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Closing Indonesia's Sugar Productivity Gap: An Integrated Farm-To-Mill Intensification Strategy for Sustainable Sugar Self-Sufficiency Without Premature Land Expansion—A Review

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A R T I C L E I N F O

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A B S T R A C T

Indonesia's pursuit of sugar self-sufficiency confronts interconnected challenges involving sugarcane productivity, sucrose recovery, industrial efficiency, smallholder competitiveness, and land-use sustainability. This qualitative literature review critically synthesises research published between 2020 and 2026 to examine how integrated agricultural and industrial interventions can improve recoverable sugar production without excessive reliance on agricultural expansion. The review combines agronomic, technological, institutional, environmental, and value-chain perspectives and develops an Integrated Farm-to-Mill Sugar Productivity and Self-Sufficiency Framework. Its thematic synthesis identifies six mutually reinforcing intervention domains: varietal improvement and ratoon management; soil, nutrient, and water optimisation; precision agriculture; harvesting and logistics; milling modernisation; and farmer-centred innovation governance. Illustrative production scenarios demonstrate that simultaneous improvements in cane yield and sugar recovery can substantially increase output per hectare, although ambitious targets remain conditional on location-specific feasibility, financing, and operational performance. The review further distinguishes self-sufficiency in household-consumption sugar from the broader requirements of industrial sugar markets. It argues that an intensification-first strategy, complemented by targeted industrial investment, transparent recovery measurement, environmental safeguards, and appropriate institutional incentives, provides a more coherent development pathway than expansion-led production growth alone

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INTRODUCTION

Indonesia's sugar economy illustrates the difference between expanding agricultural production and creating an efficient food-processing system. Sugarcane is simultaneously a biological crop, a bulky and perishable industrial feedstock, an important source of farm income, and a possible foundation for bioenergy and biobased manufacturing. Consequently, cane harvested per hectare does not fully describe sectoral performance. The economic objective is to generate more recoverable, marketable sugar from each hectare while limiting avoidable losses, maintaining soil and water resources, and distributing productivity gains across farmers and mills. Studies of sugarcane yield formation and agronomic sustainability increasingly reveal how strongly these objectives interact (Mehdi et al., 2024; Wakchaure et al., 2025; Wang et al., 2026). The Indonesian context makes this distinction particularly consequential. The Ministry of Agriculture reported 2025 sugarcane production of approximately 39.07 million tonnes, a harvested area of 563,357 hectares, and white crystal sugar output of 2,668,075 tonnes. The resulting average cane productivity was about 69.35 tonnes per hectare, while reported sugar recovery, locally termed rendemen, was 6.83%. A mid-milling 2026 assessment projected 40.20 million tonnes of cane, 585,390 hectares and approximately 3.018 million tonnes of white crystal sugar, with reported recovery increasing to 7.51%. These 2026 figures are estimates, not an independently established final annual outcome, and other official statements used somewhat different coverage and forecast dates (Ministry of Agriculture of Indonesia, 2026a; Ministry of Agriculture of Indonesia, 2026b). The review therefore retains 2025 as its dated baseline and treats 2026 statistics as provisional observations rather than evidence of an accomplished structural transition. These numbers also expose a frequently neglected indicator problem. Dividing 40.20 million tonnes of cane by the approximately 585,390 hectares reported in the mid-season assessment yields around 68.67 tonnes of cane per hectare, slightly below the 2025 ratio, even though projected sugar output and recovery rise. Yield and industrial recovery can move in different directions. Similarly, a forecast surplus in white crystal sugar for direct consumption cannot be interpreted as comprehensive sugar independence when refined sugar and other industrial requirements remain substantial. Statements in 2026 distinguish approximately 2.8–2.9 million tonnes of household or consumption sugar requirements from approximately 3.8–3.9 million tonnes associated with industrial demand (Ministry of Agriculture of Indonesia, 2026b; Ministry of Agriculture of Indonesia, 2026c). A careful review must separate these markets and avoid comparing quantities with different product specifications. International experience demonstrates that improved genetics, ratoon longevity, reliable water management and nutrient efficiency can generate gains without proportional increases in land area. Yet mechanisms are strongly location dependent. Sugarcane breeding systems and long-term germplasm development in Brazil have supported recurrent genetic improvement, while evidence from India highlights irrigation management, soil constraints and subsoiling in multi-ratoon systems (Cursi et al., 2022; Dingre, 2023; Shukla et al., 2021). Indonesian studies of ratooning material and

production efficiency suggest that the country's priorities must be grounded in actual smallholder practices rather than inferred from average performance abroad (Ariyanto et al., 2023; Rosidah et al., 2023).

Industrial operations further complicate simplistic claims that sugar is produced entirely in the field. Sucrose is accumulated biologically in growing cane, but cutting, storage, transport, extraction, evaporation and crystallization determine how much of that potential is recovered as saleable sugar. Microbial deterioration and time-to-crush effects have measurable consequences, while optimised harvesting schedules must balance factory demand with farmers' access and logistical costs (Misra et al., 2022; Jarumaneeroj et al., 2021). Modernization therefore cannot substitute for agronomic improvements, but neither can greater cane tonnage compensate indefinitely for operational losses and unreliable industrial capacity. An additional policy tension concerns land expansion. Increasing area may be commercially rational in selected environments, but it carries water, carbon, biodiversity and tenure implications that must be evaluated against the alternative of raising output from established fields. Spatial studies of Brazilian sugarcane demonstrate that land-use emissions and hydrological impacts vary substantially across location and management conditions, while economic modelling indicates that expansion can dominate marginal supply responses under some market incentives (Duden et al., 2021; Guarenghi et al., 2023; Sant'Anna, 2024). These studies cannot be imported as numerical predictions for Indonesia, but they establish why expansion is not environmentally neutral. This article asks how Indonesia can close its recoverable-sugar productivity gap through coordinated interventions across agricultural, logistical, industrial and institutional stages. Its objectives are to synthesise contemporary evidence, differentiate robust findings from conditional claims, define a consistent productivity-accounting framework, examine potential output scenarios, and formulate a phased policy agenda. The central contribution is an Integrated Farm-to-Mill Sugar Productivity and Self-Sufficiency Framework (IFMSP-SF), in which biological productivity and industrial recovery are jointly shaped by innovation governance, farmer incentives and environmental constraints. Rather than presenting an unsupported forecast of national self-sufficiency, the review specifies what must be measured and tested before such a claim becomes defensible.

