ISSN: 3144-1920

Wissen PUBLICATION GROUP

Journal of
Environmental Sustainability and Renewable Systems

Review Article

Volume: 1 | Isssue: 1 | October 2026 | Pages 01–14

From E20 Ambition to Sustainable Implementation: Prospects, Structural Challenges, and Strategic Pathways for Sugarcane-Based Bioethanol Development in Indonesia

Loso Judijanto

IPOSS Jakarta, Indonesia

*Corresponding Author: Loso Judijanto, IPOSS Jakarta, Indonesia.

Submitted: 09 October 2026 **Accepted:** 14 October 2026 **Published:** 23 October 2026

Citation: Judijanto, L. (2026). From E20 Ambition to Sustainable Implementation: Prospects, Structural Challenges, and Strategic Pathways for Sugarcane-Based Bioethanol Development in Indonesia. Journal of Environmental Sustainability and Renewable Systems, 1(1), 1-14. DOI: doi.org/10.67927/JEnvironSustainRenewSyst/2026(1)111.

Abstract

Indonesia's ambition to introduce gasoline containing 20% bioethanol (E20) by approximately 2028 represents an important opportunity to diversify transportation fuels, strengthen domestic energy security, and accelerate agricultural industrialisation. Nevertheless, the feasibility and sustainability of this initiative depend on interconnected agricultural, technological, economic, environmental, and institutional conditions. This article critically examines the prospects and challenges of E20 implementation through a qualitative literature review of contemporary scientific publications from 2020–2026, supplemented by Indonesian policy documents. The analysis integrates energy-transition theory, sustainable bioeconomy perspectives, supply-chain management, lifecycle assessment, and institutional governance. Eight thematic dimensions are identified: energy security, feedstock availability, industrial readiness, automotive compatibility, economic viability, environmental sustainability, social inclusion, and policy coordination. The synthesis suggests that sugarcane-based ethanol could support gasoline substitution and rural value creation, but extensive feedstock requirements, competition with food production, industrial financing, land-use impacts, water consumption, and vehicle compatibility present substantial implementation challenges. International experience demonstrates the importance of diversified feedstocks, integrated biorefineries, transparent pricing, and enforceable sustainability safeguards. The article proposes an Integrated E20 Implementation Readiness and Sustainability Framework and a phased, stage-gated implementation roadmap. Successful implementation requires coordinated agricultural productivity improvements, certified fuel infrastructure, vehicle testing, inclusive investment arrangements, and lifecycle-based environmental monitoring. E20 should consequently be pursued as one component of Indonesia's broader sustainable transportation transition rather than as an isolated fuel-blending mandate.

Keywords: E20, Bioethanol, Sugarcane, Energy Security, Fuel Blending, Indonesia, Land-Use Change, Life-Cycle Assessment, Food–Energy–Water Nexus, Sustainable Industrial Policy.

Introduction

Background and Strategic Context

The global transition toward sustainable energy systems has intensified pressure on developing economies to reduce dependence on imported fossil fuels while ensuring that energy remains affordable and accessible. Transportation represents a particularly challenging sector because existing vehicle fleets, liquid-fuel distribution systems, and consumer preferences create substantial technological and institutional inertia. Although electrification offers a promising long-term decarbonization pathway, renewable liquid fuels can potentially contribute to near-term diversification where compatible combustion-engine vehicles remain in operation. Bioethanol has consequently attracted renewed attention as an oxygenated renewable fuel that can be blended with gasoline and incorporated into established liquid-fuel supply systems, subject to appropriate technical adaptations [1-3].

For Indonesia, the relevance of bioethanol extends beyond environmental considerations. Petroleum-import dependence exposes domestic fuel markets and public finances to fluctuations in international energy prices, exchange rates, and geopolitical conditions. At the same time, Indonesia possesses agricultural resources and established commodity-processing industries that could contribute to a domestic renewable-fuel economy. The strategic question is therefore whether agricultural and industrial capabilities can be reorganized to produce reliable and competitively priced transportation fuels without undermining food security or environmental sustainability. Existing studies indicate that biofuel development requires simultaneous attention to energy demand, domestic productive capacity, institutional arrangements, and the distribution of economic benefits [4,5].

Indonesia's biofuel experience provides both encouragement and caution. The country has developed substantial experience with biodiesel production and mandatory blending, demonstrating that coordinated agricultural production, industrial investment, and regulatory intervention can establish a significant domestic biofuel market. However, bioethanol deployment has progressed much more slowly, reflecting differences in feedstock availability, processing economics, market arrangements, and the technological

requirements of gasoline blending. Therefore, policies effective in the biodiesel sector cannot simply be transferred to bioethanol without considering the structural differences between the two industries [6,7].

On 16 September 2026, the Indonesian government announced an ambition to achieve production of gasoline containing approximately 20% ethanol within two years. The initiative identified sugarcane as the preferred initial feedstock and referred to a prospective agricultural development programme involving approximately two million hectares across several Indonesian regions. The announcement also identified a role for Danantara in developing the associated processing industries. Subsequently, on 21 September 2026, the Ministry of Agriculture described a broader programme involving sugarcane, cassava, and maize, indicating that feedstock selection and implementation arrangements were still evolving [8,9].

These announcements signal a major policy ambition rather than proof that the complete production and distribution system is already commercially operational. Several interconnected questions remain unresolved, including the annual volume of ethanol required, the suitability and legal availability of proposed agricultural land, the capacity of existing sugar industries to supply feedstocks, and the investment needed for processing, storage, and fuel blending. There are also uncertainties concerning vehicle compatibility, fuel prices, public acceptance, and environmental impacts. Resolving such questions is necessary before a production target can become a credible national implementation programme [7,10].

Research Urgency and Problem Definition

The principal research problem is the potential mismatch between the speed of policy ambition and the time required to develop a sustainable bioethanol supply system. Sugarcane cultivation depends on soil conditions, rainfall, irrigation, planting material, agricultural management, and harvesting infrastructure. Ethanol production requires fermentation, distillation, dehydration, quality control, and commercially reliable industrial operations. Finished E20 gasoline must subsequently be blended, transported, stored, and sold under appropriate product specifications. The performance of the entire programme is therefore constrained by its least-prepared component rather than by the readiness of any single industry [10-13].

Environmental uncertainty represents a second major concern. Ethanol produced from renewable biomass is not automatically a low-carbon fuel under all production conditions. Its actual environmental performance depends on agricultural inputs, industrial energy sources, transportation distances, coproduct allocation, and direct or indirect land-use changes. Irrigation requirements, fertilizer-related emissions, soil degradation, and habitat conversion may substantially modify the benefits expected from replacing a portion of fossil gasoline. Consequently, the sustainability of E20 must be evaluated across the complete production and utilization chain rather than inferred from the renewable origin of its feedstock [14-16].

International experience demonstrates that the economic and environmental consequences of ethanol policies can also extend beyond the energy sector. In India, ethanol-blending expansion has been associated with trade-offs involving agricultural land, water consumption, nitrogen emissions, and food prices. Comparative research further shows that the food-security consequences of biofuel development differ according to feedstocks, domestic agricultural productivity, and national institutional conditions. Such findings are especially relevant for Indonesia, where bioethanol expansion could interact with policies aimed at improving sugar self-sufficiency and strengthening rural livelihoods [17-19].

Objectives and Contributions

This article aims to critically evaluate the prospects and structural challenges of E20 implementation in Indonesia through an integrated qualitative synthesis of recent scientific literature. It examines energy security, feedstock supply, industrial technologies, automotive compatibility, economic feasibility, environmental sustainability, social inclusion, and institutional governance. These dimensions are assessed jointly because a technically feasible ethanol-production pathway may remain economically unattractive or environmentally problematic under particular conditions [20,21].

