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Energy Cane for Indonesia's E20 Transition: From High-Biomass Agronomy to Integrated 1G–2G Bioethanol on Suboptimal Land

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ABSTRACT

Indonesia's emerging E20 gasoline–ethanol agenda creates a feedstock challenge that cannot be resolved by considering ethanol-processing capacity alone. Large-scale deployment requires an integrated assessment of feedstock productivity, land suitability, conversion efficiency, logistics, environmental performance, and industrial readiness. This qualitative literature review examines whether energy cane—a high-biomass *Saccharum* feedstock bred more strongly for vegetative biomass than sucrose concentration—could complement conventional sugarcane and other crops in Indonesia's bioethanol transition. Recent evidence shows that energy-cane genotypes can substantially outperform conventional sugarcane in biomass and fiber yield, although performance varies considerably among genotypes and environments. Type I energy cane retains sufficient fermentable sugars to support first-generation ethanol while supplying additional lignocellulosic biomass, whereas high-fiber Type II material depends much more strongly on economically viable second-generation conversion. Consequently, high biomass productivity cannot automatically be interpreted as high commercially recoverable ethanol productivity. The review further finds that “suboptimal” or “marginal” land should not be treated as unused land: biophysical suitability, existing livelihoods, biodiversity, water resources, infrastructure, tenure, and opportunity costs must be considered simultaneously. Integrated 1G–2G biorefineries, cogeneration, and coproduct valorisation could strengthen the economics of energy cane, but pretreatment, enzymes, pentose fermentation, capital intensity, and biomass logistics remain significant constraints. A staged Indonesian pathway centered on genotype evaluation, spatially explicit land screening, demonstration-scale integration with existing sugar infrastructure, and progressively larger 2G deployment is therefore proposed.

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Introduction

Indonesia's renewed interest in ethanol-blended gasoline represents more than a fuel-substitution programme. It potentially links transport-energy security, agricultural development, bioindustrialisation, land policy, technology acquisition, rural investment and greenhouse-gas mitigation. On 27 June 2026, the Ministry of Energy and Mineral Resources reported national gasoline demand of approximately 40 million kilolitres (kL) per year and a government planning requirement of approximately 4 million kL of ethanol for E20. Ethanol-gasoline blending is technically established for spark-ignition applications, but national deployment depends on fuel specifications, market coverage, feedstock supply and infrastructure (Kementerian Energi dan Sumber Daya Mineral, 2026) [1].

The scale of the prospective programme makes feedstock availability a central problem. If a 20% volumetric ethanol share were applied illustratively to a 40 million kL reference gasoline volume, the arithmetic requirement would be approximately 8 million kL of ethanol, whereas the June 2026 government planning

statement cited approximately 4 million kL. These figures should therefore not be treated as interchangeable they reflect different assumptions about the effective market and blending denominator. This review consequently treats Indonesian ethanol demand as scenario-dependent because cropland, feedstock tonnage, fermentation capacity, storage, logistics and capital requirements all depend on the effective blending coverage (Kementerian Energi dan Sumber Daya Mineral, 2026).

The feedstock narrative is also changing rapidly. On 16 September 2026, the Presidential Secretariat reported a government objective to prepare domestic E20 production within approximately two years and identified sugarcane as the most feasible large-scale ethanol feedstock discussed at that meeting, with around 2 million ha of land mentioned in the associated planning. Five days later, the Ministry of Agriculture described up to 2 million ha for a broader three-feedstock portfolio comprising sugarcane, cassava and maize, while the Directorate General of Estate Crops separately mapped potential sugarcane development of approximately 700,000–1,000,000 ha with indicative ethanol productivity of around 3,100–4,900 L/ha. These dated announcements demonstrate that the feedstock and land-allocation framework remained under development as of 22 September 2026 rather than constituting one final, fully allocated single-crop programme (Sekretariat Presiden Republik Indonesia, 2026; Kementerian Pertanian Republik Indonesia, 2026; Direktorat Jenderal Perkebunan, 2026).

Conventional sugarcane is an obvious candidate because it combines an established agricultural system with a mature sucrose-fermentation route. Nevertheless, expansion for ethanol must coexist with sugar production, regional land competition, seasonal milling capacity, irrigation constraints and the need to avoid shifting environmental burdens elsewhere. Modern sugarcane biorefineries can produce sugar, ethanol, steam, electricity and multiple coproducts, yet system performance depends strongly on feedstock composition and allocation of bagasse between electricity and cellulosic ethanol [2–7].

These constraints provide the rationale for investigating energy cane. Energy cane comprises *Saccharum* hybrids selected more intensively for biomass yield, tillering, fiber content, ratooning and—in some germplasm—stress tolerance than for maximum sucrose concentration. Comparisons between conventional sugarcane and energy-cane materials demonstrate important differences in developmental patterns, biomass partitioning, fiber concentration, non-structural carbohydrate metabolism and total biomass productivity. Recent evaluation of novel accessions has further demonstrated that particular clones can generate substantially greater energy and potential 2G ethanol per unit area than conventional sugarcane, although their suitability for crystallised sugar production is generally poorer. This distinction produces two strategically different feedstock classes. Type I energy cane generally represents an intermediate sugar–fiber phenotype: it may retain useful quantities of fermentable sugar while generating considerably more structural biomass. Type II material is more strongly biomass-oriented and therefore has greater dependence on lignocellulosic processing. The relevance of this distinction to Indonesia is fundamental [9–11].

Type I material could theoretically be introduced into systems where conventional juice fermentation already exists, whereas the value proposition of Type II energy cane depends far more heavily on whether commercially viable second-generation ethanol, advanced cogeneration, or other biomass-valorisation routes are available. A second source of potential misunderstanding concerns

land. Indonesia has frequently been described as possessing very large areas of marginal or suboptimal land, including an historical estimate of approximately 149.5 million ha used in the initial scoping material. Contemporary literature cautions strongly against treating “marginal land” as synonymous with unused, unoccupied or environmentally dispensable land because marginality can be agronomic, economic, infrastructural or institutional. Areas with low conventional crop productivity may nevertheless support local livelihoods, customary land uses, ecosystem services or high biodiversity values, and water limitations can materially reduce technically suitable bioethanol potential (Pancaldi and Trindade). The central analytical proposition of this review is therefore not that high-biomass energy cane can automatically “solve” E20 feedstock requirements. Rather, energy cane becomes strategically relevant only when agricultural biomass production, fermentable composition, conversion technology, logistics, biorefinery configuration, land suitability and environmental performance are considered together. The relevant productivity metric is ultimately not simply tonnes of fresh cane per hectare but sustainably deliverable litres of ethanol and other valuable energy products per hectare over repeated production cycles. Accordingly, this article addresses six questions: (1) to what extent could energy cane complement conventional feedstocks for an Indonesian E20 transition; (2) how do Type I and Type II energy cane differ in their roles in 1G and 2G ethanol systems; (3) under what conditions could energy cane be deployed on suboptimal land; (4) which technological and economic bottlenecks limit 2G utilisation; (5) how might integrated biorefineries improve whole-biomass value; and (6) what research and deployment sequence follows from the international evidence for Indonesia. Together, these questions frame energy cane as an integrated feedstock–technology–land system rather than as a yield-maximising crop considered in isolation. The relationship between the E20 target and land requirement is not linear because ethanol demand must first be translated into feedstock requirements, and those requirements depend on crop yield, fermentable composition and conversion efficiency [12–18].