LITERATURE RIVIEW

1. Yield-Gap Theory and the Distinction Between Cane and Sugar Yield

A useful theoretical starting point separates potential yield under favourable conditions, attainable yield under local biophysical constraints, and observed yield under prevailing technology, inputs and institutions. For sugarcane, the difference between these quantities is especially sensitive to planting cycles, harvest age, ratoon number and variation in rainfall, temperature and soil conditions. Crop improvement consequently requires closing management gaps as well as genetic gaps. Evidence of contrasting yield decay across ratoon environments confirms that a single national productivity coefficient conceals distinct production trajectories (Resende et al., 2025; Islam et

al., 2023). Recoverable sugar yield is a more complete measure of integrated performance than cane biomass alone. A heavier crop does not necessarily yield more sugar if the proportion of extractable sucrose declines or mills lose a higher fraction during processing. Climate simulations in India have identified possible divergence between stalk fresh mass and sucrose mass under warming, emphasizing that crop weight and sugar formation should be monitored independently (Jaiswal et al., 2023; Guhan et al., 2024). Biological reviews likewise describe sucrose accumulation as the outcome of genetic, physiological and environmental interactions, not a stable percentage across all varieties or harvest dates (Mehdi et al., 2024; Krishnapriya et al., 2026). The practical implication is a hierarchy of indicators. At the field level, managers should measure cane tonnage, juice quality, recoverable sugar potential, input cost and water productivity. At the factory gate, they should measure delivered cane weight, sucrose or pol indicators, trash and extraneous matter, freshness, and quality-adjusted payments. At the mill, they should account for extraction, clarification, crystallisation, process losses and factory uptime. Only then can analysts explain variation in final sugar output without mistakenly attributing all differences to farm productivity (Misra et al., 2022; Zhou et al., 2024).

2. Sustainable Intensification as a Constrained Optimisation Problem

Sustainable intensification is often described as producing more from existing land, but this formulation is incomplete if additional output requires unsustainable irrigation, nitrogen inputs or energy use. The objective must instead consider multiple performance dimensions: sugar yield per hectare, profit per unit of output, water and nutrient productivity, greenhouse gas emissions, and impacts on soil quality. Studies from China show that high nitrogen rates do not necessarily increase yields proportionally and that management can reduce reactive nitrogen losses while sustaining crop performance (Yang et al., 2024; Yuan et al., 2025). Other analyses demonstrate that management packages combining nutrient optimisation with cultivation innovations can improve both economic and ecological outcomes (Wang et al., 2026; Zhu et al., 2026). The existence of trade-offs means that maximising cane tonnage is not the same as maximising social welfare. In Brazil, organomineral fertilisers and nitrification inhibitors produced differing outcomes for ammonia loss, nitrous oxide and yield across seasons, demonstrating that a practice beneficial for one endpoint may worsen another (Oliveira et al., 2023). Newer research similarly emphasizes optimising nitrogen to balance marginal yield response and environmental cost rather than prescribing universal rates (Moro et al., 2026; Yang et al., 2025). For Indonesia, the relevant research question is not simply whether inputs should increase or decrease, but how site-specific decisions alter economic and ecological outcomes under realistic adoption conditions.

3. Agricultural Innovation Systems and Institutional Coordination

Productivity technologies are not self-implementing. Their uptake depends on seed multiplication, extension quality, credit, secure marketing arrangements, trust in measurement, and the timing of cash outflows relative to harvest income. Indonesian research finds meaningful variation in contract-farming arrangements and the characteristics of participating growers, indicating that uniform intervention packages may produce uneven adoption and welfare effects (Hakim et al., 2024). Efficiency research among PTPN X partner farmers also identifies a need to understand how resources are allocated at farm level, rather than assuming that low yields always reflect lack of technical knowledge (Rosidah et al., 2023). Innovation-system theory therefore focuses on relationships among public research institutions, universities, mills, growers, equipment providers and financial intermediaries. Breeding institutions supply adaptive genetic material, but the rate of realized gain depends on validation, seed quality and distribution. Research on disease-resistance genetics and modern breeding illustrates substantial technical opportunity, although these methods require multi-location testing and years of institutional continuity before commercial deployment (Meena et al., 2020; Cursi et al., 2022; O'Connell et al., 2022). A viable strategy must strengthen translational capacity, not merely publish breeding results or purchase new machinery. A complementary Indonesian study of 8,831 sugarcane farm households identifies land tenure, farm area, certified seed, cooperative membership and extension access among the characteristics associated with participation in contract farming. The associations do not establish that contracts alone raise yields, but they demonstrate that adoption cannot be separated from farmer characteristics and institutional access. This reinforces the need for differentiated enrolment, transparent agreements and locally accessible advisory services rather than uniform policy directives (Rokhani et al., 2020).

4. Value-Chain Systems and Circular Industrial Development

Sugarcane should be analysed as a tightly coupled chain because the quality and timing of upstream actions affect downstream feasibility. A factory that receives a highly variable cane flow may alternate between underutilization and congestion. A farmer who faces long queues, uncertain weighing or delayed payments may rationally prioritise delivery convenience over biological optimality. Thai harvest-scheduling research illustrates the importance of reconciling output maximisation, grower equity and supply-chain performance rather than treating logistics as a purely technical routing exercise (Jarumaneeroj et al., 2021). The factory is also an energy and material-conversion complex. Bagasse can support steam and electricity generation, while bagasse-derived feedstocks can provide materials, fuels and other products. However, process design and energy performance are not identical to improvements in sugar recovery; electricity output, exergy efficiency and recovered sucrose should be reported separately (Chantasiriwan, 2021; Abouelsoud et al., 2025). Circular bioeconomy reviews describe potential value-added uses of residues but also

discuss scale, pretreatment, capital and commercialization barriers (Ajala et al., 2021; Konde et al., 2021; Shabbirahmed et al., 2022).

