (2025) collectively indicate opportunities to combine productivity, soil health and biological functions rather than treating fertilizer decisions solely as N-P-K application problems.

Krishnapriya et al. (2026) add a longer-term perspective by highlighting plant-level nutrient-use efficiency as a breeding and physiological target. Consequently, the future productivity frontier depends not merely on supplying more nutrients but on increasing the proportion captured and converted into recoverable sugar.

Finding 5: Ratoon Decline Is a Structural but Manageable Source of Lost Production

Successive ratooning creates cost savings because fields do not need to be completely replanted after every harvest. Nevertheless, the productivity advantages decline when stools are damaged, plant populations thin, weeds or diseases become

established, roots encounter compacted soil, or nutrient and water conditions deteriorate.

Commercial evidence from Eswatini confirms significant ratoon yield decline associated with soil quality, crop age and harvest timing (Dlamini and Zhou, 2022). Studies of Indonesian ratoon production likewise point to the importance of residue, fertilizer and field-management decisions (Ridwan et al., 2022; Ariyanto et al., 2023).

The appropriate solution is not universal annual replanting. Instead, Indonesia requires a **ratoon-renewal decision system** combining yield histories, stand density, disease status, soil condition, predicted sugar content and replanting economics. Fields whose productivity has fallen below an economically justified threshold should be rejuvenated with high-quality planting material.

Finding 6: Mechanization Must Be Designed around Soil Protection

Labour constraints will make mechanization increasingly important, but poorly designed mechanization can shift productivity problems rather than solve them. Heavy harvest and transport equipment can compress soil, restrict rooting and reduce future ratoon productivity (Jimenez et al., 2021; Delmond et al., 2024).

Controlled traffic, automatic steering and permanent wheel lanes can concentrate machinery movement in designated areas, protecting crop rows and improving soil physical functionality (Esteban et al., 2020; Luz et al., 2023). Transport vehicle configuration is equally important because trailers and trucks can impose substantial subsoil stresses (Esteban et al., 2024).

Thailand offers an important institutional lesson. The main obstacle to mechanization is not solely engineering. Capital cost, credit terms, machine utilization rates, field size and service access strongly shape adoption. Choice-experiment research shows that financing conditions and incentives influence farmers' willingness to use mechanized harvesting (Mahasuweerachai and Suksawat, 2022).

The evidence therefore supports contractor-based, cooperative or mill-coordinated machinery services rather than universal individual ownership by smallholders. A service-based model can spread capital costs, raise machine-utilization rates and make controlled-traffic principles more feasible in fragmented production landscapes, provided field access, scheduling and quality incentives are coordinated.

Finding 7: Digital Agriculture Can Make Yield Gaps Visible

One of the most significant developments in the recent literature is the rapid improvement of remote-sensing-based sugarcane monitoring. Canata et al. (2021) demonstrated the use of high-resolution imagery and machine learning for sugarcane yield mapping. Shendryk et al. (2021) integrated satellite, climate and environmental information to forecast cane and sugar yields in Australia. Luciano et al. (2021) combined Landsat imagery, agronomic variables and meteorological data to generate local-scale yield forecasts in Brazil.

Later work strengthened these capabilities. Dimov et al. (2022) used Sentinel-2 time-series and phenological metrics; Das et al. (2023) combined optical and radar information through ensemble machine learning; Zhu et al. (2023) integrated Sentinel-1 and Sentinel-2 information for high-resolution yield prediction.

Thailand demonstrates the relevance of these technologies to smallholder-dominated Asian production systems. Som-ard et al. (2024a) integrated UAV and Sentinel-2 information to estimate yield across multiple spatial scales, while Som-ard et al. (2024b) evaluated multi-temporal Sentinel and Landsat data with machine-learning models in smallholder conditions.

Digital agriculture is valuable not because satellite maps themselves produce sugar but because they allow managers to locate productivity losses earlier, target interventions and coordinate harvesting with milling capacity. Figure 2 summarizes this information-to-action cycle.