Figure 1: Therefore, Separates the Policy Target from the Agronomic and Industrial Variables That Ultimately Determine Land Demand

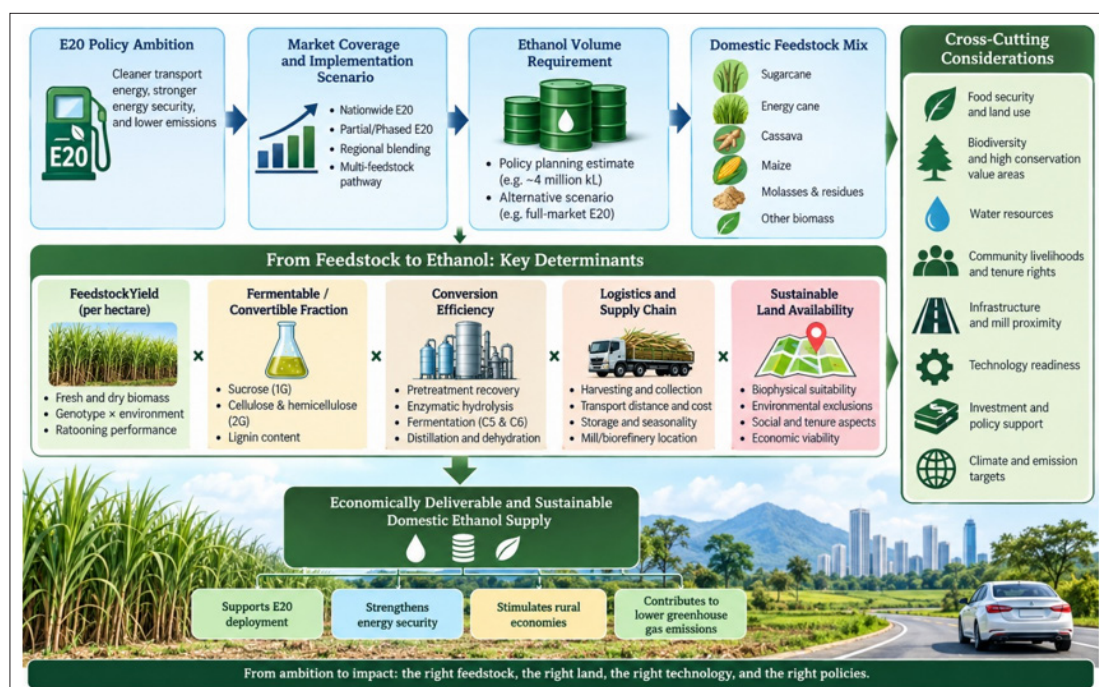


Figure 1: Analytical Chain Linking Indonesia's E20 Ambition to Sustainable Feedstock Requirements

Figure 1 highlights why a headline biomass yield cannot directly answer the E20 question. Two cultivars producing similar fresh biomass may deliver different ethanol yields because their sucrose, cellulose, hemicellulose, lignin and moisture profiles differ. Similarly, theoretical ethanol production can diverge considerably from commercially delivered ethanol after pretreatment recovery, enzymatic hydrolysis, fermentation and logistical losses are considered [19-22].

Literature Review

Energy Cane as a Bioenergy Feedstock

Energy cane emerged from breeding strategies that relax the conventional emphasis on stalk sucrose concentration and instead exploit the biological capacity of *Saccharum* germplasm to accumulate large quantities of lignocellulosic biomass. Interspecific germplasm incorporating characteristics associated with *S. spontaneum* can express vigorous tillering, high fiber content and substantial total dry matter. Comparative developmental research indicates that biomass advantages arise from whole-plant architecture and carbon partitioning rather than from a single trait. The term “energy cane”, however, covers substantial genetic diversity. Recent analysis of 190 genotypes identified meaningful variation in cellulose, hemicellulose and lignin composition, with implications for potential ethanol, xylitol and other biorefinery outputs. This reinforces the principle that energy-cane development should target specific end uses rather than assume all high-biomass genotypes are functionally equivalent. Plant development also affects industrial quality. Internode age influences cell-wall architecture and recalcitrance, while lignin and xylose distribution can affect enzymatic accessibility. Metabolomic evidence further suggests differences between conventional sugarcane and energy cane in patterns of starch, hexose and non-structural carbohydrate accumulation. These findings imply that harvest timing may need optimisation for the intended biorefinery process rather than solely for maximum field tonnage [23,24].

Type I and Type II: Different Industrial Propositions

Type I energy cane retains a meaningful soluble-sugar fraction and can therefore offer a transitional route between conventional sugarcane processing and biomass-oriented systems. The soluble fraction can be extracted and fermented using established 1G technology, while bagasse and field residues provide feedstock for cogeneration or 2G processing. In comparative accessions, particular high-biomass clones have demonstrated the possibility of producing greater quantities of 1G ethanol per hectare despite lower sugar concentration, because higher agricultural yield compensates for compositional dilution. Type II energy cane shifts further toward fiber and total biomass. Its potential advantage therefore becomes much more dependent on efficient cellulose and hemicellulose conversion. A tonne of high-fiber material is not equivalent to a tonne of readily fermentable sugar because lignocellulosic carbohydrates must first be made accessible through pretreatment and hydrolysis, while fermentation organisms must efficiently utilise the resulting C5 and C6 sugars. Energy-cane biomass can therefore be highly productive agronomically while remaining economically constrained if 2G conversion is inefficient. These differences by linking feedstock composition to the relative dependence of each cane type on 1G, 2G and cogeneration pathways [25-27].