The article makes three contributions. First, it integrates fragmented evidence concerning the Indonesian bioethanol transition into a multidimensional assessment that explicitly distinguishes implementation ambition from demonstrated readiness. Second, it proposes an Integrated E20 Implementation Readiness and Sustainability Framework to identify interactions among the agricultural, industrial, transportation, economic, and environmental systems. Third, it develops a phased policy roadmap incorporating measurable readiness conditions, diversified feedstocks, inclusive agricultural participation, and lifecycle-based sustainability safeguards. This approach complements existing Indonesian research on bioethanol readiness and supply-chain development while extending its consideration of governance and sustainability [7,22,23].

Literature Review

Bioethanol as a Transitional Transportation Fuel

Bioethanol is an alcohol fuel produced through the biological conversion of fermentable sugars or carbohydrates derived from biomass. Conventional production relies primarily on sugar-rich or starch-rich crops, while advanced pathways convert lignocellulosic materials through pretreatment, hydrolysis, fermentation, and downstream purification. Ethanol may be blended with gasoline at different volumetric concentrations, allowing renewable components to replace a portion of petroleum-derived fuel. Its relatively high octane characteristics can support particular combustion strategies, although its lower volumetric energy content introduces important implications for fuel consumption and vehicle calibration [24,25]. E20 ordinarily denotes a finished gasoline blend containing approximately 20% fuel-grade ethanol and 80% gasoline by volume. This definition is important because ethanol is blended with appropriately formulated gasoline components rather than directly with crude oil. Ethanol addition changes fuel oxygen content, volatility characteristics, material compatibility, and combustion behavior. Consequently, the successful introduction of E20 requires specifications for both the ethanol component and the finished gasoline blend, supported by compatible storage, blending, and distribution infrastructure [26-28].

The theoretical role of bioethanol in energy transitions is best understood through the concept of technological complementarity. Renewable liquid fuels can potentially reduce fossil-fuel consumption within existing compatible vehicle fleets while

longer-term transport electrification develops. However, their contribution must be evaluated relative to competing uses of land, biomass, renewable electricity, and financial resources. Policies should therefore prioritize demonstrable emissions reduction, energy security, and welfare improvements instead of assuming that the maximum possible ethanol-blending percentage necessarily constitutes the optimal national outcome [3,5].

Feedstock Systems and Conversion Technologies

Sugarcane possesses several characteristics that make it attractive for ethanol production. Its stalks contain fermentable sugars, while processing generates molasses and fibrous residues that can be integrated into broader biorefinery operations. Sugarcane processing systems can potentially produce sugar, ethanol, electricity, fertilizer-related products, and other industrial materials. Such integration creates opportunities to diversify revenue and improve resource efficiency, particularly when agricultural production and industrial facilities are geographically coordinated [29,30]. Nevertheless, different sugarcane-derived feedstocks have distinct economic and environmental implications. Direct conversion of cane juice into ethanol competes with alternative uses of fermentable sugars, including sugar production. Molasses-based ethanol uses an existing sugar-processing output but remains constrained by the amount of molasses generated and by competing markets for that material. Bagasse-based ethanol offers an alternative lignocellulosic pathway but requires additional processing technologies and must account for the established use of bagasse as industrial fuel or a feedstock for electricity generation. These pathways cannot be treated as interchangeable simply because they originate from the same crop [14,31].

Feedstock diversification may improve resilience by reducing dependence on a single crop, growing season, or geographic region. Cassava, maize, sweet sorghum, and agricultural residues offer different combinations of yield potential, production costs, resource requirements, and processing characteristics. Sweet sorghum, for example, has attracted interest because of its capacity to produce fermentable sugars and useful biomass under selected climatic conditions. However, its commercial attractiveness depends on agricultural productivity, harvest scheduling, market development, and plant-scale economics [22,32].

Lignocellulosic materials provide another potential route for long-term diversification. Sugarcane bagasse, oil-palm empty fruit bunches, and other agricultural residues contain structural carbohydrates that can be converted into ethanol following suitable pretreatment and enzymatic hydrolysis. Yet lignin-related recalcitrance, processing chemicals, enzyme requirements, inhibitor formation, and conversion efficiency can increase costs and operational risks. Second-generation bioethanol should therefore be regarded as a strategically important development opportunity rather than an immediately guaranteed substitute for commercially established first-generation production [33-35].

Recent reviews emphasize that fermentation efficiency depends on substrate preparation, microbial performance, temperature, pH, contamination control, and downstream product recovery. Process configurations combining saccharification and fermentation may reduce certain conversion inefficiencies, although performance varies across different lignocellulosic feedstocks. Efficient integration of agricultural supply, biological conversion, and industrial energy systems is therefore a fundamental requirement for competitive ethanol production [36,37].

Bioethanol Supply Chains and Industrial Organization

The economic viability of bioethanol depends not only on the conversion technology but also on the organization of its supply chain. Agricultural biomass is geographically dispersed, seasonally variable, and frequently expensive to transport relative to its economic value. Processing plants require reliable quantities of feedstock to maintain capacity utilization, while farmers need predictable purchasing arrangements to justify investments in production. These interdependencies make spatial planning, contracting, inventory management, and infrastructure coordination important determinants of industrial success [38,39].

Indonesia-specific research illustrates the importance of supply-chain configuration. Studies involving sorghum-based bioethanol and oil-palm empty fruit bunches show how regional feedstock availability, facility location, transportation requirements, and plant scale influence economic outcomes. Such studies are especially relevant because Indonesia's archipelagic geography creates different logistics conditions from those found in large contiguous agricultural production regions. Consequently, optimal industrial development may involve regional processing clusters connected to national fuel distribution systems rather than uniformly distributed facilities [13,23].

Integrated biorefineries can further modify project economics by generating multiple products from a shared agricultural resource. In addition to ethanol, facilities may produce industrial heat, electricity, fertilizer-related products, recovered lignin, and other biomaterials. These revenue streams can improve economic resilience and reduce the quantity of unused residues. Nevertheless, their benefits depend on actual product markets, additional capital requirements, and consistent allocation of environmental impacts among coproducts [31,40].

Automotive Compatibility and Fuel Performance

Ethanol–gasoline blends can influence engine combustion through changes in octane characteristics, oxygen availability, flame development, latent heat of vaporization, and air–fuel mixture properties. Experimental studies demonstrate that combustion performance and exhaust emissions depend on engine architecture, compression ratio, injection timing, combustion calibration, and operating conditions. As a result, findings obtained from laboratory engines or specially calibrated systems cannot automatically be generalized to all vehicles operating in Indonesia [41,42].

Higher ethanol concentrations can also affect fuel-system materials and operating performance. Relevant considerations include compatibility with elastomers, metals, seals, storage materials, and components exposed to alcohol-containing fuels. Water absorption and the potential for phase separation under unsuitable storage conditions further reinforce the need for careful fuel-quality management. Therefore, national E20 implementation requires coordinated fuel standards, compatibility testing, and clear vehicle-manufacturer guidance rather than relying solely on favorable laboratory combustion results [27,43].

Emission outcomes require particularly cautious interpretation. Ethanol blending can reduce certain pollutants under particular conditions, while other pollutants may increase depending on engine design, temperature, fuel formulation, and operating regime. Studies examining nitrogen oxides, volatile organic compounds, particulate matter, and unregulated emissions provide mixed and context-dependent results. Consequently, an Indonesian

E20 programme should evaluate both regulated and relevant unregulated emissions under realistic vehicle-use conditions [44,45].

