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Beyond Bigger Sugar Mills: Business Unit Consolidation, Feedstock Geography, Farmer Incentives, and Circular Biorefinery Pathways for Indonesia

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ABSTRACT

Indonesia's sugar industry faces a persistent structural challenge in reconciling aging processing assets, limited milling efficiency, fragmented sugarcane supply, farmer incentives, logistics, and the ambition to strengthen domestic sugar production. This qualitative literature review critically examines business unit consolidation as one possible pathway for restructuring the national sugar industry. Rather than assuming that larger factories are inherently superior, the review develops a conditional framework in which processing scale must be evaluated jointly with feedstock geography, transport economics, cut-to-crush time, farmer–factory relationships, technological capability, and opportunities for by-product valorization. Evidence from Indonesia and other major sugar-producing economies indicates that larger processing units may capture fixed-cost, energy, automation, and diversification advantages, but these benefits can be offset when expanded capacity requires excessively large cane catchments, longer transport distances, unstable farmer participation, or underutilized milling capacity. The review further argues that modern sugar factories should increasingly be evaluated as integrated circular biorefineries producing sugar alongside electricity, ethanol, biogas, fertilizer, biochar, and potentially higher-value bioproducts. A three-pathway restructuring framework is proposed: revitalize, consolidate and replace, or repurpose, selected through mill-specific and region-specific diagnostics. Sustainable restructuring therefore requires optimizing total value per tonne of cane rather than maximizing factory size alone.

Keywords

Sugar industry, Sugarcane, Business unit consolidation, Sugar mills, Economies of scale, Supply chain, Farmer–mill partnerships, Circular bioeconomy, Biorefinery, Indonesia.

JEL Classification: Q13; Q18; L66; O14; Q42

Introduction

Sugar occupies an important position within Indonesia's food economy because it simultaneously represents a basic consumer product, an agricultural commodity supporting farmer livelihoods, and an industrial input. Yet the national sugar system has historically faced a persistent mismatch between growing demand and the performance of domestic production. Indonesian studies associate this situation with a combination of farm-level productivity constraints, aging processing facilities, limited recovery rates, competing land uses, institutional fragmentation, and policy and market distortions rather than with a single technological bottleneck [1-5]. Comparative experience from other major sugar-producing economies likewise shows that self-reliance depends on coordinated improvements in agricultural productivity, processing performance, diversification, and institutional support rather than factory investment alone [6].

The persistence of these structural constraints has revived interest in restructuring groups of older and comparatively small sugar-

processing facilities through business unit consolidation. The underlying industrial logic is straightforward. Where several small factories duplicate administrative functions, operate aging machinery, incur high maintenance costs, and cannot economically justify modern cogeneration, automation, or advanced process-control equipment, concentrating processing activity in fewer modern units may reduce average fixed costs, improve capacity utilization, strengthen energy efficiency, and support investment in more sophisticated recovery and diversification technologies. International studies confirm that industrial scale can contribute to productivity, although they also demonstrate that scale is only one component of efficiency. Large plants can perform well economically, while smaller plants may retain advantages under particular social, environmental, geographic, or feedstock conditions [7-9].

This distinction is crucial for Indonesia. Sugar factories do not operate like manufacturing plants whose principal inputs can be transported cheaply over unlimited distances and stored without material deterioration. Sugarcane is bulky, spatially dispersed, seasonal, costly to transport, and biologically vulnerable after harvest. Delays between harvesting and crushing can cause deterioration that reduces recoverable sucrose and affects processing quality. Consequently, enlargement of milling capacity tends to enlarge the geographical area required to support the factory unless yield per hectare rises proportionately. Larger catchments, in turn, create transport, scheduling, coordination, road-infrastructure, queueing, and cane-quality risks [10-13].

A frequently proposed restructuring scenario is to replace clusters of small, historically inherited factories with fewer modern facilities of substantially greater capacity. An illustrative capacity of approximately 10,000 tonnes of cane per day (TCD) is useful for examining the potential benefits and risks of such a strategy, but it should be treated as a scenario rather than a predetermined optimum. At the same time, sugarcane has become increasingly mobile across traditional factory territories, while price, sugar recovery, service quality, and cutting-loading-transport performance increasingly influence farmers' marketing choices. These developments imply that factory capacity cannot be selected independently of the evolving economics of the surrounding cane-supply region.

Recent Indonesian evidence reinforces this point. Farmer participation in contract farming is associated with farm characteristics, cooperative participation, extension access, land tenure, cultivated area, and institutional arrangements. More recent research also identifies heterogeneity among farmers participating in contract arrangements and persistent information asymmetries within sugarcane supply relationships [14-16]. The latter study is particularly relevant because it reports that cane supply can be unstable when farmers are able to redirect production toward factories offering more attractive prices, demonstrating that historical supply territories cannot automatically be regarded as captive feedstock zones.

Business unit consolidation must therefore be treated as an **agro-industrial systems problem**, rather than merely an engineering problem. Factory scale influences the quantity of cane required; cane requirements influence land and farmer requirements; catchment expansion influences transport distance; distance and scheduling influence cane quality and cost; farmer incentives influence whether the theoretically available cane actually reaches the factory; and processing configuration determines how much economic value can be extracted from every tonne delivered. A restructuring decision made without integrating these relationships may create a technically modern factory that nevertheless operates below capacity because the surrounding production system cannot supply it economically.

A second structural change further strengthens the case for reconsidering conventional restructuring models. Modern sugar processing is increasingly moving toward the concept of an integrated biorefinery. Bagasse can provide process steam and electricity and can also become feedstock for advanced fuels, chemicals, biochar, and biochemical processes, while molasses, vinasse, and other organic streams can support ethanol, microbial products, fertilizer, biogas, water recovery, and additional high-value outputs. Recent reviews emphasize that integrated first- and second-generation configurations can improve resource efficiency and diversify revenue streams, although their feasibility remains sensitive to pretreatment costs, process integration, product markets, and scale [17-22].