METHODOLOGY

1. Research Design and Review Boundaries

This study adopts a qualitative literature review with an integrative and interpretive orientation. It is not a systematic literature review, does not claim exhaustive database retrieval, and does not use PRISMA screening counts. The method is suited to a question that spans heterogeneous agronomic experiments, breeding studies, engineering assessments, environmental modelling and rural institutional analyses. Its aim is to explain relationships between mechanisms, identify contradictions and build a defensible conceptual framework rather than estimate a pooled causal effect across incomparable studies. The principal literature window is 2020–2026. The review draws on peer-reviewed journals addressing sugarcane genetics, ratoon productivity, irrigation, nutrition, climate risk, digital agriculture, harvest scheduling, postharvest losses, milling, waste utilization, land use and smallholder governance. Publisher article pages, journal records and identifiable DOI entries were prioritised for source traceability. Official Indonesian production statements are included as contextual primary statistics, not counted as peer-reviewed journal evidence. National data are distinguished from the international literature throughout the interpretation.

2. Source Appraisal and Thematic Coding

Sources were appraised for their connection to at least one of six analytic domains: field biological productivity; input and environmental efficiency; sensing and decision support; harvesting and transport; industrial conversion; and technology adoption and governance. Greater interpretive weight was assigned to field-based studies and directly relevant Indonesian evidence for claims about attainable performance. Reviews and modelling papers were used primarily for identifying mechanisms, hypothesis generation and boundary conditions. Findings from China, Brazil, India, Thailand and Australia were labeled as international evidence, since agroecology and institutions may differ from those of Indonesia. Thematic synthesis proceeded by comparing mechanisms within each domain and tracing dependencies across domains. For example, improved varieties affect attainable cane yield and maturity patterns; maturity affects scheduling; scheduling affects deterioration; and deterioration affects mill recovery and farmer payments. Similar chains link nitrogen management to biomass, sucrose concentration, emissions and profit. Contradictions were not removed by averaging heterogeneous results; instead, they were interpreted in relation to site, season, cultivar, treatment intensity or measurement differences (Castro et al., 2023; Oliveira et al., 2023; Yang et al., 2025).

3. Production Accounting and Scenario Approach

A transparent accounting identity supplements the narrative synthesis. Equation (1) defines illustrative commercial sugar output as the product of effectively harvested area, delivered cane yield and a single net commercial sugar

recovery fraction. The variables are defined below, and the identity is intended for mass-balance accounting rather than for estimating a production function or proving technological feasibility. Cane sucrose content, extraction efficiency, overall factory recovery and nationally reported rendemen have different denominators and must not be multiplied together without reconciling their physical definitions.

$$Q_s = A_h \times Y_c \times r_n \quad (1)$$

In Equation (1), Q_s denotes recovered commercial sugar (tonnes), A_h is effective harvested area (ha), Y_c is delivered cane yield (tonnes/ha), and r_n is net sugar recovery (tonnes of commercial sugar per tonne of delivered cane). The latter is dimensionless, so the product correctly yields tonnes of sugar. Because the identity aggregates heterogeneous farms and mills, it assumes representative average values for the scenario exercise; operational projections would require disaggregation and explicit loss accounting.

The analysis uses a common illustrative area of 560,000 hectares to isolate changes in yield and recovery. One baseline resembles 2025 official averages; additional cases examine moderate, advanced and ambitious intensification. These are sensitivity examples with transparent arithmetic, not empirical forecasts, and their interpretation explicitly acknowledges investment, water, climate, cultivar maturity, mill capacity and adoption constraints. A separate comparison considers the area that would be required to produce the same quantity if yield and recovery did not change.

4. Trustworthiness and Limitations

Because source selection is purposeful rather than exhaustive, the review cannot quantify publication bias or guarantee that every study on a topic has been captured. Moreover, results from published trials can exceed outcomes achievable among resource-constrained smallholders at scale. The framework is therefore offered as an analytically coherent proposal awaiting local validation. The review also avoids attributing environmental benefits to intensification without accounting for rebound effects, irrigation demand or displaced land use (Duden et al., 2021; Sant'Anna, 2024).

RESULT

1. Theme I: The Sugarcane Productivity Gap is Multidimensional

The reviewed literature consistently identifies multiple interacting determinants of sugarcane output. Genetics establish a potential productivity frontier, but observed performance is conditioned by crop establishment, repeated ratooning, soil compaction, water availability, plant nutrition and damage from insects or diseases. A study evaluating ratoon performance in contrasting water-supply environments shows why the economically optimal ratoon cycle may differ by environment rather than following a single national replacement schedule (Resende et al., 2025). Genetic prediction research similarly suggests opportunities to select for ratooning ability, while acknowledging the complexities of a genetically polyploid crop (Islam et al., 2023). Disease control and resilience are central rather than peripheral issues. Quantitative trait loci

associated with red rot resistance and sugarcane mosaic disease illustrate how genomic advances can strengthen selection pipelines (Banerjee et al., 2023; Lu et al., 2023). Genomic prediction for smut and Pachymetra root rot provides another example of tools that could support more consistent crop performance (Chen et al., 2024). However, genomic correlations and candidate genes do not by themselves establish commercially significant yield gains in Indonesian production settings, where pathogen pressure and genotype-by-environment interactions must be tested. Indonesian research provides a practical counterweight to the assumption that gains are exclusively generated by importing foreign technologies. Ariyanto et al. (2023) examined mutation-derived sugarcane material across plant and ratoon crops and documented genotype-specific yield-component responses. Their findings support a research agenda based on locally tested varieties and longevity, although a small experiment cannot alone determine national varietal policy. Integrated performance measurement should connect varietal trials with field economics, harvest scheduling and mill extraction outcomes, which are generally not assessed together.