Environmental Sustainability and the Food–Energy–Water Nexus

Lifecycle assessment provides an important theoretical foundation for evaluating bioethanol sustainability. Rather than examining only combustion-related emissions, lifecycle analysis considers emissions and resource use associated with agricultural inputs, cultivation, harvesting, feedstock transportation, processing, fuel distribution, and final utilization. Results are sensitive to system boundaries, functional units, coproduct allocation, and assumptions concerning land-use changes. Comparisons are therefore meaningful only when methodological choices are explicitly documented [14,46].

The food–energy–water nexus further highlights the potential competition created by agricultural biofuel expansion. Sugarcane and other ethanol feedstocks require land, nutrients, labor, and water that may have alternative uses in food production or ecosystem conservation. Expansion may raise rural incomes and stimulate industrial development, but it can also affect agricultural prices and access to productive resources. The net outcome depends on crop selection, technological progress, local environmental conditions, trade, and public-policy design [17,19].

Land-use change deserves special attention because clearing carbon-rich ecosystems can create substantial emissions that offset the benefits of fossil-fuel substitution. Even where new cultivation occurs outside forests, displacement of existing agricultural production may induce environmental pressures elsewhere. Accordingly, sustainability assessments should consider direct land conversion, indirect land-use effects, soil carbon, biodiversity, irrigation, and nutrient management. Research on Brazilian sugarcane systems illustrates the importance of land-use accounting and local environmental context when interpreting bioethanol's climate performance [15,47].

Economic Governance and Inclusive Development

Bioethanol markets are affected by the prices of crude oil, gasoline, agricultural commodities, industrial inputs, transportation services, and capital. Their commercial viability may also depend on blending mandates, fiscal incentives, guaranteed offtake arrangements, and carbon-related policy instruments. However, policies that stimulate production can impose costs on fuel consumers or public budgets, particularly when domestic production costs exceed the market value of the petroleum components being displaced. Economic assessment must therefore consider both private investment returns and broader social welfare [20,48].

The distribution of benefits is another central consideration. Smallholder farmers may gain more secure markets, access to technology, and additional income through participation in bioethanol supply chains. Nevertheless, unequal bargaining power, opaque purchasing formulas, delayed payments, and land-related conflicts can undermine these advantages. Contract farming is therefore most effective where farmers retain meaningful bargaining opportunities and receive institutional support for productivity, financing, and dispute resolution [49].

These conceptual foundations suggest that E20 implementation should be evaluated as a coordinated socio-technical transition. Its prospects depend on aligning agricultural productivity, industrial investment, fuel specifications, price formation, environmental safeguards, and community participation. A programme that advances only one of these dimensions may create new bottlenecks rather than achieving sustainable national energy diversification [10,50].

Method

Research Design

This study adopts a qualitative literature review approach to critically interpret and integrate interdisciplinary evidence concerning E20 implementation in Indonesia. The approach is appropriate because the research problem encompasses technological performance, agricultural systems, economics, environmental sustainability, and institutional governance, which cannot be adequately represented by a single quantitative indicator. The review emphasizes conceptual integration, contextual interpretation, and the identification of relationships among implementation conditions rather than statistical aggregation of empirical results. The review is explicitly distinguished from a systematic literature review and meta-analysis. It does not claim exhaustive identification of all published studies, predetermined statistical inclusion thresholds, PRISMA screening, or pooled effect estimates. Instead, it adopts a purposeful, concept-driven strategy for identifying influential, directly relevant, and comparatively informative scientific publications. This distinction is important because the article's central objective is to construct an integrated understanding of E20 implementation challenges rather than estimate a single treatment effect.

Literature Coverage and Source Selection

The principal scientific evidence base comprises peer-reviewed journal publications from 2020 through October 2026. Priority is given to studies addressing bioethanol production, sugarcane systems, alternative feedstocks, fuel-blending policies, vehicle compatibility, lifecycle assessment, supply-chain management, and sustainable agricultural development. Indonesia-specific studies receive particular attention, while evidence from Brazil, India, and other countries is considered where it provides transferable technological or policy insights. Official Indonesian policy announcements are used to establish the contemporary policy context rather than to substantiate claims about demonstrated technological or environmental performance. The announcement of 16 September 2026 and the Ministry of Agriculture communication of 21 September 2026 are treated as evidence of governmental intentions and preliminary implementation priorities. Scientific studies are used to evaluate the plausibility, limitations, and conditions associated with these ambitions. Selection emphasizes thematic relevance, methodological credibility, publication quality, and the applicability of findings to Indonesian circumstances. Both favorable and unfavorable evidence is considered to reduce confirmation bias. Particular attention is given to distinctions between laboratory experiments, techno-economic simulations, lifecycle models, observed industrial operations, and policy projections because these forms of evidence support different levels of inference.

Thematic Synthesis

The analytical process is organized into three interpretive stages. First, the literature is grouped according to eight preliminary themes: energy security, feedstock availability, industrial readiness, automotive compatibility, economic feasibility, environmental sustainability, social inclusion, and institutional coordination.

Second, relationships, contradictions, and dependencies among these themes are examined. Third, the resulting synthesis is translated into an integrated implementation framework and a conditional policy roadmap. Deductive thematic organization provides continuity with the research questions, while inductive interpretation allows emerging issues to influence the discussion. For example, the interaction between sugar production and ethanol manufacturing is considered not merely an agricultural constraint but also a pricing, food-security, and governance issue. Similarly, vehicle compatibility is interpreted as a technological requirement with consequences for consumer confidence, infrastructure investment, and policy legitimacy.

Analytical Scope and Limitations

The article does not claim to measure actual nationwide readiness through original field surveys, vehicle experiments, or industrial audits. Nor does it provide a definitive forecast of future gasoline consumption, ethanol production, or greenhouse-gas reductions. Where accounting relationships or illustrative scenarios are presented, their assumptions are stated explicitly and their outputs are distinguished from empirical national projections. The conclusions should therefore be interpreted as evidence-informed analytical judgments concerning necessary conditions and strategic choices. Quantitative feasibility, location-specific land suitability, refinery economics, and lifecycle emissions remain important subjects for subsequent empirical investigation. These limitations do not eliminate the value of qualitative synthesis; rather, they clarify which decisions can be informed by existing scientific knowledge and which require additional Indonesian evidence.

Results: Thematic Findings

Theme One: Energy Security and Strategic Opportunities

The reviewed literature indicates that domestically produced bioethanol could provide Indonesia with a supplementary source of transportation fuel and reduce reliance on imported petroleum-derived gasoline components. The potential benefit derives from replacing part of the gasoline volume with an energy carrier produced from domestic agricultural resources. Nevertheless, the magnitude of the benefit depends on actual ethanol availability, the volume of E20 sold, fuel-energy differences, and changes in vehicle consumption. A blending mandate alone cannot establish the amount of petroleum import expenditure ultimately avoided [4,18].

Domestic ethanol production could also support agricultural industrialization. Investments in sugarcane cultivation, distilleries, logistics, engineering, and associated services may create employment and deepen domestic industrial capabilities. Integrated biorefineries could generate additional economic value through electricity, fertilizers, and other products, strengthening connections between agricultural and manufacturing activities. However, realized benefits will depend on domestic procurement, technological learning, local supplier participation, and the commercial viability of related industries [25,29]. The literature further suggests that energy security should not be defined solely through domestic production volumes. A system dependent on one agricultural crop may remain vulnerable to drought, crop disease, rainfall variability, fertilizer prices, or local logistical disruptions. A diversified supply portfolio and suitable reserves may therefore contribute more effectively to resilience than nominal self-sufficiency based on a narrowly concentrated feedstock strategy [13,39].