This transformation alters the economic question. A factory should no longer necessarily be assessed by sugar output alone. A larger modern facility may justify its scale partly because it can support high-pressure cogeneration, ethanol production, anaerobic digestion, nutrient recovery, or other processes unavailable to small factories. Conversely, some existing units could remain economically relevant if modernization and diversification generate more value than closure and replacement. The appropriate metric is therefore moving toward **total economic value recovered per tonne of cane**, subject to environmental, farmer-welfare, logistical, and social constraints.

Against this background, this article addresses five questions: (1) Under what conditions can business unit consolidation generate meaningful scale and efficiency benefits? (2) How do cane-supply geography and transport economics constrain factory size? (3) How do changing farmer incentives influence feedstock security? (4) Can integrated circular biorefineries strengthen the economic case for restructuring? and (5) How can Indonesian factories be differentiated among revitalization, consolidation and replacement, and productive repurposing? Together, these questions connect factory economics with feedstock geography, farmer behavior, logistics, and circular-resource utilization in a single analytical framework.

The objective is consequently not to establish a universal preferred mill size. Rather, this review develops an analytical framework in which business unit consolidation becomes a conditional strategy

dependent on industrial efficiency, feedstock density, logistics, farmer participation, circular-resource utilization, and territorial consequences.

Literature Review

Industrial Scale, Technical Efficiency, and the Economics of Processing Capacity

Economies of scale provide the traditional economic foundation for factory consolidation. Large processing facilities can distribute administrative, laboratory, maintenance, utilities, and capital costs over greater production volumes. Larger facilities may also economically justify advanced boilers, automation, process control, predictive maintenance, higher-performance extraction systems, and specialized technical personnel. In sugar processing, these technologies can influence extraction, steam use, electricity generation, downtime, and overall recovery.

Evidence nevertheless cautions against interpreting scale mechanically. Dotta e Silva and Périco [7], studying Brazilian sugar-energy plants, found that large plants demonstrated economic-efficiency advantages associated with economies of scale, yet smaller plants also emerged as benchmarks under some social and environmental criteria. Danelon et al. [8] similarly found potential productivity benefits from greater production scale in Brazil but framed them within broader efficiency and land-use considerations. Mexican mill studies also identify considerable heterogeneity in technical efficiency and returns to scale [9].

The implication is that **minimum efficient scale is contextual rather than universal**. Factory economics depend on cane availability, length of the crushing season, extraction efficiency, utilization rates, wage structure, fuel systems, capital costs, product mix, and the extent to which fixed investments are operated near design capacity. Thus, an indicative 10,000-TCD processing target should be investigated as a scenario rather than adopted automatically as a national technological rule.

Industrial optimization also occurs below the level of factory size. Li et al. [23], for example, demonstrate how data-driven multi-objective optimization can improve milling-system operations. Such work indicates that significant performance gains may come from better operational management, automation, and control rather than solely from expanding nominal capacity. Likewise, Rosidah et al. [24] and Santosa et al. [25] show that production efficiency at the farm level remains consequential because an efficient factory cannot compensate indefinitely for insufficient cane yield or inefficient input use.

Therefore, business unit consolidation should be compared against a counterfactual strategy of **selective revitalization**. If an older mill sits inside a dense, productive cane zone, enjoys relatively short transport distances, retains farmer confidence, and can be technically modernized at reasonable cost, revitalization might generate a better system-level outcome than transferring the cane to a distant new facility.

Feedstock Geography and the Scale–Distance Trade-off

Sugarcane creates an unusually strong linkage between industrial scale and agricultural geography. A factory increasing its daily crushing capacity requires either a larger surrounding planted area, higher yields, a longer operating season, greater cane density, or some combination of these factors. Where surrounding land is fragmented or occupied by competing crops, expansion of the catchment radius becomes increasingly likely.

Tregeagle and Zilberman [26] formalize an important feature of biomass-processing economics: increasing the feedstock area around a processing facility raises average delivery distance. The economic implication is that delivery costs grow as processing scale draws feedstock from progressively more distant land. This produces an intrinsic tension between economies of scale inside the factory and diseconomies of distance outside the factory.

The same trade-off has practical significance for sugarcane because cane transport is not merely a freight-cost problem. Harvest timing, truck availability, road conditions, field access, loading capacity, factory queues, and crushing schedules interact. Morales Chavez et al. [11], Almeida et al. [12], Utomo et al. [13] and Purnomo and Supartiningrum [27] demonstrate that integrated scheduling and routing can reduce transport and waiting costs, indicating that logistics design should be evaluated jointly with factory capacity.

The problem is compounded by perishability. Misra et al. [10] review evidence that post-harvest deterioration begins after cutting and that prolonged cut-to-crush intervals can reduce sucrose recovery and create processing complications. Indonesian evidence on cutting and transport operations similarly underscores the importance of limiting quality losses between harvest and milling [28]. Consequently, the relevant logistical objective is not simply to minimize rupiah per tonne transported; it is to minimize the delivered cost of recoverable sugar, or more broadly the delivered cost of recoverable cane value.

Purnomo and Supartiningrum [27] provide a particularly relevant East Java illustration, showing how optimized harvest and loading schedules can substantially reduce operational costs while meeting factory requirements. This reinforces the argument that factory restructuring should be accompanied by investment in logistics planning, transport coordination, cane collection, digital scheduling and potentially satellite transfer facilities. More broadly, robust sugarcane supply-network models show the value of considering facility location, feedstock flows, uncertainty, and sustainability criteria within the same decision architecture [29].

Figure 1 illustrates the core proposition underlying this review: factory-level unit processing costs may decline as throughput rises, while cane-procurement and transportation costs tend eventually to rise as the catchment area expands. The economically meaningful capacity is therefore located near the minimum of total system cost, not necessarily at the minimum factory processing cost.