2. Theme II: Biological Improvement Must Integrate Varieties, Ratoons and Soil-Water Management

Varietal improvement is most valuable when coupled with suitable crop management. Studies selecting variety, nitrogen rate, and plant regulators have shown that sugar yield depends on treatment combinations rather than one intervention in isolation (Desalegn et al., 2023). International breeding reviews explain the value of long-term germplasm improvement and genomic tools for resilience under drought, salinity and other stresses (Cursi et al., 2022; Meena et al., 2020). These findings suggest prioritising locally adapted varieties whose performance can be evaluated for both cane tonnage and recoverable sucrose over multiple ratoon cycles. Ratoon management is another major opportunity because repeated harvests can reduce land preparation costs while also accumulating compaction, fertility and disease problems. Research in subtropical India linked soil subsoiling to improved physical conditions and ratoon performance, while experiments combining crop-residue management and Trichoderma treatments reported changes in photosynthesis, soil-carbon indicators and yield (Shukla et al., 2021; Shukla et al., 2022). Such findings justify field experimentation, but not universal prescriptions for deep tillage or microbial inoculants. Appropriate practices depend on texture, drainage, machinery pressure, residue handling and biological context. Water management studies emphasise both irrigation technology and the timing of supply. Drip systems, fertigation, mulching and improved scheduling can support water productivity, although economic returns depend on infrastructure, energy pricing and reliable water access (Dingre, 2023; Anjaly et al., 2024). Multi-year experiments combining trash mulching and irrigation regimes show how soil condition and water efficiency can respond jointly to management (Kumar et al., 2024). Separate research examining tillage, residue retention and fertigation illustrates possible improvements in productivity alongside reductions in water and carbon footprints, reinforcing the need for

package-level rather than single-input evaluations (Wakchaure et al., 2025). Nutrient management illustrates both the potential and risk of intensification. Experimental comparisons of fertilizer source, application method and harvest season demonstrate responses that depend on management context (Castro et al., 2023). Work on cover crops and nitrogen in Brazil suggests that biological inputs and soil cover can influence soil nutrient pools and subsequent yields (Tenelli et al., 2021). However, concentrated vinasse-based organomineral formulations may change ammonia and nitrous oxide losses differently across seasons, and more fertilizer cannot simply be assumed to improve the sustainability of sugar production (Oliveira et al., 2023).

3. Theme III: The Optimal Nitrogen Strategy is Location-Specific and Environmentally Bounded

Recent nitrogen studies challenge the simplistic assumption that higher input intensity necessarily closes yield gaps. Field evidence in China found that substantial reductions in reactive nitrogen losses could coexist with high sugarcane yields under lower nitrogen application than farmers' existing practice (Yang et al., 2024). International synthesis further indicates that soil properties, temperature, rainfall and management history help explain why nitrogen responses differ between Brazil and China (Yuan et al., 2025). These results directly caution against adopting an externally derived nitrogen rate as a nationwide Indonesian standard. A complementary set of studies examines broader management outcomes. Substituting some conventional mineral nitrogen with coated or organic forms can alter leaching, soil processes and environmental performance, although the most sustainable treatment varies according to local constraints (Yang et al., 2025). Integrated management trials in China report combinations of improved productivity, profitability and reduced environmental costs, illustrating the potential for joint rather than competing gains (Wang et al., 2026). Meta-analytic and optimisation research similarly finds that the preferred nitrogen rate may differ depending on whether the objective is yield, profit, pollution control or aggregate social benefit (Zhu et al., 2026). The evidence also emphasizes climate interactions. Moro et al. (2026) show why nitrous oxide response to nitrogen rates matters even when yields remain relatively high. Physiological and molecular perspectives on nutrient-use efficiency indicate that improved acquisition and assimilation could reduce reliance on ever-greater inputs over time (Krishnapriya et al., 2026). The relevant Indonesian research frontier therefore combines soil-test interpretation, local response trials, realistic input prices and environmental monitoring, not the pursuit of high nitrogen rates as a proxy for management quality.

4. Theme IV: Climate Change Threatens Sugar Accumulation as well as Cane Biomass

Climate stress affects sugarcane through direct plant physiology and through constraints on the production system. Reviews report that drought, heat, pests and diseases can influence growth and sucrose accumulation through overlapping biological pathways (Mehdi et al., 2024). Drought assessment in

China identifies the importance of growth-stage-specific water deficits, rather than total seasonal rainfall alone (Qin et al., 2023). This distinction is relevant to Indonesian sites that can experience both short drought episodes and intense rainfall or waterlogging within the same crop cycle. Crop-modelling studies underscore the need to distinguish biomass from sucrose. Indian simulations project that warming may increase stalk fresh mass under some conditions while reducing sucrose mass in others, showing why cane tonnage is an incomplete indicator of climate resilience (Jaiswal et al., 2023). Modeling for Tamil Nadu links warming to changes in crop water needs and yield, whereas Brazil-focused scenarios identify geographically variable implications for yield, water productivity and emissions (Guhan et al., 2024; Leite et al., 2026). These models are not forecasts for Indonesia, but they support a research design that measures climatic exposure, varietal responses and sucrose recovery together. Climate-adaptive management should include drainage, water harvesting where hydrologically viable, drought-aware planting calendars and varietal diversification rather than irrigation expansion by default. The economic attractiveness of each practice depends on crop stage, local water competition, soil conditions and the probability of extremes. Long-term intensification that increases water withdrawal without assessing downstream needs may move the productivity problem from agriculture to the watershed, undermining the sustainability objective (Duden et al., 2021; Anjaly et al., 2024). Multi-driver climate analysis adds a further caution to forecasts built around temperature or rainfall alone. Flack-Prain et al. (2021) demonstrate that the effects of climate change and extreme events on sugarcane are sensitive to interacting meteorological drivers and model assumptions. For Indonesia, scenario assessments should therefore encompass heat exposure, rainfall timing, vapour-pressure deficit, waterlogging and water deficits as joint sources of uncertainty, with validation against local observations rather than transfer of foreign response coefficients.

5. Theme V: Digital Agriculture Can Improve Diagnosis But Does Not Eliminate Institutional Constraints

Remote sensing and data-driven tools can improve visibility into the spatial heterogeneity masked by district or national averages. Sugarcane yield mapping using high-resolution imagery and machine-learning methods has demonstrated approaches to identifying within-field variability (Canata et al., 2021). Satellite and environmental data have also been applied to predict Australian cane and sugar yields at field and regional scales, providing a basis for early intervention and industrial planning (Shendryk et al., 2021). UAV-LiDAR studies add detail on crop structure and potential yield, although data requirements, calibration and cost influence scalability (Xu et al., 2020). Different technologies address different decisions. Multispectral imagery and neural-network approaches have been applied to plot-level yield estimation in Australia, while integrated UAV and Sentinel-2 methods in Thailand highlight the challenge of upscaling from limited ground reference data (Akbarian et al., 2024; Som-ard et al., 2024). Harvesting-machine data can produce near-real-time yield estimates that support field-level analysis and equipment coordination