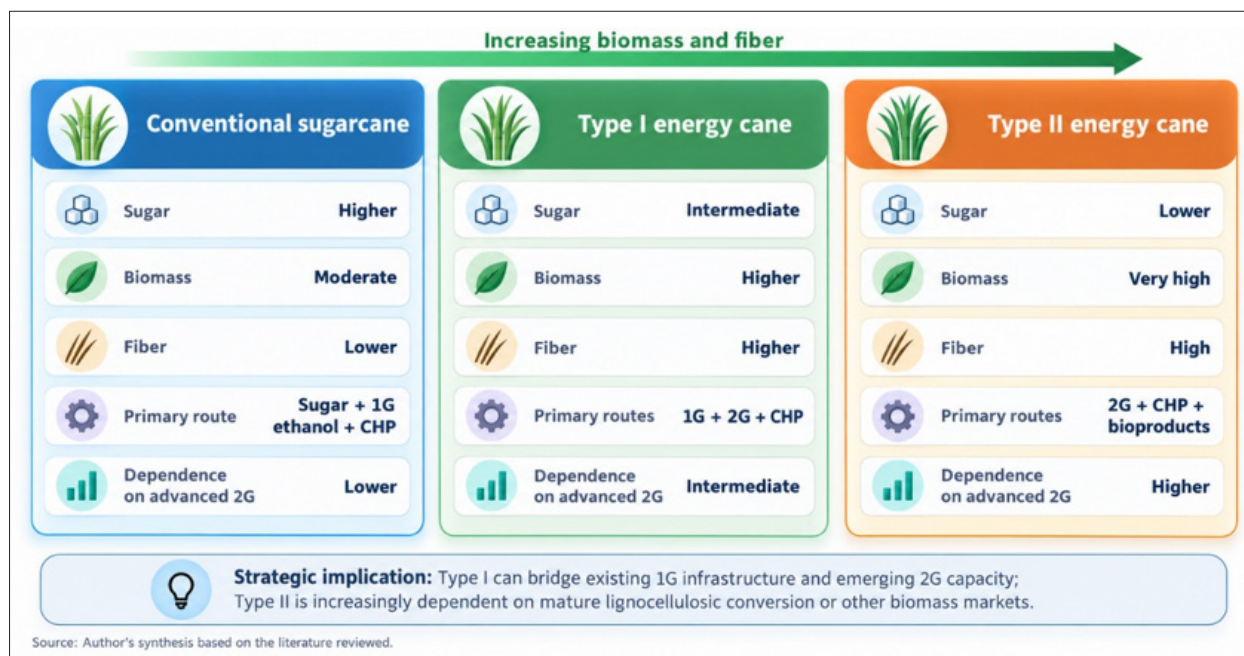


Figure 2: Functional distinction among conventional sugarcane and energy-cane types

The distinction in Figure 2 explains why a single national “energy cane strategy” would be analytically inadequate. Type I material may have greater near- or medium-term compatibility with existing milling systems, whereas Type II development is more appropriately aligned with regions or facilities in which lignocellulosic conversion, high-efficiency cogeneration or additional biomass products are commercially established. Recent work showing substantial 2G and energy-production advantages among selected clones strengthens this genotype–conversion matching approach rather than a generic high-biomass approach [28].

Productivity, Nutrients and Ratooning

Large biomass yield is frequently presented as an intrinsic sustainability advantage because more feedstock can theoretically be obtained from a given land area. Yet greater biological production also entails nutrient capture and, when whole plants are removed, nutrient export. found that including leaves in energy-cane harvest increased biomass production substantially but simultaneously increased nitrogen, phosphorus and potassium removal. likewise emphasised genotype-specific differences in biomass production, nutrient removal and composition. Consequently, the common description of energy cane as a universally “low-input crop” should be treated as a hypothesis requiring location-specific verification rather than a fixed characteristic [29].

This issue becomes particularly significant in Indonesia if energy cane is targeted toward acidic, nutrient-poor or drought-prone soils. High annual biomass export from already fertility-constrained soils can eventually require substantial nutrient replacement. Residue retention, recycling of vinasse and filter cake, nutrient recovery from processing residues, cultivar selection and site-specific fertilisation therefore become integral components of sustainability rather than peripheral agronomic details. Research on rainfed *Saccharum* hybrids nevertheless indicates considerable biomass potential in environments where conventional high-sucrose sugarcane may be less attractive. documented the bioenergy potential of *Erianthus*- and *S. spontaneum*-derived hybrids under rainfed conditions, while multi-location research on bioenergy grasses demonstrates that biomass quality and theoretical ethanol yield can vary substantially across environments Such evidence is relevant to Indonesia because prospective expansion may include locations outside established irrigated sugar regions; however, yields observed in India, Brazil, China or the United States cannot be mechanically transferred to Indonesian soils and rainfall regimes. High-throughput field phenotyping may also help accelerate genotype-by-environment screening as energy-cane breeding programmes expand [30–32].

Marginal Land and the Availability Problem

A major attraction of dedicated bioenergy crops is the possibility of avoiding direct competition with food production by cultivating them on land that is less profitable for conventional agriculture. Yet the marginal-land literature demonstrates that the concept is highly sensitive to definition. Biophysical criteria may identify land with poor soil, steep slopes or climatic limitations, while economic criteria identify land with low expected returns; neither definition establishes that land is institutionally accessible or socially unused Sustainability analysis therefore requires progressive screening. Land containing intact forest, peatland, high biodiversity value or significant carbon stocks should not become attractive simply because agricultural suitability is limited, while areas supporting grazing, shifting cultivation or community livelihoods are similarly not “empty”. Bioenergy expansion can also create indirect effects if existing activities are displaced into other landscapes, and integrated environmental-economic assessments demonstrate that land management choices can materially alter lifecycle outcomes The gross size of Indonesia’s suboptimal-land resource therefore provides little information about sustainably deployable energy-cane area until multiple exclusions have been applied [33–36].

Figure 3 Reframes Land Availability as a Screening Funnel Rather Than A Single National Hectare Statistic