Theme Two: Feedstock Availability and Agricultural Constraints

The availability of competitively priced and sustainably produced feedstock emerges as one of the most consequential requirements for E20 implementation. Sugarcane production cannot be expanded instantaneously because plantation establishment, varietal adaptation, irrigation systems, mechanization, and harvesting arrangements require investment and operational preparation. Moreover, agricultural yields differ substantially across locations and farming practices. Land classified as potentially available should therefore not be automatically interpreted as suitable, legally accessible, or capable of supporting high-yield cane production [14,49]. An additional challenge concerns the relationship between ethanol feedstock demand and domestic sugar production. Sugarcane can support both industries, but allocating fermentable sugars to ethanol may reduce their availability for sugar manufacturing under certain conditions. Conversely, productivity gains, improved milling efficiency, and better utilization of available molasses could expand ethanol output without an equivalent increase in cultivated area. Consequently, the feasible contribution of existing sugar industries must be evaluated before assumptions are made about extensive new agricultural development [11,19]. The literature identifies alternative feedstocks as potential mechanisms for reducing supply concentration. Cassava, maize, and sweet sorghum can contribute to ethanol production under suitable agricultural and industrial conditions. However, their use introduces different considerations concerning food markets, harvesting technologies, processing infrastructure, agricultural seasonality, and opportunity costs. Diversification therefore requires comparative assessment rather than indiscriminate substitution between crops [21,22,32]. The indicative two-million-hectare development programme should consequently be interpreted as a scale under policy consideration rather than a demonstrated requirement. Its adequacy cannot be determined without defining the quantity of ethanol needed, the distribution of feedstock pathways, realistic annual agricultural yields, industrial conversion rates, and sustainability restrictions. This finding underscores the importance of integrating agricultural land planning with energy-demand analysis before establishing irreversible investment commitments.

Theme Three: Industrial Capacity and Infrastructure Readiness

Bioethanol production requires processing facilities capable of converting feedstock into fuel-grade ethanol at commercial scale. Conventional sugar-based pathways rely on fermentation, distillation, and dehydration, while advanced feedstocks frequently require additional pretreatment and hydrolysis operations. Industrial performance depends on continuous feedstock supply, fermentation control, energy efficiency, water management, equipment reliability, and product quality. The literature indicates that weak coordination between agricultural supply and processing capacity can undermine profitability even when the conversion technology itself is technically established [12,24]. Investment timing presents a particularly important issue. Processing facilities built before reliable feedstock supplies are available may experience low utilization, while agricultural expansion undertaken without operational purchasing facilities may expose farmers to substantial commercial risks. These opposing risks support coordinated investment sequencing and enforceable offtake arrangements. Regional supply-chain studies in Indonesia further demonstrate the importance of processing location, transport distances, and integrated production planning [13,23]. Distribution

infrastructure constitutes an additional constraint. Fuel-grade ethanol requires suitable handling systems and quality controls, while E20 must be blended and distributed through appropriate terminals, storage tanks, transport systems, and retail equipment. Equipment suitability, moisture control, product segregation, and quality testing are necessary to preserve fuel specifications. These requirements mean that producing ethanol at a distillery does not, by itself, establish commercial readiness to distribute E20 to consumers [27,43]. The literature also identifies opportunities for integrated industrial development. Sugar factories may be retrofitted or complemented with distillation facilities, while biorefinery configurations may valorize bagasse, process residues, and additional products. Such integration can improve resource utilization and potentially strengthen project returns. However, its commercial viability depends on engineering compatibility, capital costs, electricity and coproduct markets, and appropriate financial arrangements [31,40].

Theme Four: Fuel Quality, Engine Performance, and Vehicle Compatibility

Experimental research indicates that ethanol blending can influence combustion efficiency, engine power, fuel consumption, and emissions. Ethanol's oxygen content and octane characteristics can offer combustion advantages under selected engine configurations, while its relatively low energy content may increase fuel consumption by volume. The resulting performance therefore depends on the design and calibration of the engine rather than solely on the ethanol concentration in the fuel [41,51]. Studies examining different injection strategies, compression ratios, and operating conditions confirm that E20-related outcomes are not uniform across engines. Appropriate calibration may improve certain performance characteristics, whereas incompatible operating strategies can produce unfavorable results. Consequently, laboratory findings involving optimized or experimental engines should not be generalized automatically to Indonesia's diverse passenger-car and motorcycle fleets [52,53].

Research on gasoline–ethanol mixtures also reveals trade-offs involving emissions. Some combinations can reduce particular pollutants, while effects on nitrogen oxides, hydrocarbons, volatile organic compounds, and particulate emissions remain operating-condition dependent. Cold-temperature conditions, engine warm-up strategies, injection configurations, and exhaust aftertreatment technologies can influence actual outcomes. National testing must therefore include representative driving cycles and vehicle technologies rather than relying on a single laboratory performance indicator [45,54-56]. Material compatibility is particularly relevant for existing vehicles that were not designed or certified for E20. Alcohol-containing fuels may interact differently with metals, elastomers, seals, coatings, and fuel-system components. Reliable implementation requires fuel specifications, representative durability testing, manufacturer coordination, consumer guidance, and transparent warranty arrangements. Findings from studies of component corrosion and ethanol–gasoline blends reinforce the necessity of a differentiated compatibility strategy rather than an assumption of universal suitability [43,57]. Additional investigations of ethanol–gasoline blends emphasize the complex relationships among fuel formulation, combustion stability, injection methods, and emissions performance. Experimental improvements under optimized conditions do not establish that every legacy vehicle will perform equivalently without adaptation. These findings support a phased market introduction involving certified vehicle categories, monitored pilot locations, and progressive expansion after independent technical verification [16,28,58].

Theme Five: Economic Feasibility and Investment Requirements

The economic viability of domestic E20 depends on the relationship between ethanol production costs, petroleum blendstock prices, distribution expenses, and policy incentives. Agricultural feedstock procurement is a major cost determinant, while processing energy, plant utilization, logistics, and financing conditions affect the overall cost structure. Production costs may also fluctuate with weather, commodity prices, and exchange rates. Consequently, the economics of E20 cannot be reliably inferred from a single historical price comparison [21,38].

Large-scale industrial investment creates additional challenges. Distilleries, dehydration units, storage facilities, blending terminals, and supporting infrastructure require substantial capital before fuel revenues are generated. The ability to attract finance depends on regulatory certainty, expected market demand, feedstock contracts, technology reliability, and credible revenue projections. Ambitious timelines may increase the risk of committing capital before these conditions are established [7,39].

Blending mandates and fiscal incentives may help establish a domestic market, but their costs must be transparently evaluated. Guaranteed purchase prices, tax adjustments, subsidies, and producer incentives can redistribute financial risks among governments, companies, farmers, and consumers. An economically defensible policy therefore needs to demonstrate not only sufficient private returns but also an acceptable distribution of public costs and benefits [20,48].

Theme Six: Environmental Sustainability and Resource Competition

The reviewed lifecycle literature demonstrates that the environmental performance of sugarcane ethanol depends strongly on cultivation practices, processing systems, energy inputs, and accounting conventions. Analysis of Brazilian sugarcane ethanol using industrial data reported substantial greenhouse-gas reductions relative to a specified gasoline reference under its defined boundaries, but the published comparison excluded land-use change. This distinction is important because environmental performance may differ when new agricultural expansion, soil-carbon changes, and ecosystem conversion are considered [16]. Water requirements represent a further challenge. Sugarcane cultivation can require substantial quantities of water, and resource pressure depends on rainfall, irrigation efficiency, local hydrology, and competing demands. Lifecycle research demonstrates that water footprints vary according to cultivation systems and the allocation of impacts across sugar, ethanol, and electricity. The implication for Indonesia is that regional water availability must be assessed at the watershed level rather than treated as a uniform national resource [14,15]. Land-use change may also weaken the environmental justification for bioethanol. Expanding agricultural production into carbon-rich landscapes can generate emissions and damage biodiversity, while displacement of existing production may transfer pressure to other regions. The literature therefore supports a precautionary approach involving spatial restrictions, environmental monitoring, and consistent lifecycle accounting. Land-use safeguards should be treated as fundamental project-selection criteria rather than as measures introduced after cultivation begins [46,47].