(Maldaner et al., 2021). However, model accuracy depends on representative training observations, maintenance, sensor quality and changing management conditions; apparent precision is not equivalent to causal knowledge about the best intervention. Indonesia should therefore prioritise a modest, interoperable digital backbone before purchasing highly sophisticated platforms. Geo-referenced field boundaries, cultivar and ratoon records, soil tests, yield tickets, harvest dates and factory recovery measurements would already improve diagnosis and accountability. Digital service models, producer organisations and mill-provided extension may help smaller farms gain access without owning equipment themselves. Data governance is equally important: growers should understand how measurements affect payments, who may access their data, and how inaccurate records can be corrected (Hakim et al., 2024; Rosidah et al., 2023). Experience in adjacent bioenergy systems also illustrates both the capabilities and limitations of artificial-intelligence-assisted modelling. Liao and Yao (2021) identify opportunities for prediction, process optimisation and supply-chain support, while emphasising consistent data preparation, transparent model selection and lifecycle evaluation. Applied to Indonesian cane procurement, such lessons support phased experimentation with auditable data pipelines and field-tested decision usefulness before public or private institutions commit to proprietary digital platforms.

6. Theme VI: Harvesting, Logistics and Milling Mediate the Conversion of Crop Potential Into Sugar

Sucrose losses after harvest explain why agronomic improvement must be matched by timely industrial throughput. Reviews of postharvest biology describe the role of respiration, microorganisms, temperature and cut-to-crush delays in degrading cane quality (Misra et al., 2022). Mechanical harvesting can reduce labour bottlenecks but may introduce chopping damage and juice loss when equipment is poorly configured or maintained (Zhou et al., 2024). Harvest timing is therefore both an agronomic and an operations-management problem. Supply-chain models make the institutional trade-offs visible. A Thai multi-objective harvesting study shows that schedules optimised for total output may differ from those preferred for grower equity or logistics efficiency, and that cooperative arrangements affect implementation (Jarumaneeroj et al., 2021). For Indonesia, the analogous problem is to coordinate maturity windows, transport distances, road access, factory crushing schedules and transparent quality measurements. Simply increasing cane production without smoothing deliveries can produce longer queues, elevated deterioration and higher operating costs.

Mill modernisation should be assessed through explicit loss accounts rather than a single technological slogan. Replacement of worn extraction components, better control of imbibition and temperature, preventive maintenance, instrumentation, and reliable utilities can improve system performance when they address verified bottlenecks. Research in a sugar factory using energy and exergy analysis identifies major process and boiler inefficiencies, illustrating the value of plant-level audits before capital allocation (Abouelsoud et al., 2025). Cogeneration analysis also shows how steam and

drying configurations influence energy efficiency, though energy savings must not be misreported as automatically equivalent to higher sucrose recovery (Chantasiriwan, 2021). Circular use of bagasse and straw provides additional industrial value but creates allocation choices. Residues may support cogeneration and industrial feedstocks, yet removal from fields can reduce mulch availability and soil-carbon benefits. International reviews identify opportunities and technological limitations in bagasse electricity generation and biorefineries (Fioranelli and Bizzo, 2023; Ajala et al., 2021; Konde et al., 2021). Other assessments document material-conversion pathways and show that environmental performance varies with energy inputs, transport and processing design (Shabbirahmed et al., 2022; Hiloidhari et al., 2021). An integrated policy must evaluate sugar recovery and by-product revenue alongside ecological functions of retained residue. A techno-economic review of bagasse-based biofuel pathways similarly highlights that attractive feedstock availability does not remove barriers in pretreatment, processing economics and the environmental performance of integrated facilities (Pan et al., 2022). The appropriate objective is therefore a location-specific cascade of uses for fibre, steam, power, fuel and soil residues, rather than assuming that each additional bioenergy product is automatically beneficial. Evaluation should keep sugar recovery, energy sales, marginal profitability and life-cycle burdens as separate outcome measures.

7. Theme VII: Governance Determines Whether Productivity Improvements Reach Smallholders

The literature does not support treating smallholders as a homogeneous group. Differences in land size, financial access, risk exposure and contract conditions can influence technology adoption as strongly as differences in agronomic knowledge. Indonesian contract-farming research points to heterogeneity among sugarcane growers, while production-efficiency research identifies allocation problems that cannot be solved by distributing equipment alone (Hakim et al., 2024; Rosidah et al., 2023). Policies that require farmers to bear immediate replanting costs without affordable financing or dependable off-take may fail even where biological benefits are plausible. Payment mechanisms create another critical relationship. If cane is purchased primarily by mass rather than fairly measured recoverable sugar quality, farmers may have weak incentives to prioritise sucrose content, freshness or maturity. Conversely, opaque measurement systems can transfer bargaining power from farmers to mills without creating genuine efficiency. The design challenge is to establish auditable sampling, understandable deductions and timely payment while accounting for differences in location and harvest access. In this respect, logistics efficiency, contractual fairness and industrial productivity form one institutional problem rather than three unrelated issues (Jarumaneeroj et al., 2021; Hakim et al., 2024). Research agencies such as P3GI, together with universities and relevant public and private partners, can contribute to breeding, technology testing, extension training and performance standardisation. Their influence depends on whether research targets reflect field realities and whether mill-farmer systems provide credible demand for the innovations being developed. Long-horizon

genomic research can contribute to disease-resistance breeding, but the immediate task may be multiplication and adoption of already validated material, coupled with clear ratoon replacement advice and service delivery (Banerjee et al., 2023; Chen et al., 2024; O'Connell et al., 2022).

DISCUSSION

1. Why an Integrated Output Measure Changes Policy Priorities

The strongest implication of the synthesis is that the conventional distinction between upstream and downstream investment is analytically misleading when used to allocate responsibility for sugar output. Cane yields create feedstock, but recoverable sugar depends on crop quality, harvesting, handling, crushing and commercial conversion. These processes can reinforce or offset one another. A breeding program that improves cane biomass without improving recoverable sugar may raise transport and processing burdens, while a sophisticated factory with insufficient or degraded cane may fail to realise its designed capacity. This finding links physiological accounts of sucrose accumulation to evidence of cut-to-crush deterioration and logistical coordination (Mehdi et al., 2024; Misra et al., 2022; Jarumaneeroj et al., 2021).