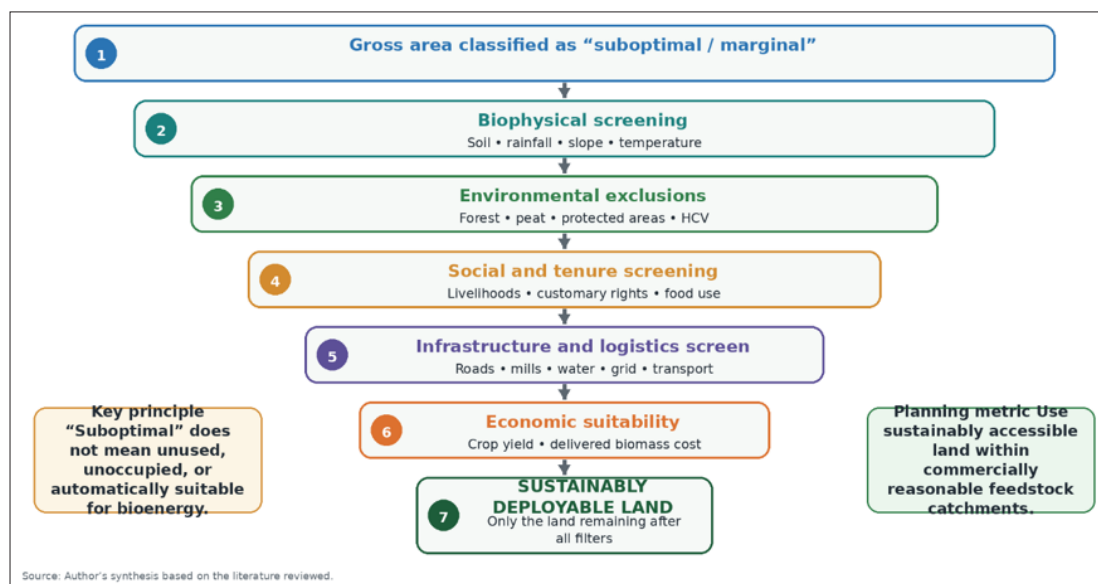


Figure 3: Sustainable Land-Screening Funnel for Energy-Cane Deployment

This hierarchy is consistent with contemporary marginal-land scholarship, which recommends integrating economic and environmental performance with biophysical characteristics rather than applying static soil-quality thresholds. Recent evidence further shows that water constraints, local yield potential and management intensity can substantially reduce the portion of nominally marginal land that produces positive net-energy and greenhouse-gas outcomes Brazil’s experience similarly demonstrates that spatial restrictions can materially alter the environmental consequences of ethanol expansion.

The 1G–2G Technological Interface

First-generation sugarcane ethanol is technically mature because sucrose extracted in cane juice can be directly fermented after appropriate preparation. Type I energy cane could exploit this infrastructure. However, increasing fiber relative to juice changes mill mass and energy balances; greater quantities of bagasse must be transported through milling equipment, burned, stored or diverted toward lignocellulosic conversion. Second-generation ethanol adds considerably greater process complexity. Pretreatment must disrupt lignin-carbohydrate associations, reduce cellulose recalcitrance and expose polysaccharides while minimising degradation products that inhibit fermentation. Experimental pathways include dilute-acid, alkaline, hydrothermal, steam-based and other physicochemical processes, while biochemical conversion studies demonstrate the broader potential of bagasse-derived sugars for alcohol production. Subcritical-water studies, for example, show that hydrothermal processing combined with enzymatic hydrolysis can release fermentable sugars from bagasse, while integrated C5 and C6 fermentation demonstrates the technical possibility of recovering ethanol from both cellulose and hemicellulose fractions. A 2021 dilute-acid bagasse study reported a mass-balance potential of approximately 243 L of ethanol per tonne of bagasse when both pentose- and hexose-rich streams were considered. The broader literature likewise indicates that realised yields depend on pretreatment recovery, solids loading, saccharification and fermentation performance rather than on carbohydrate content alone. Yet technical feasibility does not equal commercial competitiveness. Enzymes, pretreatment severity, detoxification, solids handling, water use, inhibitors, fermentation yields and capital utilisation collectively determine cost. It showed that fermentation of the xylose liquor could materially increase bagasse-to-ethanol yield while enzyme cost remained an important constraint. Broader techno-economic studies similarly identify plant configuration, enzyme production, feedstock composition and coproduct allocation as major determinants of profitability [37–41].

From Ethanol Plant to Integrated Biorefinery

A high-fiber feedstock becomes more attractive if every component is allocated to its most valuable use. Bagasse can be combusted for process steam and electricity, hydrolysed for cellulosic ethanol, digested after appropriate treatment, or converted into chemicals and materials. Lignin may provide process energy; vinasse can participate in nutrient or biogas pathways; and hemicellulosic sugars can support ethanol or higher-value biochemical production. Reviews and system studies increasingly frame sugarcane bagasse as a biorefinery platform rather than a waste stream and emphasise the trade-off between electricity generation and alternative biomass uses. Recent energy-cane research strengthens this logic. It demonstrated sequential valorisation of energy-cane bagasse for xylooligosaccharides and second-generation ethanol, illustrating how higher-value coproducts could offset some of the economic burden associated with lignocellulosic processing. Metabolically engineered energy cane has also been investigated as a platform for accumulated oils and advanced fuels, although this remains a much more technologically advanced pathway than conventional ethanol production [42–50].

Methodology

This study adopts a qualitative literature review (QLR) with a critical and integrative orientation. It is explicitly not a systematic literature review, and consequently does not employ PRISMA procedures, meta-analytic pooling or a claim of exhaustive bibliographic coverage. The objective is instead to integrate evidence from agronomy, biomass science, industrial

biotechnology, techno-economics, life-cycle assessment, land-use research and bioenergy policy into an interdisciplinary assessment of energy cane for Indonesia. The principal literature window is 2020–2026, consistent with the need to capture recent developments in energy-cane breeding, lignocellulosic conversion and integrated biorefinery systems. Searches were conceptually organised around combinations of terms including energy cane, energy cane, sugarcane, first-generation ethanol, second-generation ethanol, lignocellulosic ethanol, bagasse, biorefinery, marginal land, bioenergy crops, life-cycle assessment, techno-economic analysis, cogeneration, and bioethanol. Peer-reviewed journal literature indexed through major scholarly databases and publisher platforms was prioritised.

The synthesis uses six thematic domains: (i) energy-cane biology and agronomy; (ii) land suitability; (iii) 1G and 2G conversion; (iv) biorefinery economics; (v) environmental sustainability; and (vi) implications for Indonesian deployment. Individual findings were interpreted in relation to geographic transferability. Evidence from Brazil, India, Thailand and the United States was not assumed to predict Indonesian yields directly; rather, it was used to identify mechanisms, ranges of outcomes, technological possibilities and variables requiring domestic validation. The analysis also distinguishes three concepts frequently conflated in bioenergy discussions: theoretical potential, technical potential and economically deliverable potential. Theoretical potential refers to biomass or ethanol estimated from biological and stoichiometric relationships. Technical potential adjusts for actual conversion efficiency and available technology. Economically deliverable potential further incorporates production cost, infrastructure, transportation, capital utilisation and land-access constraints.

Official Indonesian government sources are used only to establish contemporary policy context and are analytically distinguished from peer-reviewed evidence. This distinction is necessary because the E20 programme was developing rapidly during 2026: the Ministry of Energy and Mineral Resources reported an approximately 4 million kL planning requirement in June, the Presidential Secretariat reported a two-year E20 preparation objective in September, and subsequent agricultural statements refined the prospective feedstock and land-development framing. These sources are therefore treated as dated policy statements current to 22 September 2026 rather than as immutable long-term parameters (Kementerian Energi dan Sumber Daya Mineral, 2026; Sekretariat Presiden Republik Indonesia, 2026; Kementerian Pertanian Republik Indonesia, 2026; Direktorat Jenderal Perkebunan, 2026).