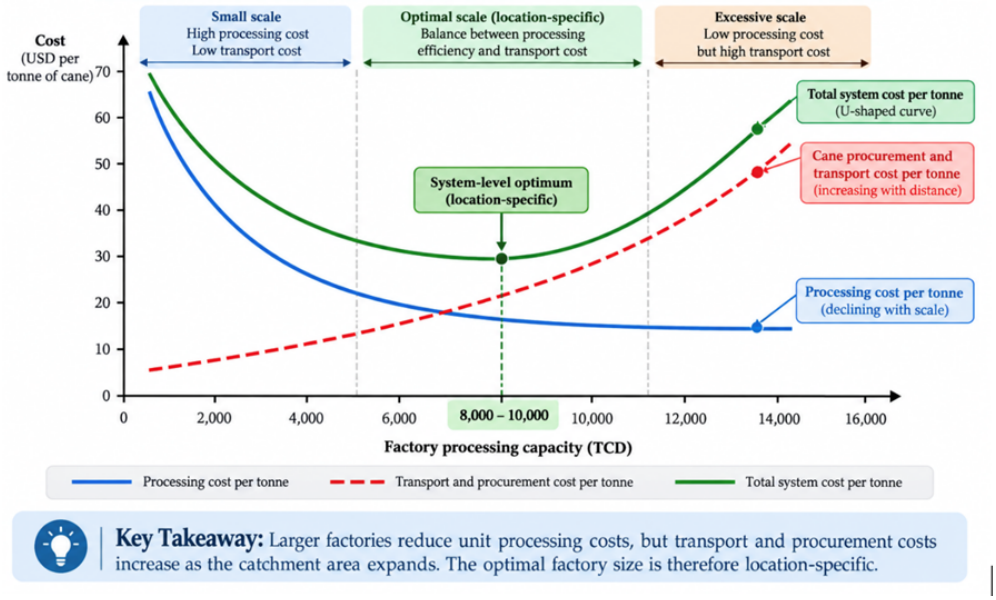


Figure 1: The Scale-Distance Trade-off in Business Unit Consolidation of Sugar Factories.

Figure 1 also shows why the position of the system-level optimum will differ among regions. A high-yield, geographically concentrated cane area with reliable roads may support a larger facility than a region characterized by scattered smallholdings, land conversion, weak roads, competing mills, and volatile farmer participation. For this reason, a fixed TCD threshold applied nationwide risks confusing engineering capacity with economically sustainable capacity [10,11,26].

Farmer–Factory Relationships and Feedstock Security

A large factory has little economic value if it cannot secure sufficient cane during the crushing season. Feedstock security is therefore at least as important as installed capacity. This issue is particularly significant where a substantial proportion of cane is supplied by independent or partner farmers rather than directly controlled estates.

Rokhani et al. [14] found that cooperative membership, extension access, farmer associations, cultivated area, land tenure, and other characteristics influence participation in Indonesian sugarcane contract farming. Hakim et al. [15] further demonstrate heterogeneity among farmers participating in contractual arrangements, indicating that smallholders cannot be regarded as a homogeneous supply group. Partnership quality consequently influences the reliability of industrial feedstock.

Partnerships involve more than contracts. They include input provision, financing, extension, technical assistance, harvest scheduling, transportation, transparency in quality measurement, payment procedures, and perceptions of fairness. Indonesian case studies at PG Takalar and PG Madukismo show that collaboration models, rights and obligations, satisfaction, and social capital influence farmer-factory relationships [30-32].

Recent evidence from Jember makes this issue particularly important for restructuring decisions. Suwandari et al. [16] identify information asymmetry, reliance on factories as information sources, high transaction costs, and unstable supply conditions in which farmers may sell to factories offering higher prices. This implies that the historical concept of a fixed cane territory around one factory is becoming increasingly unreliable where transport capacity and market information allow cane to move across traditional boundaries.

Such mobility can improve farmers' bargaining position but complicate industrial planning. A newly constructed high-capacity unit may appear to have adequate cane within a certain geographic radius when calculated from planted hectares, yet actual deliveries may fall short if neighboring factories offer superior effective prices, better sugar-recovery terms, quicker unloading, faster payment, or more reliable services.

Sahara et al. [33] similarly stress the strategic importance of partnerships between farmers and factories and connect factory performance, waste management, farmer perceptions, and socioeconomic effects. Thus, restructuring programs should treat farmers not simply as suppliers but as economic partners whose allocation decisions determine plant utilization.

This produces an important distinction between **physical cane availability** and **commercially secured cane availability**. The first measures tonnes potentially grown within the region. The second measures tonnes likely to be delivered under realistic prices, contracts, transport costs, relationships, and competition. Only the second quantity should underpin investment decisions.

Methodology

This study adopts a **qualitative literature review** methodology designed to synthesize conceptual, empirical, technological, economic, and institutional evidence relevant to restructuring Indonesia's sugar-processing industry. It is deliberately **not**

a systematic literature review, because its purpose is not to estimate an exhaustive publication universe or conduct a formal meta-analysis. Rather, it uses theoretically guided and purposive literature selection to integrate evidence from fields that are often examined separately: agricultural economics, industrial efficiency, logistics, farmer institutions, biomass engineering, energy, circular economy, and biorefinery development.

Literature published primarily between **2020 and 2026** was prioritized. Indonesian studies were used to establish the institutional, farm, partnership, supply-chain, policy, and industrial context. International studies from Brazil, India, Mexico, South Africa, and other sugar-producing economies were incorporated when they offered transferable insights into mill efficiency, economies of scale, logistics optimization, biomass valorization, and integrated biorefineries.

The search architecture centered on combinations of concepts including *sugar factory efficiency*, *sugarcane technical efficiency*, *economies of scale*, *sugarcane logistics*, *harvesting and transport*, *farmer–mill partnership*, *contract farming*, *sugar industry restructuring*, *bagasse cogeneration*, *molasses valorization*, *vinasse*, *bioethanol*, *circular bioeconomy*, *sugarcane biorefinery*, and *Indonesia sugar self-sufficiency*. Literature was then interpreted through seven themes: **industrial scale; farm productivity; feedstock geography; farmer institutions; supply-chain logistics; circular resource utilization; and industrial restructuring**.

The thematic synthesis follows an explanatory logic rather than merely cataloguing findings. Evidence is used to identify relationships and trade-offs, especially the interaction between factory-scale economies and procurement-distance diseconomies. Research on sugarcane efficiency, for example, was linked to factory utilization because improved cane productivity changes the land area required to supply a given milling capacity [24,25,34]. Research on farmer contracts was linked to investment risk because contractual participation affects whether theoretically available cane becomes commercially secured feedstock [14,15].