Figure 1 expresses the proposed Integrated Farm-to-Mill Sugar Productivity and Self-Sufficiency Framework as a connected set of intervention domains. Its principal innovation is to place a consistently measured recoverable-sugar outcome at the intersection of field productivity, operating performance and governance. The environmental and distributional domains operate as constraints and evaluation criteria, not as assumed benefits of higher production. This representation explains why an intervention can succeed agronomically yet fail economically, or improve mill performance without increasing smallholder returns (Rosidah et al., 2023; Wang et al., 2026).



Figure 1. Integrated Farm-to-Mill Sugar Productivity and Self-Sufficiency Framework (Conceptual Synthesis Created for this Review).

Figure 1 should be read from contextual constraints through six coordinated intervention areas to outcomes. The biological and water-nutrient domains raise recoverable sugar potential; logistics and processing preserve that potential; and innovation, incentives and safeguards determine the feasibility of implementation at scale. Monitoring should report both aggregate national

output and its components, because the same production volume may be achieved through very different combinations of land, input use and industrial efficiency. The framework is a causal hypothesis to be evaluated, not evidence that a particular policy package will necessarily deliver its intended benefits.

2. A Transparent Scenario Comparison

The quantitative scenarios illustrate why combined improvements in cane yield and net sugar recovery can be important. At a constant illustrative harvested area of 560,000 hectares, a 2025-like yield of 69.35 tonnes per hectare with 6.83% net recovery implies approximately 2.653 million tonnes of sugar. At 75 tonnes per hectare and 7.50% recovery, the accounting total rises to 3.150 million tonnes. A more ambitious combination of 82 tonnes and 8.00% yields approximately 3.674 million tonnes; 90 tonnes and 9.00% yields 4.536 million tonnes. Table 1 reports these fixed-area scenarios and separates hypothetical values from the officially reported 2025 production total. These calculations use an intentionally fixed area and are distinct from the official 2025 production quantity, which involves actual reported area and detailed accounting conventions (Ministry of Agriculture of Indonesia, 2026a).

Table 1. Illustrative Fixed-Area Scenarios for Sugar Output in Indonesia (Author Calculations; Scenarios are Not Forecasts).

Scenario	Cane yield (t/ha)	Net recovery (%)	Sugar (million t)
S0: 2025-like baseline	69.35	6.83	2.65
S1: Moderate intensification	75.00	7.50	3.15
S2: Advanced intensification	82.00	8.00	3.67
S3: Ambitious target	90.00	9.00	4.54

Note: Author calculations at a fixed area of 560,000 ha. These scenarios are not projections or validated targets.

Figure 2 compares the hypothetical sugar yield per hectare underlying these scenarios. The difference between the baseline and the most ambitious scenario is about 3.36 tonnes per hectare, a rise of approximately 71%. The arithmetic is straightforward but the agronomic interpretation is not. Simultaneously increasing cane yield and net sugar recovery requires management changes whose costs and interdependencies may be non-linear. Enhanced vegetative growth, for example, cannot simply be assumed to produce proportional increases in sucrose concentration; this is a core insight of yield-formation and climate research (Jaiswal et al., 2023; Desalegn et al., 2023).

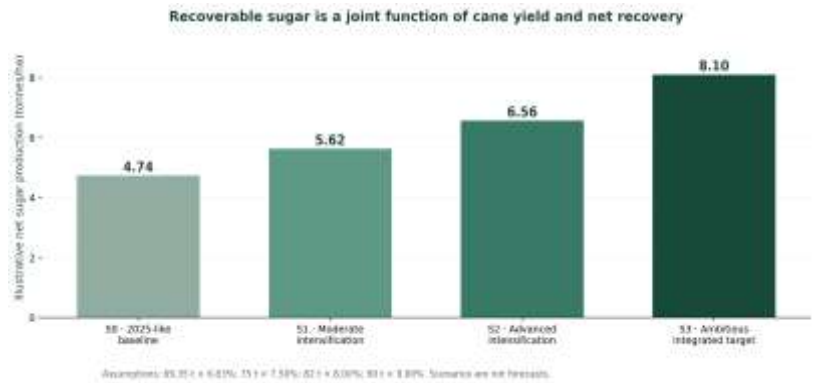


Figure 2. Illustrative Recoverable Sugar Output Per Hectare Under Four Cane-Yield and Net-Recovery Combinations (Author Calculations)

Figure 2 demonstrates a difference between arithmetic opportunity and practical attainability. Under the baseline recovery of 6.83%, obtaining the output of the most ambitious scenario through land alone would require approximately 957,000 hectares at 69.35 tonnes of cane per hectare, about 397,000 hectares more than the common scenario base. This comparison isolates the land arithmetic and must not be interpreted as evidence that expansion of that magnitude is planned, feasible or necessary. It highlights why the ecological and economic cost of land expansion should be evaluated against the expense and risk of improving productivity on established land (Duden et al., 2021; Sant'Anna, 2024). The scenarios also illustrate the importance of sensitivity testing. Figure 3 shows sugar output across a two-dimensional range of yields and recovery assumptions at fixed area. Any chosen national target occupies only one point on this surface. If net recovery remains at 6.83%, reaching 4.536 million tonnes on 560,000 hectares would require about 118.6 tonnes of cane per hectare; if cane yield remains 69.35 tonnes, net recovery would have to reach approximately 11.68%. Whether either combination is realistic for particular Indonesian environments can only be established through data from farms and mills, cultivar tests, quality accounting and capital assessments (Resende et al., 2025; Abouelsoud et al., 2025).