Results

Indonesia's E20 Feedstock Requirement Cannot Be Represented by One Static Number

The literature-policy synthesis first reveals that defining ethanol demand is itself an analytical requirement. The Ministry of Energy and Mineral Resources reported approximately 40 million kL of annual gasoline demand and an E20 planning requirement of approximately 4 million kL of ethanol in June 2026, while a simple illustrative 20% volumetric calculation against a 40 million kL reference volume yields approximately 8 million kL. Rather than treating the difference as trivial, the analysis interprets it as evidence that market coverage and the blending denominator must be specified explicitly. The feedstock system should therefore be evaluated under phased, broader-market and diversified multi-feedstock scenarios (Kementerian Energi dan Sumber Daya Mineral, 2026). The difference also illustrates why land requirements should be derived from ethanol output rather

than announced independently. Required hectares depend on the actual volume blended, litres of ethanol produced per tonne, crop productivity, industrial recovery and the fraction of feedstock devoted to other outputs. A programme using conventional sugarcane juice, Type I energy cane, cellulosic Type II energy cane, cassava and residues will have a fundamentally different land footprint from a programme relying on one feedstock.

Energy Cane Can Raise Biomass Yield, but Genotype Matters

International evidence consistently supports the proposition that selected energy-cane genotypes can generate considerably more biomass than conventional sugarcane. However, the magnitude of the advantage is neither universal nor fixed. Developmental physiology, genotype, harvest timing, rainfall, soil and management interact to determine output. The recent evaluation by is particularly important because 190 genotypes displayed measurable differences in cellulose, hemicellulose and lignin. Some selected materials had substantially greater theoretical biorefinery output, illustrating that breeding decisions can target not only tonnes of biomass but also composition suited to specific industrial processes. The expanding use of high-throughput field phenotyping also offers a practical route to evaluating large energy-cane populations more efficiently across breeding environments. Similarly, comparative work on newly developed energy-cane accessions has shown that selected clones can provide more biomass, fiber and prospective 2G-ethanol output than a conventional sugarcane comparator; some high-biomass clones can also improve 1G ethanol output per unit area when agricultural productivity compensates for lower sugar concentration. The practical implication is that energy cane should be evaluated in litres of recoverable ethanol or total biorefinery value per hectare rather than merely in tonnes of fresh biomass per hectare.

Type I Offers an Earlier Integration Opportunity than Type II

The synthesis indicates a potential technological sequencing. Type I materials that retain fermentable sugars can interact with existing 1G infrastructure earlier because juice fermentation does not require commercial-scale lignocellulosic hydrolysis. Additional bagasse could initially supply process heat and electricity while later being progressively redirected to 2G conversion. This route is supported by studies demonstrating integration of 1G and 2G systems and by process analyses in which sugar streams and bagasse-derived carbohydrates share parts of the industrial. Integrated processing can substantially increase total ethanol recovered from cultivated biomass when additional structural carbohydrates are converted rather than solely combusted. The extent of the advantage, however, remains configuration-specific because bagasse may also have significant value for steam and electricity generation.

Type II energy cane presents a different risk profile. Its high-fiber phenotype potentially offers greater biomass and cellulose per hectare, but the economic value of that advantage depends strongly on pretreatment, hydrolysis, fermentation and coproduct markets. Commercial adoption ahead of sufficient 2G capacity could generate large quantities of biomass without an economically optimal conversion route.

The “Marginal Land” Opportunity Shrinks as Sustainability Criteria Are Applied

A second strong result is that gross estimates of suboptimal land substantially overstate immediately deployable bioenergy land. Screening for rainfall, soils and slopes would eliminate some areas. Exclusion of forests, peatlands, protected areas and

biodiversity-sensitive landscapes would reduce the area further. Existing agricultural activities and customary or community land use would narrow it again. Finally, transport distance, roads, water, electricity and proximity to processing capacity determine whether agronomically feasible land is economically usable. This result is consistent with who argue that marginality should incorporate economic and environmental outcomes instead of being defined solely through static biophysical thresholds. International studies of biofuel-driven land-use change also show that environmentally informed spatial planning can substantially influence biodiversity and carbon consequences. For Indonesia, this means that an historical gross estimate of approximately 149.5 million ha of suboptimal land should not be used as the denominator for energy-cane potential without contemporary geospatial reassessment. The more meaningful variable is sustainably accessible land within commercially reasonable feedstock catchments, after considering water availability, yield potential, tenure, conservation exclusions and infrastructure. Recent international studies show that suitability screening can materially reduce nominal marginal-land potential while improving net-energy and greenhouse-gas performance.

Nutrient Removal Challenges the Simplest “Low-Input” Narrative
Energy cane may have greater resilience than conventional commercial sugarcane in some environments, yet higher biomass removal can export more nutrients. In Dalen et al. (2022), whole-plant harvesting increased biomass but markedly increased N, P and K removal, raising concerns about long-term soil fertility. Likewise demonstrated the importance of genotype-specific nutrient-removal characteristics. This matters for any strategy targeting low-fertility Indonesian lands. An agronomic system that produces large biomass only by progressively mining soil potassium or other nutrients would not constitute a durable solution. Fertiliser demand must therefore be included in both techno-economic and life-cycle calculations, together with opportunities to recycle process residues.

Conversion Efficiency Remains the Gatekeeper for Type II Energy Cane

Lignocellulosic conversion proceeds through several potential efficiency losses: pretreatment recovery, enzymatic conversion, sugar losses, inhibitor formation, C5 utilisation and fermentation performance. Pretreatment can substantially improve accessibility, but industrial choices involve trade-offs in chemicals, temperature, pressure, water and downstream detoxification. Demonstrated that utilisation of xylose can materially increase total ethanol yield, illustrating the importance of converting hemicellulose rather than concentrating solely on cellulose. Other work demonstrates that lignin modification and pretreatment strategies can improve saccharification in sugarcane and energy-cane biomass. These findings reinforce the need to optimise carbohydrate recovery across the full lignocellulosic matrix rather than treating cellulose yield as the sole conversion metric. The implication is that improved crop productivity and improved conversion efficiency are multiplicative rather than substitutable. Breeding a crop that produces twice the fiber does not double ethanol output if the additional fraction cannot be efficiently hydrolysed and fermented. The technological findings suggest that energy cane should be considered within a whole-crop biorefinery, rather than as a crop whose sole output is ethanol.

Figure 4: Illustrates The Possible Integration Of 1g Ethanol, 2g Ethanol, Cogeneration and Coproduct Pathways.