Theme Seven: Social Inclusion and Rural Development

Bioethanol expansion could stimulate rural development through demand for agricultural labor, machinery services, transport, and processing activities. Smallholder farmers could benefit from more diversified markets and additional opportunities to participate in industrial value chains. Yet these benefits depend on access to land, affordable finance, reliable extension services, and fair purchasing arrangements. Without such institutions, agricultural-industrial integration may concentrate economic gains among larger enterprises [17,49]. Land rights and community participation are particularly important where large-scale agricultural development is proposed. Identifying land as potentially suitable for cultivation does not necessarily establish that it is free from community claims, customary rights, conservation obligations, or alternative livelihood uses. Investment planning should therefore incorporate transparent land verification, meaningful participation, grievance mechanisms, and enforceable social safeguards. These conditions are essential for maintaining legitimacy and preventing an energy-security programme from generating new social conflicts.

Theme Eight: Institutional Governance and International Experience

International experience suggests that successful bioethanol development requires persistent coordination among agricultural producers, industrial processors, fuel suppliers, regulatory authorities, and vehicle manufacturers. Brazil demonstrates the potential advantages of integrated sugarcane industries and lifecycle-based carbon-performance mechanisms. However, these outcomes reflect decades of technological and institutional development and cannot be transferred automatically to a country with a different production structure or vehicle market [16,47]. India's ethanol-blending experience demonstrates both the potential for rapid policy mobilization and the complexity of managing agricultural resource pressures. Economic and environmental studies highlight the importance of feedstock choices, pricing arrangements, technological development, and trade conditions. Recent modelling identifies significant tensions between blending targets and demands on agricultural land, water, nitrogen inputs, and food markets. These findings offer relevant warnings for Indonesia as it considers expansion of sugarcane cultivation [10,18,19,]. Indonesia's principal institutional challenge is the need to establish a coherent governance mechanism spanning multiple sectors. Agriculture determines feedstock production, industry influences processing capacity, the energy sector regulates fuel distribution, fiscal authorities shape investment incentives, environmental institutions oversee sustainability, and vehicle manufacturers determine compatibility requirements. Coordinated decisions must precede rather than merely follow large-scale investment. The available literature therefore supports a national implementation framework with clearly allocated responsibilities, measurable milestones, and independent performance verification[7,50].

Discussion and Analysis

Reconciling Policy Ambition with Implementation Readiness

The synthesis suggests that Indonesia's E20 ambition should be understood as a complex programme of coordinated industrial transformation. Its feasibility depends not only on whether bioethanol can be produced domestically but also on whether certified volumes can be delivered to fuel markets at appropriate cost, quality, and reliability. This distinction is essential because policy targets can create the appearance of progress even when critical supply-chain components remain incomplete. A credible national roadmap should consequently distinguish ethanol-production readiness, blending readiness, vehicle compatibility, and commercial deployment. The experience of Indonesia's biodiesel programme demonstrates the potential value of sustained policy direction and coordinated industrial development. Nevertheless, ethanol production involves different agricultural resources, industrial economics, product specifications, and vehicle systems. The success of biodiesel therefore provides an institutional learning opportunity rather than definitive evidence of equivalent bioethanol feasibility. Adapting the relevant lessons requires comprehensive analysis of domestic sugarcane resources, processing investments, petroleum markets, and automotive-sector conditions [6,7].

A useful interpretation is that E20 readiness is a system property governed by the compatibility of different components. Even highly productive sugarcane farms may not guarantee market readiness if distillation capacity is insufficient. Similarly, industrial processing capacity may remain underutilized if agricultural supply is unreliable or fuel distribution facilities are incompatible. The readiness of the complete system therefore depends on synchronized investment, clear standards, and effective institutional coordination.

Assessing Ethanol Demand and Land Requirements

The relationship between the volume of E20 sold and its ethanol requirement provides a necessary starting point for policy planning. For a finished gasoline blend containing 20% ethanol by volume, nominal ethanol demand is represented by Equation (1), before storage losses, reserve allowances, and production contingencies are included.

$$V_{EtOH} = 0.20 \times V_{E20}$$

In Equation (1), V_{EtOH} denotes the required annual volume of fuel-grade ethanol (litres) and V_{E20} denotes the annual volume of finished E20 sold (litres). The expression is strictly volumetric: equal-volume substitution should not be interpreted as equal-energy substitution because gasoline and ethanol have different lower heating values.

For analytical illustration, a market supplying 30 billion litres of finished E20 annually would require approximately 6 billion litres of ethanol before accounting for production losses, strategic reserves, and operational contingencies. This example is not a forecast of Indonesia's actual gasoline consumption or ethanol requirement. Reliable national estimates require official fuel-sales data, market-coverage assumptions, and verified industrial supply information. The productive sugarcane area associated with direct cane-to-ethanol production can be approximated by Equation (2). This simplified calculation is illustrative and is not directly applicable to ethanol produced from molasses, which must instead be linked to the material balance of sugar processing.

$$A_{cane} = \frac{V_{EtOH,cane}}{(Y_{cane} \times C_{cane})}$$

In Equation (2), A_{cane} is productive area (hectares), V_{EtOH},cane is annual ethanol volume supplied specifically by the direct cane-based pathway (litres), Y_{cane} is recovered annual sugarcane yield (tonnes per hectare), and C_{cane} is recovered fuel-ethanol yield (litres per tonne of cane). For example, hypothetical yields of 80 tonnes of cane per hectare and 70 litres of ethanol per tonne would produce approximately 5,600 litres per hectare. Supplying 6 billion

litres under these assumptions would require about 1.07 million productive hectares before crop establishment, losses, competing sugar uses, and sustainability constraints are considered. These are scenario inputs rather than measured Indonesian national averages. The exercise illustrates why the indicative two-million-hectare programme cannot be independently assessed without detailed agronomic information. Some locations may support higher productivity, while others may experience unfavorable soils, water shortages, limited infrastructure, or legal restrictions. Additionally, ethanol produced from molasses requires a different accounting method because molasses availability depends on sugar-processing operations and the allocation of cane outputs. A robust national feedstock balance should therefore differentiate direct cane-juice conversion, molasses-based production, and lignocellulosic pathways.

Evaluating Feedstock Diversification

The central strategic choice is whether E20 should rely predominantly on sugarcane or utilize a portfolio of agricultural feedstocks. Sugarcane offers processing advantages and established industrial applications, but geographical and seasonal concentration may create vulnerabilities. Cassava, maize, and sweet sorghum could potentially supplement production where regional conditions favor their cultivation. Nevertheless, diversification should be based on comparative resource efficiency rather than solely on the technical possibility of converting a crop into ethanol [20,21]. Figure 1 traces the principal feedstock-to-fuel sequence, highlighting the logistical and technical hand-offs between cultivation, conversion, certification, gasoline blending, retail distribution, and compatible vehicles. The diagram is intended to identify necessary coordination points rather than to indicate verified commercial capacity in Indonesia.