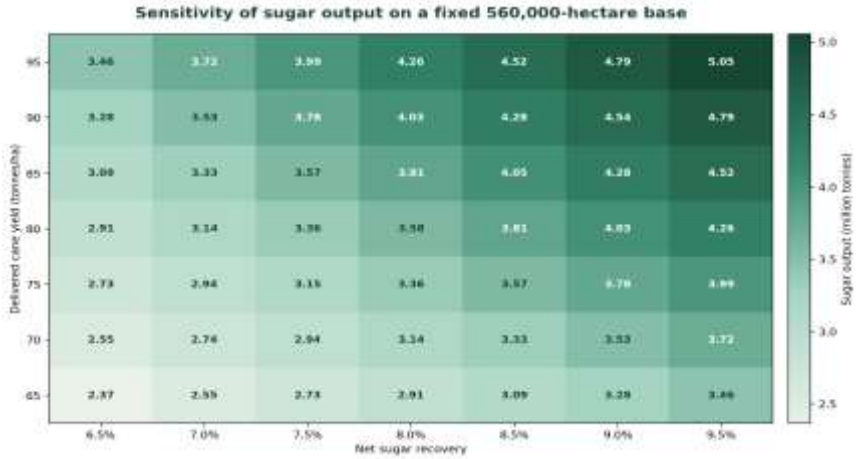


Figure 3. Sensitivity of Illustrative National Sugar Output to Cane Yield and Net Sugar Recovery at 560,000 Hectares (Author Calculations).

Figure 3 is intended as a decision aid rather than a prediction surface. Movement toward its higher-output region can result from greater field productivity, better crop quality, fewer postharvest losses, higher extraction efficiency or a combination of these. Yet the associated investment costs and environmental effects are not represented by the arithmetic itself. For policymaking, each cell should ultimately be linked to regional adoption rates, energy and water balances, net present value, mill utilisation, and uncertainty intervals. The correct decision criterion is not the largest output number but the best feasible combination of production, profitability, resilience and environmental performance (Zhu et al., 2026; Wakchaure et al., 2025).

3. Prioritisation Should Follow Constraints, Not a Uniform National Recipe

The review suggests a practical intervention hierarchy. First, diagnose whether the binding constraint in a district is inadequate plant population, unsuitable varieties, declining ratoon condition, soil compaction, low water reliability, pest pressure, harvesting delays or factory downtime. Second, select packages based on measured constraints and locally credible response evidence. Third, evaluate their cost-effectiveness under farm and mill accounting. Fourth, scale successful interventions using extension, financing and quality assurance systems. This diagnosis-first principle follows from the diversity of responses observed in ratoon, irrigation, nutrient and integrated management studies (Shukla et al., 2021; Kumar et al., 2024; Yang et al., 2024; Wang et al., 2026). Replanting deserves priority where ratoon productivity has fallen enough to justify the expense, but it is not a universal immediate solution. Replacement can entail lost revenue during crop establishment, high seed costs, rental machinery and cash-flow stress. The optimal schedule depends on expected future yields, varietal characteristics, labour, soil condition and access to financing. Similarly, drip irrigation may be attractive under water scarcity and suitable farm structure but less appealing where surface systems are efficient, or drainage is the principal problem (Islam et al., 2023; Dingre, 2023; Resende et al., 2025). Public subsidies should be conditional on agronomic and economic appraisal, not the visibility of the purchased technology. Factory modernisation should also follow a bottleneck audit. A mill whose dominant losses arise from poor incoming-cane quality requires better scheduling and field coordination as well as process controls. Where chronic breakdowns, inappropriate steam systems or deficient instrumentation are more important, engineering investment may achieve higher marginal returns. Process studies on exergy efficiency and cogeneration illustrate the benefits of audited technical interventions but do not establish a universal threshold for overall sugar recovery (Abouelsoud et al., 2025; Chantasiriwan, 2021). The proposed jump to an overall recovery rate above 85% in the initial literature therefore requires a precise definition of the numerator, denominator and plant process, as it is not automatically equivalent to 8.5% or 9.0% of cane mass being converted into sugar.

4. Institutional Design: Align Research Incentives, Farmer Payment and Mill Accountability

A farm-to-mill strategy requires coordinated measurement and credible contracts. Growers should have access to independently auditable cane weight and quality results, with appropriate procedures for sampling disputes. Mills should disclose operational indicators in standardised formats that protect commercially sensitive information while allowing performance benchmarking. Payment rules should reward recoverable sugar rather than crude tonnage alone, but only when growers can influence the quality indicators and are not penalised for congestion caused by mills or transport systems. This institutional implication follows from the demonstrated importance of farm efficiency, contract heterogeneity and multi-objective logistics (Rosidah et al., 2023; Hakim et al., 2024; Jarumaneeroj et al., 2021). A revitalised national research network would connect P3GI, universities, seed multipliers, producer organisations and mills through multi-site field trials. Research priorities should include genotype-by-environment interactions, sugar concentration, ratoon longevity, disease resistance, water stress and processing quality. Genomic approaches can accelerate the discovery of traits, but Indonesia also needs operational breeding pipelines, validated nursery systems and accessible field recommendations. Research on disease QTLs and genomic selection supports this direction, while Indonesian ratoon trials underscore the value of adaptation to local agroecological conditions (Banerjee et al., 2023; Lu et al., 2023; Ariyanto et al., 2023). Digital integration could make shared governance measurable. Each participating production cluster could establish a minimally sufficient registry of plots, planted varieties, ratoon age, fertiliser applications, planting and harvest dates, cane weights and sugar-quality results. Those records would support simple dashboards long before more sophisticated forecasting systems were added. Remote sensing and harvester-based yield mapping can be useful, but the most important institutional innovation may be trustworthy ground data and data portability across agencies and mills (Canata et al., 2021; Maldaner et al., 2021; Som-ard et al., 2024).

5. Environmental Safeguards and the Conditional Case For Expansion

The case for an intensification-first approach is strong as a sequencing principle, not as a categorical prohibition on all expansion. Better yields on established land may reduce pressure for conversion elsewhere, but this potential land-sparing effect is not guaranteed. Higher profitability can itself encourage greater sugarcane acreage, and intensified irrigation or fertiliser use can worsen environmental pressures when governance is weak. Evidence from Brazilian land-use and hydrological studies demonstrates the importance of spatial context and indirect effects (Duden et al., 2021; Guarenghi et al., 2023; Sant'Anna, 2024). Environmental screening should compare at least four quantities: direct changes in land cover and biodiversity; water availability and competing withdrawals; soil nutrient and carbon trajectories; and lifecycle greenhouse gas emissions. Sugarcane residues can contribute to soil quality as mulch or to energy generation as industrial feedstocks, generating context-