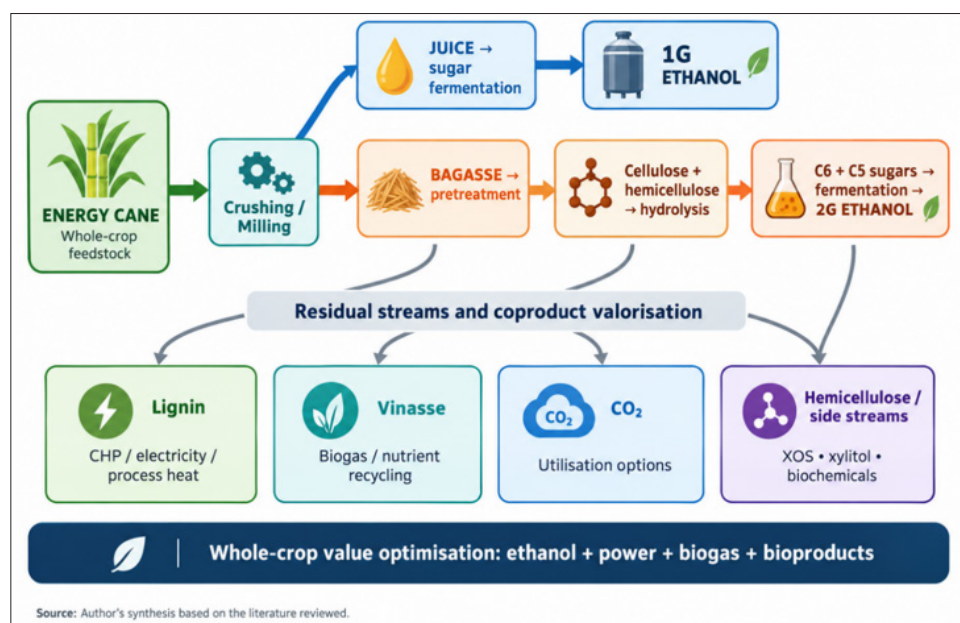


Figure 4: Integrated Energy-Cane 1g–2g Biorefinery Architecture

Figure 4: indicates why allocating all bagasse to either combustion or ethanol may be suboptimal. Electricity, process steam and 2G ethanol compete for structural biomass, while higher-value coproducts may improve profitability. Osaki (2022) demonstrated the importance of optimising bagasse allocation between ethanol and power, while Khemla et al. (2025) demonstrated sequential production of xylooligosaccharides and second-generation ethanol from energy-cane bagasse. The figure therefore represents the biorefinery as a portfolio-allocation problem in which the highest-value use of each stream can change with technology and market conditions.

Biorefinery Integration Can Improve Economics but Creates Additional Complexity

Techno-economic analyses indicate that integrated sugarcane systems can benefit from infrastructure sharing, energy integration and coproduct revenue, and show that industrial configuration materially affects costs and energy performance, while demonstrates that feedstock composition strongly influences the economics of an engineered energy-cane biorefinery. These findings caution against transferring a single cost estimate across regions or feedstock compositions without site-specific process modelling. The economic case for high-fiber cane is therefore strengthened when a facility can flexibly allocate biomass among ethanol, electricity and higher-value products. However, integration also raises capital requirements and operational complexity. Feedstock storage, solids handling, enzyme supply, lignin combustion, wastewater treatment and fermentation of multiple sugar streams all require additional capability compared with a conventional distillery.

Environmental Performance Depends on the Production System, Not the Feedstock Name

Sugarcane ethanol can provide favourable energy and carbon performance, but results vary with cultivation regime, irrigation, fertilisation, transport, allocation methodology and land-use assumptions. showed substantial sensitivity of energy, carbon and water footprints to production conditions and allocation approaches, while demonstrated the importance of production-specific data in evaluating Brazilian sugarcane ethanol. Indian evidence similarly identifies cultivation and transportation as

important contributors to the environmental footprint of molasses-based ethanol. Energy cane therefore cannot be considered low-carbon solely because it is renewable biomass. Clearing high-carbon ecosystems, applying excessive nitrogen, using irrigation in water-stressed regions, transporting wet biomass over excessive distances, or depleting soil nutrients could erode its environmental advantage.

Discussion and Analysis

Can Energy Cane “Supply E20”?

A binary answer is not analytically appropriate. The literature supports a more conditional conclusion: energy cane can potentially become a significant complementary source of biomass for Indonesian ethanol, but current evidence does not justify treating it as an immediately scalable stand-alone solution to E20.

Three layers of uncertainty explain this conclusion. First is biological transferability. High yields observed in Brazil, India, Thailand or the southeastern United States demonstrate biological potential, not Indonesian commercial yield. Indonesia requires multi-location testing across soil, rainfall and elevation gradients. Second is industrial recoverability. A Type II crop can produce impressive fiber yields while remaining constrained by conversion cost. Third is land deliverability. Even technically suitable land may be economically inaccessible because of roads, mill distance, tenure or competing use. This finding also changes the relevant comparison. Energy cane should not simply be evaluated against conventional sugarcane in “tonnes per hectare.” The comparison should include litres of 1G ethanol, litres of 2G ethanol, net electricity, coproduct revenue, nutrient replacement, delivered biomass cost and life-cycle greenhouse-gas performance per hectare.

Why Type I May Be Strategically Important During the Transition
Type I energy cane has an underappreciated potential role because it can bridge mature and emerging technologies. Its soluble sugars allow use of established fermentation infrastructure, reducing dependence on immediate commercial perfection of 2G processes. Its additional fiber simultaneously provides a pathway toward cogeneration and future lignocellulosic conversion.

This configuration could be particularly relevant around existing or newly modernised Indonesian sugar factories. Rather than building a completely new industrial ecology for high-fiber material from the outset, demonstration projects could compare conventional cultivars and Type I energy-cane candidates within the same feedstock catchment. Performance could then be measured in terms of sugar recovery, ethanol yield, bagasse generation, boiler operation, milling throughput, nutrient balance and overall revenue. The concept is consistent with work showing that integrated 1G–2G processing can improve total utilisation of cultivated biomass. It also limits technology risk by allowing fiber to supply useful heat and electricity even before its conversion into ethanol becomes fully competitive [56].