Engineering research was treated similarly. Studies on cogeneration, biomass conversion, biogas, fertilizers, and advanced bioproducts were interpreted not merely as separate technologies but as potential sources of additional revenue capable of changing the viable economics of factory modernization and consolidation [18,20,35-37].

This approach allows the review to develop a systems-level proposition: the economic viability of business unit consolidation depends on whether incremental industrial and diversification benefits exceed incremental feedstock, logistics, institutional, transition, and social costs. It therefore avoids treating factory capacity as an isolated engineering variable and instead interprets restructuring as a coupled agricultural-industrial decision problem.

Because the review is qualitative rather than systematic, it does not claim exhaustive coverage, formal publication weighting, or pooled effect estimates. Cross-country evidence is used as an analytical comparator, and its transferability to Indonesia must be tested against local cane density, transport infrastructure, farmer institutions, policy settings, energy markets, and capital costs.

Results: Thematic Findings

Theme 1 — Scale Can Improve Industrial Economics, but Capacity Utilization Is Decisive

The literature provides credible evidence that scale can improve economic performance. Danelon et al. [8] find that sugar-ethanol factories may increase total factor productivity through greater production scale, while Dotta e Silva and Périco [7] identify economies-of-scale advantages among larger Brazilian plants. These findings provide a legitimate theoretical basis for considering business unit consolidation where several inefficient factories operate within a geographically coherent cane region.

However, nominal capacity and realized throughput must be distinguished. A 10,000-TCD factory operating at a high utilization rate can distribute fixed costs across considerably more output than several small factories. A nominally efficient plant operating far below capacity because of insufficient cane can instead generate high capital costs per tonne. Consequently, the relevant variable is not installed TCD alone but **effective seasonal throughput relative to design capacity**.

This point connects mill investment directly with farm productivity. Rosidah et al. [24] estimate technical, allocative, and economic efficiency among PTPN X partner farmers and identify opportunities to improve farm performance. Santosa et al. [25] likewise examine technical efficiency in East Java. Improvements in farm productivity effectively increase cane density around a factory, allowing more feedstock to be obtained from a smaller geographical area.

Thus, business unit consolidation can be strengthened by an explicit upstream productivity program encompassing improved varieties, ratoon management, irrigation, fertilizer efficiency, mechanization where appropriate, extension, climate adaptation, and planting coordination. Hasibuan et al. [38] demonstrate the importance of farmer support systems and adaptation capabilities under climate risk, indicating that feedstock security also has a resilience dimension.

An investment strategy that modernizes the factory but neglects agricultural productivity can therefore transfer inefficiency upstream rather than eliminate it. Factory modernization and farm-productivity improvement should consequently be evaluated as mutually dependent components of the same regional production system.

Theme 2 — The Logistics Penalty Can Offset Factory-Level Economies of Scale

Transport is the principal structural constraint on unlimited mill enlargement. The larger the facility, the more cane must arrive

daily and the more precisely harvesting and transport need to be synchronized. Sugarcane logistics is therefore both a cost problem and a time-management problem.

Morales Chavez et al. [11], Almeida et al. [12], Utomo et al. [13] and Purnomo and Supartiningrum [27] consistently demonstrate that cane harvesting and transportation benefit from integrated optimization. Waiting time matters because trucks, harvesting teams, and mill reception capacity interact. Under poorly coordinated systems, increasing factory size can merely relocate bottlenecks from processing equipment to roads, loading sites, weighbridges, or mill yards.

Misra et al. [10] add a biological dimension by showing that extended delays after harvest contribute to sucrose deterioration. Rahayu et al. [28] similarly report that harvest-and-transport practices can affect juice quality in an Indonesian context. Consequently, a restructuring model must optimize harvest-to-crush continuity rather than focus on transport capacity alone.

This evidence also suggests that the technical feasibility of long-distance cane transport should not be confused with economic optimality. Whether longer movements maximize total system value depends on road quality, fuel and labor costs, recovery losses, vehicle productivity, queueing, alternative factory destinations, and the value of cane at the receiving plant. These factors become progressively more important as a larger factory extends its procurement area.

For feasibility studies, catchment distance should therefore be modeled as an endogenous outcome rather than an administratively fixed radius. GIS-based cane mapping, road-network analysis, crop-yield mapping, seasonal transport simulation, and competing-factory behavior should determine the economically relevant catchment. This systems logic is consistent with robust sugarcane bioenergy network design, in which location, feedstock allocation, uncertainty, and sustainability objectives are evaluated jointly [29].

$$S_{secured} = P_{physical} \times R_{participation} \times R_{delivery} \times R_{retention} \quad (1)$$

Theme 3 — Farmer Choice Has Become an Industrial Capacity Variable

Historically, sugar factories and cane-growing regions often developed long-lived geographical and institutional relationships. Such relationships may still matter, but recent evidence suggests that economic incentives increasingly influence cane allocation.

Rokhani et al. [14] demonstrate that institutional participation affects farmer engagement in contract farming. Purnama et al. [31] and Trimerani and Ismiasih [32] show the continued importance of partnership systems and social capital, whereas Suwandari et al. [16] identify market information, transaction costs, and farmer movement toward more attractive factory offers as important contemporary supply-chain characteristics.

For industrial planning, this means that farmer behavior should enter the capacity equation. A practical representation of commercially secured cane is provided in Equation (1), which separates agronomic production potential from participation and delivery behavior.

Equation (1) distinguishes commercially secured cane from physical cane production. The three rate terms represent farmer participation, delivery commitment, and retention, respectively, thereby separating cane that can be produced from cane that is commercially likely to be delivered to the target factory.



Figure 2: Farmer-Factory Feedstock Allocation Framework.

These rates depend on price, recovery calculation, transparency, weighing systems, waiting time, credit, input support, harvest services, transport arrangements, payment reliability, interpersonal trust, and competing buyers. Putri et al. [39] and other partnership studies underline the institutional importance of contractual structure, while Ndlela and Worth [40] emphasize farmer capacity and livelihood sustainability in smallholder sugar systems.