sensitive allocation decisions (Shukla et al., 2022; Hiloidhari et al., 2021; Fioranelli and Bizzo, 2023). Policies should avoid rewarding by-product commercialisation in ways that deplete soil cover or increase erosion, and should assess water requirements beyond the boundaries of individual estates. Any justified land expansion should therefore require demonstrated compatibility with spatial planning, community land rights, high-conservation-value safeguards, water budgets and credible mill procurement. The policy question is not expansion versus intensification in the abstract. It is how each marginal unit of recoverable sugar can be obtained at the lowest acceptable combination of social, financial and environmental cost. Such a framing is consistent with sustainable intensification evidence showing that productivity, profit and environmental indicators can improve together but only through carefully designed and monitored practices (Wang et al., 2026; Yuan et al., 2025). Broader bioenergy-system research reinforces the importance of scale, indirect land-use effects and sustainability constraints when industrial feedstock demand increases. Calvin et al. (2021) describe how climate-mitigation benefits depend on the boundaries and deployment conditions of bioenergy systems, cautioning against attributing benefits to greater biomass throughput alone. Although the study does not estimate Indonesia-specific sugarcane impacts, it supports the requirement for explicit land, water, carbon and biodiversity accounting before new plantations or major biorefinery investments receive policy incentives.

6. A Sequenced Transformation Roadmap

Figure 4 translates the synthesis into a phased implementation roadmap. During 2027–2028, priority should be placed on measurement standards, nursery quality, targeted ratoon rehabilitation, harvest logistics and the repair of high-loss mill components. A medium-term phase during 2029–2031 would scale successful interventions, strengthen performance-based contracts, develop digital data interoperability and undertake selective factory modernisation. During 2032–2035, priorities would shift toward climate-resilient breeding pipelines, advanced monitoring, comprehensive residue utilisation and periodic adjustment of land-use and market policy. Each phase must include independent outcome evaluation so that ineffective programmes can be redesigned rather than perpetuated.



Figure 4. Proposed Phased Transformation Roadmap for Indonesia's Integrated Sugarcane and Sugar Industry, 2027–2035 (Author Synthesis)

The roadmap should be interpreted as a sequence of decisions, not a guarantee of production volumes. Its monitoring framework should report cane yield, net recoverable sugar per hectare, postharvest delays, mill extraction and downtime, water productivity, nitrogen efficiency, farm net margins, contract transparency and the distribution of gains. National reporting should additionally distinguish white crystal sugar from other product categories. Crucially, adoption and performance indicators should be evaluated by farm type and region; national averages can conceal improvements among well-capitalised producers alongside stagnation among smaller growers (Hakim et al., 2024; Rosidah et al., 2023).

7. Theoretical Contributions, Uncertainty and Research Agenda

The IFMSP-SF framework extends yield-gap analysis by explicitly embedding postharvest and processing losses within the same productivity construct. It also extends sustainable intensification beyond a land-based agronomic objective by requiring economically recoverable output and governance safeguards. Agricultural innovation theory becomes operational through the connections among breeding, extension, financing, quality incentives and mill accountability. These theoretical integrations are important because a partial improvement in a tightly coupled system may produce a smaller realised national benefit than expected from isolated trials (Mehdi et al., 2024; Misra et al., 2022; Hakim et al., 2024). Several uncertainties remain unresolved. Indonesia-specific estimates are needed for varietal performance over multiple ratoons, marginal return to irrigation and nutrients, cut-to-crush loss functions, mill-level sugar balances and farmer responses to quality-based pricing. Research should compare these relationships across Java and non-Java production environments, different farm scales and alternative milling arrangements. A credible next stage would combine longitudinal field observations, operational mill data and participatory economic assessment without assuming that a review-derived conceptual framework substitutes for causal evaluation. Cross-country evidence supplies hypotheses and intervention candidates; Indonesian experimentation must determine where, for whom and at what cost they work (Shendryk et al., 2021; Resende et al., 2025; Rosidah et al., 2023).

CONCLUSIONS AND RECOMMENDATIONS

Indonesia's sugar productivity challenge is best understood as a system-wide conversion problem involving biological yield potential, crop management, recoverable sucrose, postharvest logistics, industrial performance and institutional incentives. Increasing cane tonnage is necessary in many environments but cannot by itself secure efficient or sustainable sugar production. The literature instead supports an integrated intensification-first agenda that improves established sugarcane land and aligns agricultural interventions with the capacity of mills to convert fresh, high-quality cane into saleable sugar. The proposed Integrated Farm-to-Mill Sugar Productivity and Self-Sufficiency Framework clarifies the relationships among varietal and ratoon

improvement, soil-water-nutrient management, digital decision support, harvest coordination, factory modernisation, farmer incentives and environmental safeguards. Its principal practical implication is the need to monitor recoverable sugar per hectare alongside production costs, farmer welfare and resource-use indicators. The illustrative production scenarios demonstrate substantial arithmetic opportunities from combined yield and recovery improvements, but their ambitious values are not validated forecasts and should not be converted into national commitments without empirical evaluation. The recommended policy sequence is to diagnose performance bottlenecks, strengthen seed and ratoon management, improve field-to-factory logistics, audit mill losses, modernise equipment selectively and align quality-based incentives with transparent measurement. Public research institutions and industry partners should establish multi-location validation programmes, open and auditable performance definitions, and financing arrangements appropriate to smallholders. Environmental appraisal should govern both intensive input use and any additional land development, while national self-sufficiency claims must distinguish consumption-grade sugar from broader industrial sugar requirements.

Future research should estimate the marginal economic and environmental return of integrated intervention packages in Indonesian agroecological regions, quantify how weather and ratoon age influence recoverable sucrose, and test whether quality-based contracts improve both efficiency and equitable farmer income. Stronger longitudinal evidence, publicly comparable mill indicators and robust scenario uncertainty analysis are essential for moving from a credible framework toward defensible investment and policy decisions. Sustainable sugar self-sufficiency will depend not on one headline productivity target, but on repeated, measurable improvements across an interconnected farm-to-mill system.

FURTHER STUDY

This study still has some limitations, so more research on the topic 'Closing Indonesia's Sugar Productivity Gap: An Integrated Farm-To-Mill Intensification Strategy for Sustainable Sugar Self-Sufficiency Without Premature Land Expansion—A Review' is needed to refine this study and give more insights to both the authors and readers.

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