Why Type II Should Be Viewed as a Longer-Term Biorefinery Feedstock

Type II energy cane is potentially transformative precisely because its value is not limited to ethanol. Its high lignocellulosic output could support ethanol, power, biomaterials, chemicals or advanced fuels. Current research on biomass valorisation points toward increasingly integrated product portfolios. Yet this is also why Type II should not be promoted merely as a near-term substitute for ordinary sugarcane. Deploying large areas before secure biomass offtake exists could transfer technological risk to growers. A rational approach would link Type II acreage development to demonstrably operating 2G, cogeneration or biomass-processing capacity. Research on engineered energy cane provides a useful glimpse of the longer-term opportunity. Kumar et al. (2021) modelled biorefineries that co-produce ethanol with lipid-derived fuels, while Cao et al. (2023) showed that energy cane can serve as a platform for metabolic engineering of plant oils. These technologies are not necessary for Indonesia's initial ethanol transition, but they illustrate why dedicated biomass crops could eventually support a broader bioeconomy in which feedstock value is not determined by ethanol alone.

Replacing “Available Hectares” with “Sustainable Ethanol Landscapes”

One of the most important conceptual corrections arising from this review is the need to stop interpreting all suboptimal land as available land. The original infographic correctly notes that not all of Indonesia's estimated suboptimal land would be suitable for energy cane. The literature suggests taking the point further: land suitability should include at least five dimensions—biophysical suitability, ecological acceptability, social legitimacy, infrastructural accessibility and economic viability. This has direct consequences for spatial planning. An isolated high-biomass site hundreds of kilometres from a processor may have little commercial value because harvested cane has high moisture content and relatively low value per transported tonne. Conversely, moderately productive land near a mill, road, water source and electricity connection may generate greater net value. Hence, prospective energy-cane zones should be constructed using GIS-based multi-criteria screening. Forests, peatlands, conservation areas and high-carbon ecosystems should first be excluded. Existing cropping and livelihood uses should then be mapped. Soil, slope, rainfall and water availability should determine agronomic suitability. Infrastructure and mill catchment areas should finally identify economic feasibility. This process would convert a gross national land estimate into realistic clusters for feedstock development.

Logistics May Offset Part of the Biomass Advantage

The high-fiber characteristic that makes energy cane attractive also makes logistics important. Fresh biomass is bulky and

contains substantial water; hauling long distances can rapidly increase delivered feedstock costs and energy use. Greater hectare productivity helps because more feedstock can be collected from a smaller radius, but this advantage is reduced if cultivation becomes geographically scattered. Industrial geography should therefore be planned together with crop deployment. Feedstock catchments need sufficient annual biomass density to maintain plant utilisation without generating excessive haulage, and harvest timing must interact with mill capacity. If energy cane extends the operational season it may improve capital utilisation, whereas excessive overlap with conventional cane can create congestion. Recent biomass supply-chain optimisation research further shows that refinery scale, transport distance, marginal-land development and emissions objectives can lead to materially different spatial solutions. These factors imply that Indonesia may benefit more from regional feedstock–biorefinery clusters than from widely dispersed cultivation targets. Such clusters could integrate growers, nurseries, harvesting contractors, mills, distilleries, cogeneration facilities and biomass-processing operations [51].

Soil Fertility Must Become a Core Design Criterion

The proposed use of marginal land produces a paradox: high-biomass crops are attractive because they may tolerate relatively difficult environments, but harvesting large quantities of biomass from such environments can accelerate nutrient export. Whole-crop removal particularly affects potassium and nitrogen balances. A sustainable system should therefore retain appropriate residues where agronomically desirable, recycle organic process streams safely, recover nutrients where technically feasible and monitor soil carbon. The trade-off between leaving trash on the field and collecting it for industrial energy is especially important. Removing every available tonne may maximize short-run factory feedstock while diminishing soil protection and nutrient cycling, additionally show that mineral constituents of bagasse and straw matter for downstream thermochemical and biorefinery operations. Nutrient management is therefore not solely an agricultural issue; it links soil fertility to boiler performance, ash management and processing design. This systems perspective is especially important when high-biomass feedstocks are harvested repeatedly from soils with limited nutrient reserves [55].

The 2G Cost Problem Is a Portfolio Problem, Not Only an Enzyme Problem

Discussion of second-generation ethanol often focuses on reducing enzyme cost. Although enzymes remain important, the literature indicates a wider optimisation problem. Feedstock composition, pretreatment recovery, fermentation of pentoses, solids loading, steam integration, water use, plant utilisation and coproduct prices all affect commercial performance. This suggests that Indonesia should avoid evaluating 2G facilities solely on litres of ethanol produced. An integrated investment assessment should compare alternative uses of each biomass fraction. In some market conditions, retaining bagasse for high-efficiency cogeneration may create greater value than maximising ethanol. Under other conditions, additional cellulosic ethanol or biochemical coproducts may be preferred. Osaki (2022) demonstrates precisely why optimisation between electricity and ethanol matters. The increasing range of coproduct options reinforces the point. Xylooligosaccharides, xylitol, lignin-derived materials, biochar and biogas can alter project economics. One example in which xylan-derived products are integrated with ethanol production from energy-cane bagasse. The economically optimal configuration should therefore be regarded as a biorefinery portfolio, not an ethanol-only plant.

Environmental Credibility Requires LCA Before Scale-Up

A bioethanol programme intended partly to support decarbonisation should measure life-cycle performance before large land commitments are made. Agricultural inputs, direct land-use change, transport, processing energy and allocation of coproduct credits can substantially affect results. Brazilian land-use research is especially instructive. Duden et al. (2020) and Andrade Junior et al. (2021) show that biodiversity and carbon outcomes depend materially on where expansion occurs. This means that even a biologically efficient ethanol crop can produce poor sustainability outcomes if spatial deployment causes habitat conversion. Life-cycle assessment should consequently be conducted at regional project level rather than assigning a universal carbon-intensity factor to energy cane. Indonesian locations will differ in fertiliser requirements, rainfall, soil carbon, transport distance, electricity mix and previous land use, while land suitability and logistics interact directly with net-energy and emissions performance. This reinforces the value of linking LCA with spatial suitability and supply-chain analysis before commercial scale-up [52,53,54].

A Staged Research-to-Deployment Architecture for Indonesia

Taken together, the findings support sequential rather than instantaneous large-scale deployment. This sequencing reduces the risk of committing land and capital before genotype performance, conversion efficiency, supply-chain feasibility and environmental outcomes have been validated. Stage A—Germplasm and agronomic validation. Candidate Type I and Type II genotypes should be evaluated across representative Indonesian agroecological zones. Trials should measure dry biomass rather than only fresh stalk tonnes, together with sucrose, fiber, cellulose, hemicellulose, lignin, water demand, ratoon persistence, disease susceptibility and nutrient removal. Multi-environment trials

and high-throughput phenotyping can strengthen genotype-by-environment assessment and improve the efficiency of selection.

Stage B—Feedstock conversion testing. Indonesian-grown material should undergo juice fermentation, pretreatment and saccharification testing. This is necessary because industrial performance depends on composition, which varies among genotypes and environments.