Figure 2 highlights why cane availability should not be estimated solely from hectares planted around a factory. Farmers allocate cane according to the economic and institutional value offered by alternative processing units, so the commercially secured feedstock base may differ materially from the physical production base.

Figure 2 illustrates that a high-capacity factory can protect utilization not simply by increasing the procurement radius but by increasing the likelihood that farmers within its efficient radius choose to supply it. Better transparency in recovery measurement, predictable payments, competitive pricing, lower waiting times, credit, extension, and efficient transportation can therefore substitute partly for excessively large geographical procurement zones.

Theme 4 — Business Unit Consolidation Can Create a Platform for Energy and Co-product Integration

Factory size becomes more economically interesting when sugar is not the sole product. Bagasse represents a major source of process energy and electricity, and energy-system improvements can significantly affect industrial performance. Cavalcanti et al. [35] demonstrate the relevance of energy, exergy, and environmental performance in bagasse cogeneration, while advanced configurations continue to seek greater useful energy recovery.

Konde et al. [18] argue that restricting bagasse primarily to conventional steam and electricity generation can overlook higher-value biorefinery opportunities. Ajala et al. [41] similarly review the broad energy, environmental, and economic potential of bagasse, while more recent biorefinery research emphasizes integrated conversion pathways that combine fuels, energy, and higher-value products [21].

Shabbirahmed et al. [37] identify routes including pyrolysis, gasification, cogeneration, fermentation, lignin utilization, biofuels, bioplastics, adsorbents, and organic acids. Experimental work has also demonstrated bioethanol production from sugarcane bagasse, while subsequent studies have expanded attention to bagasse-derived lactic acid and biochar applications [42-44].

The important economic insight is that diversification can change optimal factory scale because some technologies have their own minimum efficient scales. A larger, reliable biomass stream may make investments feasible that would not be economical for a small factory. Morakile et al. [45], for example, demonstrate through techno-economic assessment that integrated sugarcane biorefineries producing higher-value chemicals can achieve attractive performance under selected configurations.

Business unit consolidation can therefore potentially create **scope economies in addition to scale economies**. The gain is no longer simply lower sugar-processing cost; it is the ability to integrate sugar, energy, fuel, fertilizer, and biochemical value chains around the same feedstock.

Theme 5 — Molasses, Vinasse, Filter Cake, and Organic Residues Change the Meaning of "Waste"

The circular-bioeconomy literature increasingly treats sugar-industry residues as intermediate resources. Meghana and Shastri [17] frame sugar-industry residues as candidates for sustainable valorization through biofuel and value-added chemical pathways. Zhang et al. [19] review microbial conversion of molasses into fuels, polysaccharides, oligosaccharides, organic acids, and enzymes, while recent reviews extend this perspective toward more integrated waste-to-energy and full-component valorization strategies [22,46].

Vinasse provides another example. Buller et al. [47] investigate spatially explicit pathways for nutrient recovery and energy generation from vinasse. Carpanez et al. [48] review its use as organo-mineral fertilizer feedstock while warning that unmanaged application creates environmental risks, whereas Carpanez et al. [49] demonstrate integrated membrane-based approaches capable of recovering water, fertilizer products, and energy.

Kiani et al. [36] analyze anaerobic reactor configurations for biogas production from vinasse and note both substantial potential and the need for appropriate operating conditions. Mendieta et al. [50], using life-cycle assessment in a cane-processing context, likewise demonstrate how anaerobic digestion can contribute to circular-bioeconomy outcomes by generating energy and digestate while reducing environmental burdens.

Chatterjee and Mohan [51] extend this logic by demonstrating an integrated system for hydrogen, ethanol, and fertilizer-related resource recovery from bagasse streams. Lee et al. [20] review sugarcane waste streams as microbial feedstocks within a broader biorefinery framework, reinforcing the argument that residues should be evaluated as potential value streams rather than disposal liabilities.

Figure 3 reframes a modern sugar factory as an integrated material-conversion platform. Sugar remains central, but economic returns can increasingly depend on the productive use of bagasse, molasses, vinasse, filter cake, and other streams, which collectively broaden the revenue base and resource-efficiency potential of the processing system.

Figure 3 illustrates how this framework changes the financial assessment of restructuring. Two factories with similar sugar recovery may differ substantially in profitability if one exports

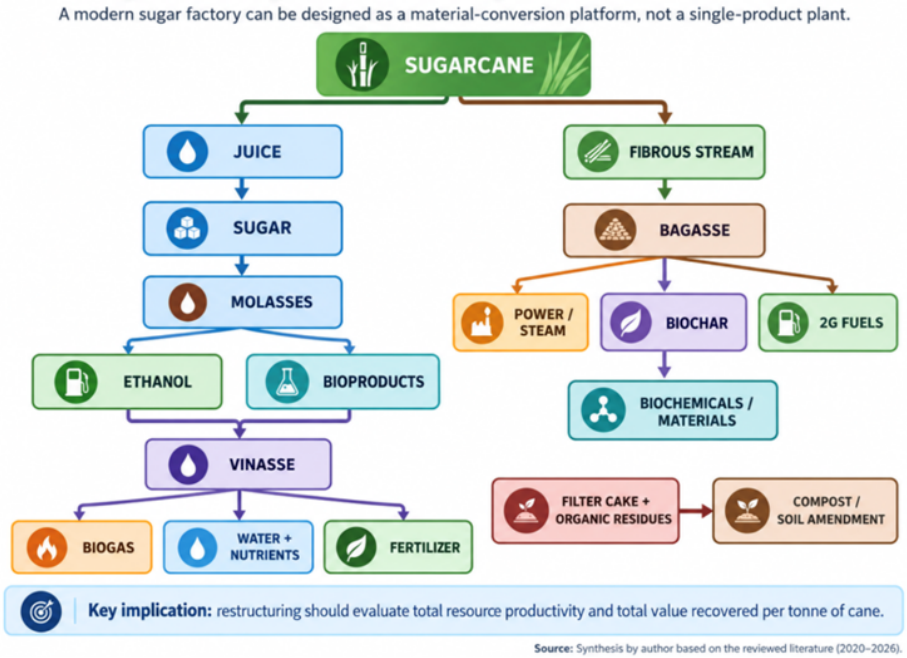


Figure 3: Integrated Circular Sugarcane Value Cascade.

electricity, produces ethanol, converts wastewater into biogas, recovers fertilizer nutrients, and produces higher-value materials. Business unit consolidation should therefore be evaluated using total resource productivity rather than sugar yield alone.