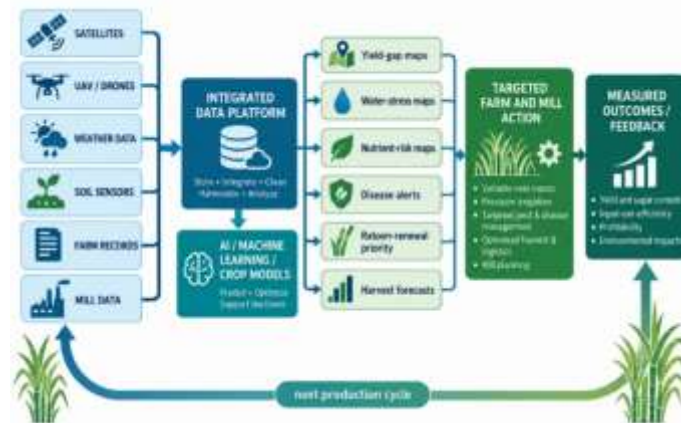


Figure 2. Digital Productivity Management Loop for Sugarcane

Source: Author synthesis based on Canata et al. (2021), Shendryk et al. (2021), Luciano et al. (2021), Dimov et al. (2022), Das et al. (2023), Zhu et al. (2023), Som-ard et al. (2024a, 2024b) and Bao et al. (2024).

Figure 2 also illustrates why farm and factory databases should not remain disconnected. Mill recovery information can be linked with individual delivery lots and ultimately with fields, varieties, harvest dates and agronomic practices. Over time, such integration can reveal whether low sugar recovery originates from specific cultivars, immature harvesting, long queueing times, poor transport, or processing conditions.

Finding 8: The Harvest-to-Mill Interface Is an Underestimated Productivity Frontier

Sugarcane is biologically perishable after harvest. Misra et al. (2022) document rapid post-harvest deterioration and the associated decline in sucrose and processing quality. Consequently, excessive cut-to-crush times convert potential sugar into avoidable losses.

The problem cannot be solved solely by requiring farmers to deliver cane quickly. Harvesting schedules, truck fleets, road conditions, mill queues, crushing capacity and factory reliability must be synchronized. Mathematical optimization studies show that sugarcane supply chains can coordinate harvesting, transport and processing decisions to reduce waiting time and improve the matching of cane supply with mill capacity (Teixeira et al., 2023).

Harvest maturity presents another coordination issue. Tischler et al. (2021) show that technological quality differs substantially with harvest timing. A mill that requires continuous feed may therefore face a conflict between maximizing capacity utilization and processing cane at physiologically optimal maturity.

This suggests that mill modernization should include not only crushers, boilers and process equipment, but also **digital cane-supply orchestration**. The factory gate should become the end point of an integrated production-information system beginning at the field.

Finding 9: Institutional Efficiency Determines Whether Technology Is Adopted

Indonesian evidence is particularly important here. Rosidah et al. (2023) report variation in technical, allocative and economic efficiency among sugarcane partner farmers, with managerial characteristics affecting performance. Maharani et al. (2024), using a much larger farmer dataset, find that credit constraints negatively affect productivity and technical efficiency and that land characteristics, seed varieties, cooperatives and partnerships matter.

Santosa et al. (2024) similarly find differences in technical efficiency between irrigated and rainfed sugarcane farming in East Java, with irrigation access, training and support factors associated with efficiency outcomes.

Technology policy that ignores these institutional constraints will underperform. A high-yield variety has little value if farmers cannot afford clean planting material. Drip irrigation cannot scale without finance and water governance. Harvesters cannot efficiently operate in fragmented fields without coordination. Yield maps provide little benefit when extension systems cannot translate them into decisions.

DISCUSSION

Reinterpreting the Historical 4.7-versus-14.7 Productivity Narrative

The historical comparison motivating this article should neither be dismissed nor taken literally. Its value is diagnostic. It demonstrates that the contemporary Indonesian sugar sector operates far below a historically observed productivity frontier expressed in sugar output per hectare.

Nevertheless, historical Java represented a highly selected and institutionally integrated production system rather than a directly comparable national average. Tegegn and Dhont (2023) emphasize the historically important position of the Java sugar economy, its international competitiveness and the combination of domestic and international factors that later contributed to decline.

The transferable historical lesson is therefore organizational capability. High productivity required coordinated research, varieties, agronomy, water control, harvesting, factory processing and logistical discipline. In modern terminology, historical Java possessed a relatively integrated **farm-to-factory innovation system**.

Contemporary Indonesia should reconstruct that integration without reconstructing the colonial institutional order. The relevant modern equivalents are smallholder-inclusive partnerships, transparent cane-quality measurement, digitally coordinated logistics, independent research capacity, accessible credit, sustainable soil management, environmentally responsible irrigation and performance-based incentives.

From a Single Benchmark to a Productivity Ladder

A national productivity target can mobilize attention, but a single headline number should not substitute for diagnosis. The same realized sugar yield can arise from very different combinations of biomass, sucrose concentration, post-harvest

retention and mill recovery, implying different corrective actions across regions and mills.