Stage C—Mill-linked demonstrations. Type I materials can be assessed near existing sugar and ethanol infrastructure. Their additional fiber can initially be utilised through cogeneration while selected streams are tested for 2G conversion.

Stage D—Integrated 1G–2G pilots. Once agronomic supply is established, pilot biorefineries can validate enzyme requirements, pentose fermentation, water balance, process integration and residue recycling at larger scale.

Stage E—Spatially constrained expansion. Only after yield, economics and LCA are validated should larger cultivation clusters be selected using the land-screening framework in Figure 3.

Stage F—Advanced Type II deployment. Large high-fiber plantations should develop together with secured demand from 2G ethanol, power, biomaterials or multiproduct biorefineries rather than precede those markets.

This sequence differs from a conventional “secure millions of hectares first, build conversion later” model.

Figure 5: Places Biological Validation and Industrial Capability Ahead of Large-Scale Land Commitment

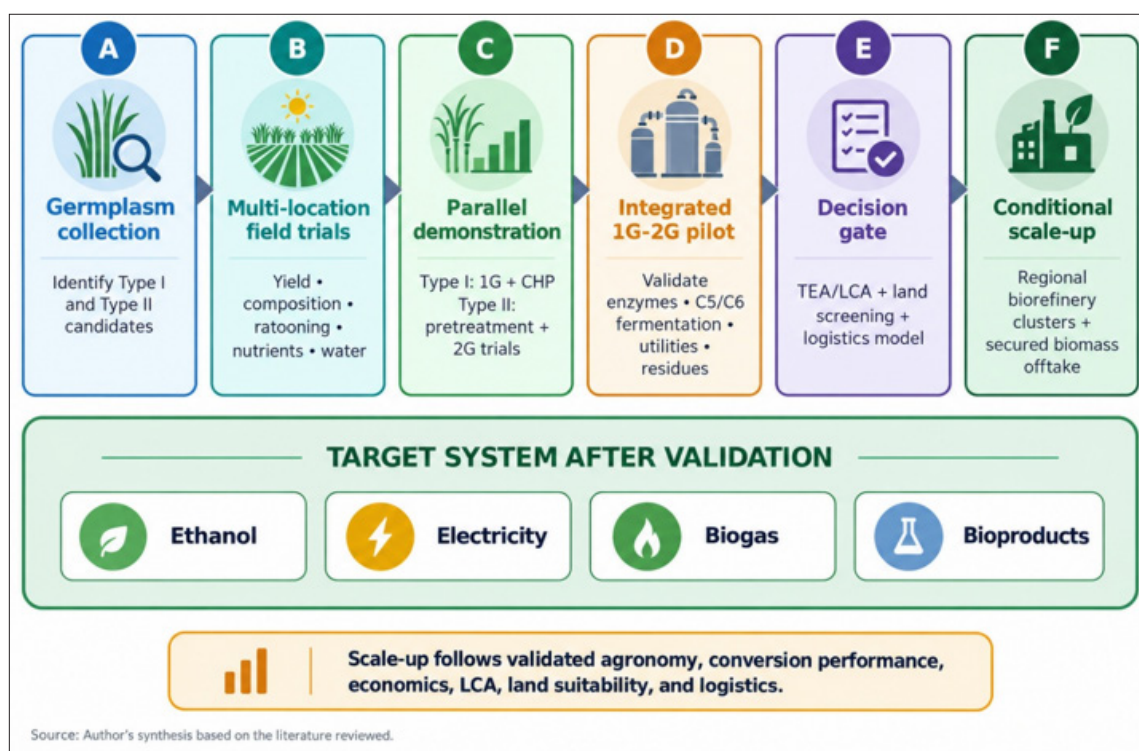


Figure 5: Proposed Indonesian Energy-Cane Research-To-Deployment Pathway

The pathway in Figure 5 treats energy cane as a technology–feedstock system rather than merely an agricultural commodity. It also creates decision points at which unsuitable genotypes, locations or industrial configurations can be rejected before very large sunk investments occur.

Conclusion and Recommendations

Indonesia's E20 transition creates a genuine need to examine feedstocks beyond the conventional assumption that larger sugarcane acreage alone will be sufficient. Energy cane deserves serious research attention because selected genotypes combine high biomass productivity, high fiber production, ratooning potential and compatibility with a broader biorefinery architecture. Evidence from 2020–2026 confirms substantial technological progress in crop development, lignocellulosic pretreatment, enzymatic conversion, integrated 1G–2G processing, and biomass valorisation. Nevertheless, three distinctions are critical. They concern the identity of the feedstock, the metric used to define productivity, and the distinction between gross land classifications and land that is sustainably and economically deployable.

First, energy cane is not one homogeneous crop. Type I and Type II materials imply different technological trajectories. Type I offers a potentially useful bridge to existing first-generation ethanol infrastructure because fermentable juice can coexist with enhanced fiber production. Type II should be understood primarily as a lignocellulosic-biorefinery feedstock whose economic performance depends on 2G conversion, cogeneration, or additional biomass products. Second, high biomass yield should never be treated as synonymous with high ethanol yield. A robust performance indicator integrates biomass dry matter, fermentable composition, pretreatment recovery, enzymatic hydrolysis, C5/C6 fermentation and logistical losses. Ultimately, the appropriate metric for the E20 challenge is economically and sustainably deliverable ethanol per hectare, complemented by the value of electricity and coproducts.

Third, suboptimal land is not automatically available land. Gross historical land estimates must be narrowed through contemporary geospatial assessment of agronomic suitability, forests, peat, biodiversity, existing livelihoods, tenure, water availability, infrastructure and economic accessibility. Failure to make these distinctions could shift an energy-security initiative into new land-use and sustainability conflicts. The evidence consequently supports a staged Indonesian strategy. The immediate scientific priority is not mass planting but multi-location genotype screening, including Type I and Type II candidates. This should be accompanied by detailed compositional analysis, ratoon trials, nutrient balances, water-use evaluation and disease assessment. The industrial priority is to test Type I feedstock around existing sugar/ethanol infrastructure while developing pilot-scale 1G–2G integration. Type II expansion should subsequently be tied to commercially demonstrated lignocellulosic conversion or other guaranteed biomass markets. Finally, Indonesia's ethanol strategy would benefit from treating conventional sugarcane, energy cane, cassava, maize, molasses and lignocellulosic residues as a portfolio of complementary feedstocks rather than competing candidates for a single national winner. The appropriate mixture will differ geographically and evolve with technology. Energy cane's strongest long-term contribution may therefore extend beyond E20 itself: it could become one component of an integrated tropical bioeconomy producing liquid fuels, renewable electricity, biogas, biochemicals and biomaterials from the same hectare of cultivated biomass.

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