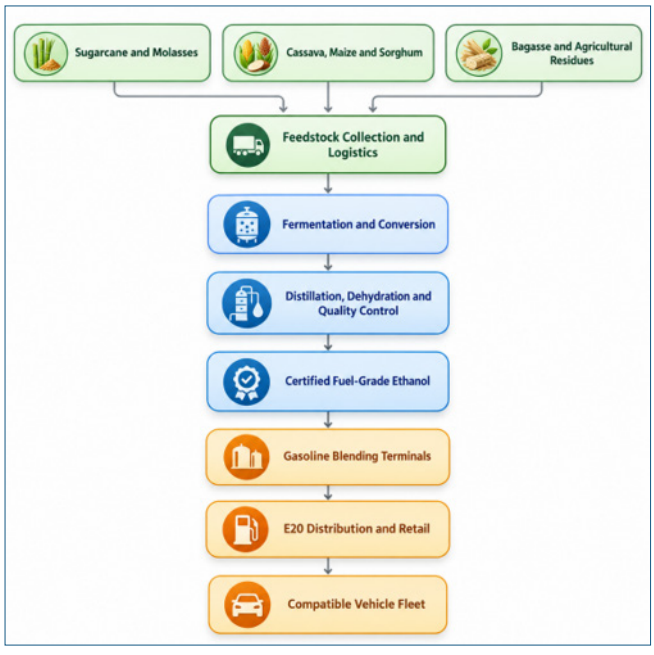


Figure 1: Integrated Feedstock-to-E20 Value Chain.

Figure 1 illustrates the interdependence between agricultural feedstock systems, ethanol-processing pathways, fuel-quality requirements, blending infrastructure, and vehicle markets. Its central implication is that successful implementation requires coordination across the entire value chain. Weaknesses in feedstock supply, processing reliability, blending facilities, or final-market compatibility can interrupt the programme even when other components are technically developed.

The use of agricultural residues presents another strategic option. Indonesia's oil-palm industry generates substantial lignocellulosic materials that have attracted interest for advanced bioethanol production. Research on empty fruit bunches identifies technological and logistical opportunities, but also emphasizes the need for careful assessment of collection costs, pretreatment requirements, processing economics, and alternative residue uses. The existence of biomass does not automatically establish that its conversion to ethanol is environmentally or economically superior to competing applications [4,59,60]. Recent Indonesian research provides a particularly useful techno-economic reference for evaluating bagasse-based ethanol. Bahar et al. modelled a sugarcane-bagasse facility using a locally specified annual feedstock supply and reported a levelised ethanol cost of USD 0.541 per litre and a payback period of 5.09 years under the study's assumptions [61]. These results illustrate a potentially viable pathway, but they must not be interpreted as a guaranteed national production cost, because financial outcomes depend on project boundaries, assumed feedstock availability, operating conditions, financing, and the selling price [61].

Second-generation conversion could improve long-term resource efficiency by utilizing selected residues without directly expanding food-crop cultivation. However, this prospect depends on commercially reliable technology, adequate collection systems, and lifecycle evidence. Large-scale policy planning should not count hypothetical advanced-ethanol volumes as guaranteed short-term supply. The more defensible approach is to establish commercial first-generation capacity while supporting targeted demonstrations and progressively incorporating advanced technologies when their performance is independently demonstrated [33,36].

Economic Feasibility and Public Finance

The economic case for E20 should be examined from both private-investment and national-welfare perspectives. Private investors require predictable feedstock costs, plant utilization, offtake arrangements, and returns on capital. The government must consider fiscal expenditure, potential petroleum-import savings, domestic value creation, and the distribution of costs among consumers and producers. These perspectives may differ when subsidies or guaranteed purchasing arrangements transfer risks from industrial investors to public institutions. A comparative cost analysis should evaluate domestic ethanol against the petroleum blendstock displaced, using consistent energy and product-quality assumptions. It should include feedstock procurement, conversion costs, distribution expenses, taxes, financing, and potential coproduct revenues. Price comparisons that ignore fuel-energy differences may overstate apparent savings. Equally, evaluations excluding the public cost of incentives may overstate national economic benefits [20,48]. Financial risk management becomes particularly important under large and accelerated investment programmes. Long-term offtake agreements can reduce revenue uncertainty, but excessive guarantees may create fiscal liabilities if domestic ethanol costs remain persistently above relevant market benchmarks. Policy support should therefore be predictable, transparent, and periodically reviewed against technological performance and market conditions. Competitive procurement, independent project appraisal, and disclosure of support mechanisms can help limit financial distortions.

The techno-economic literature also contains cautionary counter-evidence. In a comparison of three sugarcane-bagasse conversion pathways, Buthelezi, Chetty and Mohammadi found a negative net present value for the modelled ethanol pathway, whereas alternative products showed more favourable financial results under that study's assumptions [62]. Considered alongside the Indonesia-focused cost assessment of Bahar et al. these findings indicate that ethanol competitiveness is project-specific and sensitive to process configuration, market assumptions, and coproduct opportunities rather than an inherent property of sugarcane residues [61]. An additional issue concerns the allocation of investment across the supply chain. Constructing distilleries without adequate agricultural infrastructure may generate stranded capacity, while subsidizing agricultural expansion without secure markets can expose farmers to severe losses. Investments should therefore be organized into coordinated clusters with demonstrable feedstock availability, processing viability, logistics access, and fuel-market demand. This approach is consistent with research highlighting the importance of spatial configuration and resilient supply-chain design [38,39].

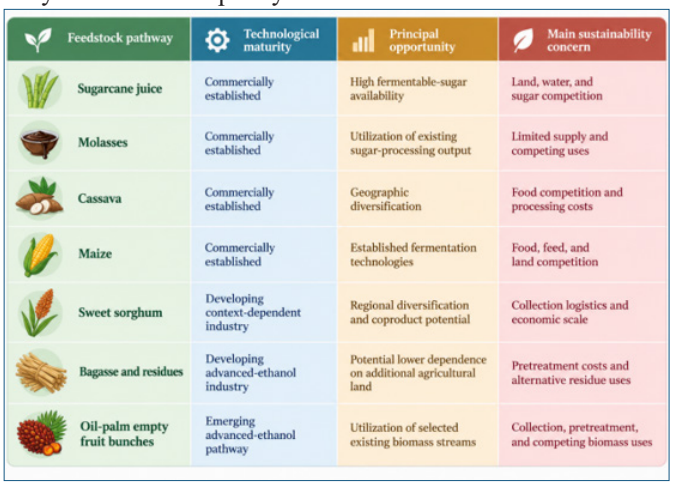
Environmental Credibility and Carbon Accounting

A critical analytical finding is that ethanol's renewable origin does not guarantee a fixed percentage reduction in greenhouse-gas emissions. Lifecycle performance depends on agricultural practices, energy inputs, industrial efficiency, transport requirements, and land-use accounting. A Brazilian study using data from 67 sugarcane mills estimated an average lifecycle carbon intensity of 35.2 gCO_2e/MJ and a 62% reduction relative to its specified gasoline reference, excluding land-use change. These results demonstrate potential benefits under particular circumstances but should not be presented as direct estimates of Indonesian E20 performance [16].

For Indonesia, the source and previous condition of agricultural land could substantially influence the climate balance. Conversion of forests, peatlands, or other carbon-rich ecosystems may create emissions that offset the benefits obtained from fossil-fuel displacement. Even development on previously cultivated land requires consideration of displaced agricultural production, soil quality, water demand, and ecosystem services. The implication is that land eligibility and lifecycle emissions should be assessed before investment approval rather than after ethanol production begins [15,47].