A more robust approach is a productivity ladder anchored in locally attainable performance. Low-performing fields should first be compared with agronomically similar local benchmarks to identify exploitable gaps. Intermediate performers can then adopt precision management, improved varieties and stronger harvest coordination, while high-performing areas can serve as learning sites for advanced irrigation, digital agriculture and high-recovery production. This differentiated approach is more consistent with spatial yield-gap diagnosis than a uniform national prescription.

This strategy is consistent with the yield-gap approach proposed by Gasparotto et al. (2022): the size and causes of the gap should be diagnosed spatially rather than assuming every hectare suffers from identical constraints.

A New Farm-to-Mill Productivity Architecture

The principal synthesis of this review is shown in Figure 3. The figure presents the proposed Indonesian sugar-productivity architecture. The central argument is that no individual technology – whether superior seed, fertilizer, irrigation, mechanization, artificial intelligence or factory modernization – is sufficient when deployed independently.



Figure 3. Integrated Architecture for Closing Indonesia's Sugar Yield Gap

Source: Author Synthesis

The architecture changes the role of the sugar factory. Rather than acting only as a buyer and processor of cane, an efficient mill becomes a **regional productivity orchestrator**. Because a mill already aggregates cane from a defined catchment, it can potentially coordinate variety planning, planting schedules, harvest dates, extension, machinery services, yield mapping, quality testing and transportation. Farmer autonomy need not disappear within such a system. Indeed, transparent contracts and quality-based remuneration could strengthen incentives. Farmers who produce high-sucrose cane and deliver it under conditions that preserve recoverable sugar should receive signals reflecting the greater value of that cane.

Sequencing the Transformation: Foundational Agronomy before Advanced Digitalization

Advanced technologies are attractive because they promise rapid gains in information and control. Their value, however, depends on the quality of the

agronomic system they are intended to manage. Sensors, UAVs and predictive models cannot compensate for poor planting material, severe soil degradation, uncontrolled disease or major water-management failures; digital capability should therefore be layered onto a functioning biological production base.

The first phase should therefore address foundational yield constraints: certified or high-quality planting material, varietal replacement, drainage and irrigation rehabilitation, soil testing, balanced nutrients, pest and disease management, and field-specific ratoon renewal. The second phase should improve operational efficiency through machinery services, controlled traffic, harvest scheduling, improved roads and shorter cut-to-crush time. The third phase should digitize the integrated system through georeferenced field registries, satellite monitoring, UAV-based diagnostics, AI-supported yield prediction, digital harvest scheduling and field-to-mill traceability. The fourth phase should develop advanced breeding and decision systems integrating genomic, phenotypic, environmental and commercial data. This sequencing prevents a common policy mistake: purchasing advanced technology before the institutional capability required to use it effectively has been developed.

Thailand Offers Useful but Conditional Lessons

Thailand provides a useful regional comparator because both countries combine commercial processing with large numbers of small and medium sugarcane producers. The comparison is most informative when it focuses on mechanisms – such as machinery-service markets, remote sensing and harvest incentives – rather than assuming that national yield outcomes are directly transferable.

First, remote sensing research demonstrates that high-resolution yield monitoring can be adapted to relatively fragmented sugarcane landscapes (Som-ard et al., 2024a, 2024b). Second, mechanization experience shows that machine adoption depends heavily on financing and service arrangements rather than technical availability alone (Mahasuweerachai and Suksawat, 2022). Third, the Thai experience illustrates the interaction between harvesting practices, environmental policy and mill incentives.

Direct replication of Thai practices would nevertheless be inappropriate. Indonesia differs in rainfall distribution, land fragmentation, road infrastructure, factory geography, land tenure and institutional arrangements. Comparative evidence should therefore be used to identify transferable mechanisms and enabling conditions rather than to import a complete production model.

Productivity Growth Must Be Environmentally Sustainable

An effort to close the yield gap through indiscriminate fertilizer, water or machinery use could create new problems. Recent nitrogen studies clearly demonstrate that large fertilizer inputs can generate substantial pollution costs and that yield gains can often be sustained with more efficient nutrient strategies (Yang et al., 2024; Oliveira et al., 2023). Research on controlled traffic and soil physical quality also shows that productivity-enhancing mechanization must be designed to protect, rather than degrade, the resource base (Luz et al., 2023; Esteban et al., 2024).

Sustainable intensification should therefore measure output relative to critical resources. Relevant performance indicators include tonnes of sugar per hectare, kilograms of sugar per unit nitrogen, kilograms of sugar per cubic metre of irrigation

water, energy use per tonne of sugar, and greenhouse-gas emissions per tonne of sugar.