Discussion and Analysis

The Central Proposition: Bigger Is Conditional, Not Automatically Better

The literature supports neither indiscriminate retention of old small factories nor indiscriminate replacement with very large factories. Instead, it supports conditional restructuring.

A large modern factory offers four broad advantages: lower average fixed costs at sufficient utilization; access to modern extraction and automation technologies; improved energy integration; and greater capacity to support diversified biorefinery investments. Danelon et al. [8], Dotta e Silva and Périco [7], Cavalcanti et al. [35] and Konde et al. [18] collectively support different components of this proposition. Multi-objective optimization and life-cycle assessment further reinforce the need to evaluate economic and environmental performance jointly rather than assuming that a single scale indicator captures system performance [52,53].

Against these advantages stand at least six potential disadvantages: greater cane requirements; expansion of procurement distance; more complex harvest and transport coordination; increased vulnerability to farmer switching; potentially greater regional consequences when older facilities close; and the risk of expensive underutilized capacity. These countervailing effects explain why business unit consolidation should be evaluated at the level of the whole cane-to-product system rather than at the factory gate alone.

This balance can be represented conceptually by Equation (2). The expression is intended as a decision framework for organizing benefits and costs rather than as an empirically estimated structural equation.

$$NB_{BUC} = SE + TE + EE + DV + DR - (LC + FR + IC + SC + TC) \quad (2)$$

In Equation (2), the left-hand term denotes the net benefit of business unit consolidation. SE, TE, EE, DV, and DR denote scale-economy gains, technological-efficiency gains, energy-efficiency gains, diversification and by-product value, and reductions in duplicated overhead, respectively, whereas LC, FR, IC, SC, and TC denote incremental logistics cost, feedstock-security risk, infrastructure cost, social and spatial adjustment costs, and transition and stranded-asset costs.

The policy implication is that the decision variable should not be framed simply as how many factories can be closed. A more defensible question is which configuration generates the highest resilient value across the agricultural-industrial system after the relevant benefits, risks, and transition costs have been internalized.

Evaluating a 10,000-TCD Scenario Rather Than Treating It as a Universal Rule

For analytical purposes, a 10,000-TCD facility can serve as a useful restructuring scenario. However, the literature on scale, transport, and feedstock procurement does not justify treating any single capacity threshold as universally optimal.

An indicative calculation illustrates why. If daily crushing capacity doubles but cane yield, planting density, and crushing-season length remain unchanged, the required sourcing area must also approximately double. If available cane land expands geographically rather than through yield intensification, average

delivery distance increases. Tregeagle and Zilberman's [26] modeling framework demonstrates the general mechanism by which larger processing requirements increase feedstock delivery costs through larger growing regions.

The appropriate approach is therefore to model alternative capacities - for example 4,000, 6,000, 8,000, 10,000, and 12,000 TCD, or other locally relevant scenarios - against actual regional feedstock density, road networks, season length, expected yield, harvest capacity, neighboring factory demand, farmer participation, and expansion potential. Sensitivity analysis should then test how the preferred capacity changes when these assumptions vary.
Such modeling could reveal that 10,000 TCD is appropriate in one cluster, excessive in another, and too small in a third. The concept of **region-specific minimum efficient scale** is therefore more defensible than a standardized capacity mandate.

Business Unit Consolidation Requires Consolidating the Supply System, Not Only Factory Assets

A key analytical insight emerging from this review is that restructuring cannot stop at the factory gate. Physically replacing multiple plants with one larger facility without reorganizing upstream cane production and logistics would represent incomplete restructuring.

The required complementary architecture includes coordinated planting calendars, reliable varieties and seed systems, farmer extension, mechanization strategies, harvesting capacity, truck fleets, collection points, road investment, digital scheduling, transparent weighing, laboratory systems, and rapid payment. These elements determine whether nominal factory capacity can be translated into reliable seasonal throughput.

Asrol et al. [54] demonstrate that sugarcane supply-chain sustainability involves economic, social, environmental, and resource dimensions and identify multiple clusters of improvement strategies. This multidimensional perspective is highly relevant because improving only the factory may generate limited benefits when upstream constraints continue to disrupt cane flow.

Fielke et al. [55] show that digitalization in sugarcane agriculture depends not merely on technology availability but on how information is embedded in farmer and advisory networks. More recent research identifies real-time monitoring, data integration, communication infrastructure, and interoperability as critical challenges and opportunities for digital sugarcane production [56]. Together, these findings support the use of digital cane-registration systems, geospatial production maps, harvesting schedules, real-time truck dispatch, queue monitoring, farmer portals, and transparent recovery reporting.

Modern business unit consolidation should therefore increasingly be conceived as physical consolidation plus digital and institutional integration. Without these complementary capabilities, additional processing capacity may amplify existing coordination failures rather than resolve them.

Farmer Welfare Must Be Embedded in the Industrial Design

Business unit consolidation can potentially improve farmer welfare when more efficient factories increase cane demand, provide predictable procurement, support higher recovery, reduce payment delays, expand extension services, and lower unit industrial costs. It can also create disadvantages when factory relocation increases farmer transport distances, weakens bargaining power, or imposes transition costs on communities previously organized around existing plants.

A farmer-centered model therefore requires transparent cane pricing, transparent recovery measurement, accessible laboratory verification, predictable payment schedules, fair transport-cost allocation, affordable financing, agronomic support, and dispute-resolution mechanisms. These arrangements influence both farmer welfare and the probability that projected cane volumes become dependable factory feedstock.

Rokhani et al. [14], Hakim et al. [15], Purnama et al. [31], Trimerani and Ismiasih [32], Sahara et al. [33] and Suwandari et al. [16] collectively demonstrate the institutional significance of farmer characteristics, contracts, collaboration, social capital, information, perceptions, and bargaining conditions. The evidence indicates that feedstock security is partly an institutional outcome rather than a simple function of planted area.