Economic evidence from Brazil further illustrates why expansion-related effects should not be ignored. Sant'Anna analysed marginal sugarcane-ethanol supply using a spatially informed land-use model and found that acreage expansion, rather than yield improvement, accounted for most additional ethanol production in the setting studied [63]. The reported contribution of direct deforestation to marginal land expansion reinforces the need for Indonesia-specific counterfactual land-use analysis, although Brazilian model estimates cannot be transferred numerically to Indonesia without validation [63]. Carbon accounting should use functional units that permit meaningful comparisons between E20 and conventional gasoline. Energy-based carbon intensity, commonly expressed in grams of carbon dioxide equivalent per megajoule, provides one useful measure. However, assessment must also consider the actual energy delivered, possible changes in fuel consumption, and emissions from relevant vehicle-use conditions. Comprehensive evaluation should distinguish lifecycle greenhouse-gas performance from local air-pollution effects, since improvement in one does not automatically guarantee improvement in the other.

The water and nutrient dimensions deserve equally rigorous consideration. Sugarcane cultivation in areas with limited water availability could increase competition among agriculture, households, industry, and ecosystems. Excessive fertiliser application may generate greenhouse-gas emissions and impair water quality. Regional agricultural practices, irrigation efficiency, fertiliser management, and wastewater treatment must therefore be incorporated into sustainability standards [14,19]. Figure 2 compares the maturity, strategic opportunities, and major sustainability concerns of seven feedstock pathways. Its classifications are qualitative, and individual pathways should be evaluated using comparable local cost, land-use, resource, and lifecycle data before policy decisions are made.



Feedstock pathway	Technological maturity	Principal opportunity	Main sustainability concern
Sugarcane juice	Commercially established	High fermentable-sugar availability	Land, water, and sugar competition
Molasses	Commercially established	Utilization of existing sugar-processing output	Limited supply and competing uses
Cassava	Commercially established	Geographic diversification	Food competition and processing costs
Maize	Commercially established	Established fermentation technologies	Food, feed, and land competition
Sweet sorghum	Developing context-dependent industry	Regional diversification and coproduct potential	Collection logistics and economic scale
Bagasse and residues	Developing advanced-ethanol industry	Potential lower dependence on additional agricultural land	Pretreatment costs and alternative residue uses
Oil-palm empty fruit bunches	Emerging advanced-ethanol pathway	Utilization of selected existing biomass streams	Collection, pretreatment, and competing biomass uses

Figure 2: Environmental and Economic Trade-Offs Among Feedstock Pathways.

Figure 2 provides a qualitative comparison of potential feedstock pathways and illustrates why no single option should automatically be ranked as environmentally superior in every location. Sugarcane juice, molasses, cassava, maize, sorghum, and agricultural residues differ in processing maturity, agricultural competition, resource requirements, and technological uncertainty. The figure is intended to guide location-specific evaluation rather than to represent numerical lifecycle assessment results.

Automotive Readiness and Consumer Acceptance

The automotive dimension represents a potentially binding constraint for rapid E20 implementation. Indonesia's existing vehicle population includes different engine technologies, vehicle ages, fuel-system materials, and manufacturer specifications. Some engines may be suitable for E20 under their approved operating conditions, while others may require additional verification or modifications. A national mandate that assumes uniform compatibility could therefore create technical risks and undermine public confidence.

A credible compatibility strategy should begin with a representative national vehicle-fleet assessment. Manufacturers, fuel suppliers, research institutions, and relevant authorities should jointly identify certified vehicle categories and undertake durability, emissions, performance, and fuel-system testing. Particular attention should be given to motorcycles and other widely used vehicles whose operating requirements and fuel-system configurations may differ

from passenger-car applications. Independent testing should distinguish the effects of fuel formulation from engine-calibration adjustments [41,43,52]. Consumer acceptance will depend on practical experience with fuel prices, vehicle performance, fuel consumption, reliability, and warranty protection. Ethanol's lower energy content per litre can increase volumetric fuel demand under certain conditions, although actual outcomes depend on engine efficiency and calibration. Public communication should therefore avoid promising identical fuel consumption or universal emissions improvements. Transparent information about vehicle suitability, quality assurance, and consumer remedies will be more credible than promotional claims unsupported by representative testing.

A phased market introduction offers advantages over an immediate universal mandate. Certified vehicle segments or selected regional markets can provide operational evidence regarding blending quality, retail infrastructure, user experience, and fuel-supply consistency. Results from these pilots can then inform expansion decisions, while incompatible vehicle categories retain access to appropriate alternatives. Such sequencing would reduce the risks associated with deploying a new fuel standard before the complete market system is ready.

Social Inclusion and Agricultural Governance

The prospects for rural development depend on how agricultural participation is organized. Large-scale sugarcane production can create opportunities for farmers, laborers, contractors, transport operators, and local enterprises. Yet successful inclusion requires more than geographic proximity to processing facilities. Farmers need access to productive planting material, extension services, financing, reliable purchasing arrangements, and transparent mechanisms for resolving disputes [49]. An inclusive E20 strategy should combine productivity improvement with safeguards against excessive concentration of agricultural resources. Smallholder participation can be supported through farmer organizations, cooperative services, shared machinery, transparent contract terms, and appropriate financing mechanisms. Pricing arrangements should allow producers to understand how crop quality, delivery conditions, and market fluctuations influence compensation. Such mechanisms can promote sustained feedstock supply while improving the distribution of economic gains. Land governance is especially sensitive where agricultural expansion is proposed across multiple provinces. Land-use planning must account for formal ownership, customary rights, existing cultivation, conservation obligations, and community dependence on ecosystem resources. Areas identified as administratively available may still require extensive social and environmental verification. Consequently, land acquisition should proceed only after independent assessment and meaningful engagement with affected communities. Food-security safeguards are equally important. Allocating food-related agricultural commodities to fuel production can affect supply and prices, particularly under adverse harvest conditions. Policies should therefore incorporate transparent rules for feedstock allocation, monitoring of relevant food markets, and contingency arrangements when agricultural supplies become constrained. International evidence demonstrates that the social consequences of biofuel expansion depend strongly on crop selection, agricultural competitiveness, and market institutions [17,19].

An Integrated E20 Implementation Readiness and Sustainability Framework

The preceding analysis supports the development of an Integrated E20 Implementation Readiness and Sustainability Framework. The framework comprises four operational readiness dimensions and three cross-cutting sustainability conditions. Operational readiness includes agricultural feedstock supply, industrial processing, fuel-market and vehicle compatibility, and institutional implementation capacity. The sustainability conditions concern lifecycle environmental performance, economic and fiscal feasibility, and equitable social outcomes. The framework emphasizes that these dimensions are interdependent rather than independent checklist items. For example, an increase in agricultural productivity can reduce land requirements but may increase fertilizer demand if achieved through input-intensive methods. Industrial integration may improve conversion efficiency while requiring additional capital and skilled labor. Higher ethanol prices may attract investment but increase fuel costs unless accompanied by appropriate market arrangements. The effectiveness of each intervention must therefore be assessed in relation to its consequences elsewhere in the system. The framework also distinguishes necessary conditions from desirable improvements. Verified fuel quality, sufficient commercial supply, and compatible vehicle systems are necessary for market deployment. Advanced biorefinery integration, expanded coproduct markets, and sophisticated digital monitoring may improve long-term efficiency but should not be treated as substitutes for minimum safety and supply requirements. This distinction is useful for prioritising investment and preventing an implementation programme from becoming excessively complex before essential capacities are secured. Figure 3 presents the article's conceptual synthesis of four operational readiness dimensions and three cross-cutting sustainability conditions. The directional links describe proposed analytical dependencies, not estimated causal effects.