This approach converts sustainability from an external constraint into a productivity strategy. Efficient nutrient use reduces fertilizer costs. Better water productivity protects output during drought. Controlled traffic protects future ratoons. Trash retention and appropriate organic amendments may protect soil carbon. Disease-resistant varieties can reduce crop losses and potentially reduce pesticide requirements.

Service-Based Integration for Smallholders

A substantial proportion of Indonesian sugarcane is associated with smallholder production. Expecting every grower to independently purchase precision-irrigation systems, UAVs, harvesters or sophisticated software would be economically unrealistic.

The appropriate institutional unit may therefore be the service platform rather than the individual farm. Cooperatives, mills, contractors and specialized agricultural-service firms can aggregate demand for machinery, drone mapping, soil testing, clean planting material, finance facilitation and crop advisory services. Such arrangements can lower fixed costs and information barriers while allowing smallholders to access technologies that would be uneconomic to own individually.

Maharani et al. (2024) demonstrate why finance matters: credit constraints reduce both productivity and technical efficiency. Rosidah et al. (2023) and Santosa et al. (2024) show that farm-management and institutional variables affect efficiency. The objective should therefore be to reduce the transaction costs confronting farmers when adopting productivity-enhancing technology. **A Sequenced Transformation Roadmap** Figure 4 converts the review findings into a sequenced implementation roadmap. The timeline is conceptual rather than a rigid national schedule because starting conditions differ among sugar regions.



Figure 4. Sequenced Roadmap for Closing Indonesia's Sugar Yield Gap

Source: Author Synthesis

The phases are intentionally overlapping rather than strictly sequential. Digital field registration, for example, can begin while agronomic rehabilitation is under way, and logistics optimization can proceed while breeding programs are

being strengthened. The sequencing principle is that advanced analytics should reinforce – rather than distract from – basic agronomic capability and reliable farm-to-mill operations.

Recommended Performance Dashboard

National monitoring should separate at least six groups of indicators. Field indicators should include cane t ha⁻¹, plant population, ratoon age, irrigation status and nutrient performance. Quality indicators should track Brix, Pol or comparable sucrose-quality measures and recoverable sugar. Logistics indicators should include harvest-to-delivery time, mill queue time and transport distance. Factory indicators should cover extraction efficiency, overall recovery, downtime and energy efficiency. Economic indicators should include cost per tonne of cane, cost per tonne of sugar, farmer margin and mill margin. Sustainability indicators should include water productivity, nitrogen-use efficiency, soil condition and emissions intensity. A policy system based only on national cane tonnage can conceal deterioration in sugar content, recovery, profitability or sustainability.

CONCLUSION

Indonesia's sugar productivity challenge is fundamentally a systems problem. Historical evidence is valuable because it demonstrates that high sugar output per unit of land has been achieved in Java, but the historical benchmark should be interpreted as a productivity frontier rather than as a mechanically transferable target. Contemporary performance must instead be understood through the interacting constraints that determine how much recoverable sugar is ultimately produced from each hectare.

The synthesis shows that realized sugar yield emerges from a chain extending from genetics and crop establishment to factory recovery. Varieties and planting material shape biological potential; soil, nutrients and water determine how much of that potential is expressed; ratoon, pest and disease management influence persistence across cycles; mechanization affects both operational efficiency and soil condition; harvest and transport determine how much sucrose is preserved; and factory performance determines how much of the remaining sucrose becomes marketable sugar. Weakness at any stage can therefore dilute gains achieved elsewhere.

Consequently, closing the yield gap requires a sequenced farm-to-mill transformation rather than a single intervention. The near-term priority is to strengthen foundational agronomy through location-appropriate varieties, clean planting material, ratoon renewal, soil and nutrient management, water control and integrated crop protection. Operational integration should then reduce compaction, improve harvest scheduling, shorten cut-to-crush time and strengthen factory reliability. Digital monitoring and advanced breeding can subsequently increase precision, learning and resilience once the underlying production system is capable of acting on the information they generate.

The central implication is that Indonesia's sugar frontier will move upward only when farms, logistics, mills and enabling institutions improve together. Historical experience demonstrates the importance of coordinated research and disciplined farm-factory integration; contemporary technology expands the tools

available to achieve those functions under more inclusive and sustainable conditions. A successful productivity strategy should therefore be judged not by a single cane-yield target, but by durable increases in recoverable sugar per hectare, resource-use efficiency, farmer profitability and system resilience.

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