Consequently, a business-unit restructuring feasibility study should contain a Farmer Supply and Welfare Module alongside engineering and financial modules. Such a module should test the distribution of benefits and costs across farmer groups and examine how contractual terms influence participation, retention, and delivery behavior.

From Sugar Recovery to Total Cane Value

Traditional performance indicators often emphasize cane throughput and sugar recovery. These remain indispensable, but the circular-bioeconomy literature suggests a broader metric for evaluating the total economic value recoverable from each tonne of cane, as represented in Equation (3).

$$TCV = V_s + V_e + V_{eth} + V_{bg} + V_f + V_b - C_{env} \quad (3)$$

In Equation (3), TCV denotes total cane value. The six positive value terms represent sugar, electricity or energy, ethanol, biogas, fertilizer or resource recovery, and other bioproducts, respectively, while the final cost term represents environmental-management costs and externalities.

This broader perspective is consistent with research on waste valorization, bagasse biorefineries, molasses conversion, vinasse resource recovery, advanced fermentation, and biochar [17-20,37,41,44,48]. Recent reviews further emphasize the importance of integrating component separation, process coupling, techno-economic constraints, and high-value outputs when designing future sugarcane biorefineries [22,44,46].

Under this approach, modernization becomes an opportunity to create an **integrated sugar–energy–bioeconomy platform**. This can improve resilience because revenue no longer depends entirely on a single output market.

A Proposed Three-Pathway Framework for Indonesia

The principal contribution of this review is a differentiated restructuring framework. Existing factories should first undergo a multidimensional diagnostic covering machinery, extraction, energy, maintenance, cane availability, transport, farmer relationships, potential for expansion, environmental systems, cultural or historical value, and alternative asset uses. This diagnostic prevents a predetermined preference for retention, enlargement, or closure from substituting for evidence-based evaluation.

Figure 4 translates the preceding evidence into a decision sequence linking diagnostic conditions to three distinct restructuring pathways: revitalization, consolidation and replacement, or repurposing. The framework emphasizes that restructuring should begin with the characteristics of the factory and its surrounding cane system rather than with a predetermined target size.

As shown in Figure 4, each pathway corresponds to a different combination of feedstock conditions, asset quality, location, and modernization potential. The framework is intended as a screening architecture for subsequent engineering, financial, social, and environmental appraisal rather than as a mechanical decision rule.

Pathway A — Revitalize

Revitalization is appropriate where an existing factory occupies a strong cane-production zone, has reasonable transportation access, retains commercially viable farmer relationships, and can achieve competitive recovery and energy efficiency through modernization. In such cases, preserving locational and institutional advantages may generate greater system value than shifting cane to a more distant replacement facility.

Revitalization could involve milling equipment, boilers, turbines, automation, process control, sugar-loss reduction, predictive maintenance, digital cane scheduling, wastewater management, and selected diversification investments. Li et al. [23] illustrate the scope for operational optimization within milling systems, demonstrating why closure should not automatically be the first response to inefficiency.

Pathway B — Consolidate and Replace

This pathway is appropriate where several old units operate below efficient scale, duplicate overheads, require large rehabilitation expenditure, and are located within a broader cane region capable of sustainably supporting a modern centralized facility. Its viability depends on whether regional feedstock and logistics can sustain high utilization without imposing disproportionate costs on farmers or the transport system.

However, the new plant should be designed only after a geospatial feedstock study identifies the viable procurement radius. Procurement scenarios should incorporate competing factories, farmer-switching behavior, transport costs, recovery deterioration, seasonal yield variability, and climate risk.

The new facility should preferably be designed as an **integrated processing hub**, not simply a larger version of an old sugar mill. Cogeneration, ethanol, biogas, nutrient recovery, water recycling, and additional product pathways can improve the economics of the transition.

Pathway C — Repurpose

Where the cane base is structurally declining, location is no longer economically advantageous, and modernization cannot generate

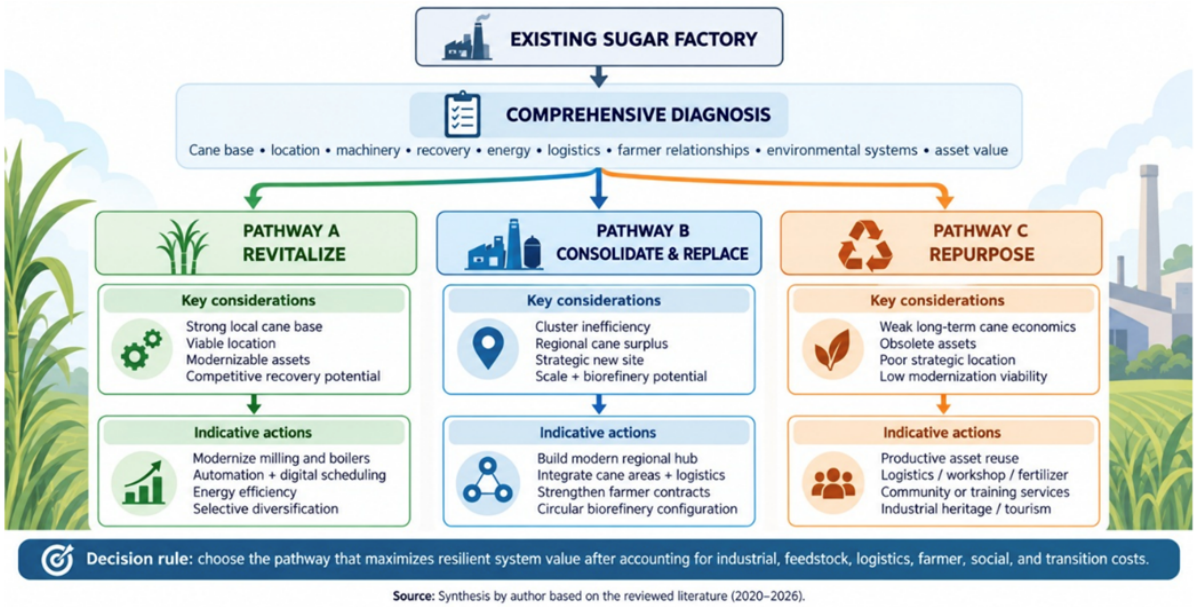


Figure 4: Three-Pathway Decision Framework for Existing Sugar Factories.

competitive performance, retaining sugar-processing activity may destroy value. In these cases, a planned transition toward productive reuse can protect part of the economic and social value embedded in the site while avoiding repeated expenditure on structurally uncompetitive processing assets.

Closure, however, need not mean abandonment. Older sites may contain land, buildings, utilities, workshops, warehouses, transport access, heritage architecture, housing, and community infrastructure. Depending on location, these assets might support agricultural service centers, machinery workshops, fertilizer plants, logistics facilities, vocational training, health facilities, industrial heritage, tourism, renewable-energy activities, or other productive uses.

This pathway is particularly important for reducing the social and territorial cost of restructuring. A complete business case should therefore assign value not only to the replacement factory but also to the **post-processing economic function of the former site**.

Policy Implications for Sustainable Sugar Self-Sufficiency

Indonesia's pursuit of stronger domestic sugar production cannot depend on factory investment alone. Studies of imports and national sugar dynamics consistently point to interactions among domestic productivity, demand, policy, farm efficiency, technology, and processing performance [1-4,57]. Comparative evidence from India similarly emphasizes that sustainable sugar-sector self-reliance requires coordinated improvements across production, processing, diversification, and institutional support [6].

A sustainable restructuring strategy should therefore proceed through **regional sugar systems** rather than isolated factory projects. Each region requires an integrated map of cane land, yield, farmer numbers, ratoon age, water availability, transport infrastructure, factory capacities, extraction performance, competing mill demand, and potential land conversion. The objective is to identify where industrial scale can expand without creating disproportionate procurement costs.

Second, feasibility studies should distinguish **theoretical cane**, **marketable cane**, and **secured cane**. Theoretical cane is agronomically producible; marketable cane is economically viable to harvest and transport; secured cane is likely to be delivered to the target factory. Financing decisions should rely primarily on the third measure.

Third, investment evaluation should adopt a system-cost methodology. Conventional factory-level cost comparisons may make large plants appear strongly superior because they capture processing economies while ignoring additional field-to-factory costs. Logistics, road investment, loading, harvesting, queueing, post-harvest deterioration, farmer incentives, and transition costs must be internalized, while life-cycle evidence indicates that environmental burdens should also be evaluated across the sugarcane supply chain rather than only at the processing site [53].

Fourth, farmer profitability should become a formal restructuring criterion. Increasing domestic sugar supply requires farmers to continue allocating land and capital to cane. A factory cannot secure sustainable feedstock by transferring excessive logistical or price risk to growers.

Fifth, circular biorefineries should be integrated selectively rather than treated as decorative environmental components. Technologies must be chosen according to feedstock volume, product markets, capital requirements, technological maturity, infrastructure, regulatory conditions, and synergies with existing processes. Conventional bagasse cogeneration is relatively mature, whereas advanced chemicals and second-generation pathways may require stronger technological, market, and integration validation [18,22,35,37].

Sixth, digital integration offers a potentially high-value enabling layer. Digital maps of farmer plots, expected yields, harvest maturity, cane quality, truck movements, factory queues, and payment status can reduce information asymmetry and improve coordination. Fielke et al. [55] show that digital innovation must be embedded in trusted agricultural knowledge systems, while Molin et al. [56] emphasize persistent challenges involving connectivity, data interoperability, and integration across mechanized sugarcane operations.

Finally, government and industry should resist using the number of new factories or nominal installed TCD as the principal measure of progress. More meaningful performance indicators include tonnes actually crushed relative to capacity, sugar recovery, recoverable sugar per hectare, farmer net returns, average cut-to-crush time, logistics cost per tonne, energy generated per tonne of cane, total co-product revenue, water reuse, waste valorization, and total value generated per tonne of cane.

Conclusion

This qualitative literature review demonstrates that business unit consolidation can form an important component of Indonesia's sugar-industry restructuring, but its economic value is conditional. The potential advantages of larger and more modern processing units are substantial, including scale economies, improved utilization of advanced technology, reduced duplication of fixed costs, better energy efficiency, more sophisticated automation, and stronger potential for integrated by-product utilization. These advantages become most relevant where sufficient cane can be secured and the resulting capacity can be utilized reliably across the crushing season.

However, sugar processing differs fundamentally from conventional manufacturing because industrial scale is inseparable from agricultural geography. Increasing milling capacity increases feedstock requirements. Unless cane productivity and local supply density rise sufficiently, larger facilities require larger catchment areas, longer transportation distances, more complex harvest scheduling, and greater coordination among farmers, trucks, harvesting contractors, and factories. These effects can offset

factory-level cost reductions.

Farmer behavior constitutes a second major constraint. Cane is increasingly better understood as commercially contestable feedstock rather than as automatically captive supply. Farmers evaluate prices, sugar recovery, transport costs, waiting times, payment reliability, technical support, financing, and trust. Therefore, high-capacity factories must compete not only through processing technology but also through superior farmer relationships and supply-chain services.

A third finding concerns the transformation of the sugar factory itself. Modern restructuring should move beyond a single-product concept. Bagasse, molasses, vinasse, filter cake, wastewater, and other streams can support electricity, ethanol, biogas, fertilizer, biochar, water recovery, and potentially higher-value biochemicals. The relevant objective therefore becomes maximizing **sustainable total value per tonne of cane**, not simply maximizing tonnes crushed.

Accordingly, this review proposes a three-pathway strategy: revitalize factories that retain strong locational and feedstock advantages; consolidate and replace clusters where regional scale economies clearly exceed additional logistics and transition costs; and repurpose facilities where neither continued operation nor modernization is economically defensible. The appropriate pathway should emerge from transparent, region-specific diagnosis rather than from a uniform national rule on factory size.

Indonesia's future sugar system would consequently benefit from moving away from a uniform factory-size paradigm toward a **region-specific industrial network** combining productive farms, reliable partnerships, optimized logistics, efficient factories, digital coordination, and circular-biorefineries. Business unit consolidation should be understood as one instrument within this broader transformation—not as an objective in itself.

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