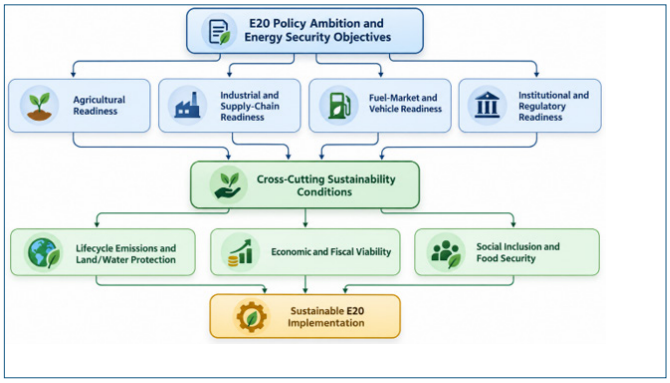


Figure 3: Integrated E20 Implementation Readiness and Sustainability Framework.

Figure 3 conceptualises implementation readiness as the interaction of agriculture, industrial processing, fuel markets, and institutions under environmental, economic, and social constraints. The expected outcome is not simply a higher ethanol-blending percentage but reliable domestic supply, credible emissions performance, economic value creation, and sustained public acceptance. The framework provides a basis for identifying implementation bottlenecks and developing measurable indicators.

Strategic Implementation Roadmap

A practical implementation roadmap should organize the E20 transition into sequential, evidence-based phases. The first phase should emphasize baseline verification, including national gasoline demand, domestic ethanol production capacity, sugarcane productivity, molasses availability, land suitability, industrial costs, and vehicle compatibility. This phase should also establish

the regulatory responsibilities of participating institutions and define the minimum environmental and social requirements for proposed projects.

Figure 4 translates these findings into a phased, stage-gated implementation proposal for 2026–2035. Progression is conditional on independently verified readiness rather than the passage of time alone, while unmet conditions trigger corrective actions and renewed assessment.

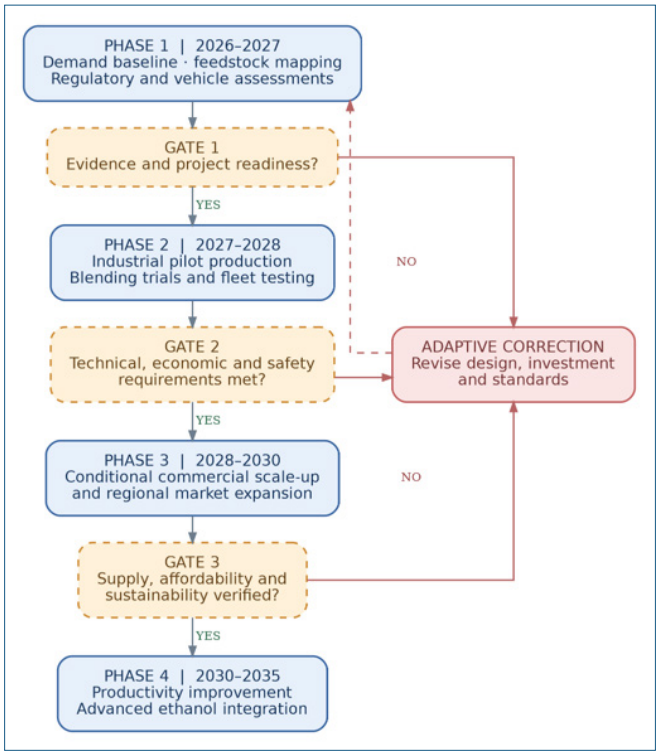


Figure 4: Proposed Stage-Gated E20 Implementation Roadmap, 2026–2035.

Figure 4 presents a conditional sequence of implementation phases from baseline verification through pilot deployment, controlled commercial scaling, and long-term technological upgrading. Its critical feature is the use of readiness gates between phases rather than unconditional calendar-based expansion. This approach enables the government to maintain strategic direction while delaying, redesigning, or restricting investments that fail to satisfy technical, economic, environmental, or social criteria.

The second phase should prioritize controlled industrial and market demonstrations. Ethanol production facilities should be developed where feedstock supply, logistics access, and economic viability can be demonstrated. Blending terminals should undergo technical verification, and vehicle trials should involve representative engine technologies. Pilot operations should collect evidence on fuel quality, actual production costs, supply reliability, consumer experience, and environmental performance before large-scale expansion proceeds.

The third phase should involve graduated commercial scaling where pilot evidence supports implementation. Production and blending capacity should increase in coordination with compatible vehicle-market coverage and reliable feedstock supply. Regulatory mechanisms should remain adaptable to emerging evidence, particularly where production costs, agricultural conditions, or environmental impacts differ from initial assumptions. Public reporting should identify whether each implementation milestone has been satisfied.

A longer-term phase should focus on industrial upgrading, agricultural productivity improvements, regional diversification, and advanced conversion technologies. Integrated biorefineries, selected residue-based ethanol pathways, and improved resource efficiency may contribute to greater resilience. However, these investments should be evaluated alongside electrification, efficiency improvements, and other transport-sector decarbonization strategies rather than through an exclusive commitment to progressively higher ethanol concentrations.

Governance, Monitoring, and Policy Recommendations

Effective implementation will require a clearly designated national coordination mechanism. Agricultural authorities should be responsible for feedstock assessments and cultivation standards, while industrial institutions should oversee processing investment, technical capability, and production development. Energy authorities should establish blending specifications, distribution arrangements, and market monitoring. Environmental and land-governance institutions should verify compliance with relevant safeguards, while vehicle manufacturers and technical agencies should provide compatibility evidence. The financing structure should distinguish commercially viable investments from activities that require temporary public support. Support mechanisms should disclose their objectives, beneficiaries, fiscal implications, performance conditions, and review procedures. Industrial projects should be assessed through independent techno-economic appraisal, while large-scale agricultural developments should be subjected to social and environmental verification before financial closure. These arrangements would improve accountability and reduce exposure to unsuccessful investments.

A national monitoring system should include production, market, economic, environmental, and social indicators. Production indicators could include certified ethanol capacity, plant utilization, feedstock productivity, and domestic supply volumes. Market indicators should cover fuel-quality compliance, compatible vehicle categories, retail distribution coverage, and supply interruptions. Economic indicators should include production costs, public fiscal support, realized import substitution, and farmer participation. Environmental and social indicators should include lifecycle carbon intensity, land-use changes, water use, food-market effects, and grievance outcomes. Independent verification is necessary because programme participants may face incentives to overstate progress or underreport costs. Public reporting should therefore distinguish announced investment, committed financing, constructed capacity, operational capacity, and actual ethanol delivered into certified fuel markets. Similarly, sustainability reporting should distinguish projected emissions savings from independently verified lifecycle results. Transparent monitoring can support public confidence and allow policy corrections before problems become structurally embedded.

Finally, E20 should be integrated into Indonesia's wider transportation transition. Ethanol blending can potentially reduce petroleum dependence in compatible combustion-engine vehicles, but it should not be assumed to replace the need for electrification, public transportation improvements, or energy-efficiency measures. The appropriate policy objective is to minimize the full social and environmental cost of mobility while strengthening

resilience and domestic economic development. E20's contribution should be judged by that broader standard rather than by blending concentration alone.

Conclusion and Future Directions

Indonesia's E20 ambition presents a potentially significant opportunity to diversify transportation fuels, reduce petroleum-import exposure, and strengthen agricultural-industrial value chains. Sugarcane provides a plausible foundation for domestic ethanol production, particularly where existing processing infrastructure, improved agricultural productivity, and integrated biorefineries can support reliable feedstock conversion. Nevertheless, successful implementation cannot be inferred from the availability of agricultural land or the technical feasibility of ethanol fermentation alone. A sustainable national programme requires coordinated feedstock supply, industrial capacity, certified fuel distribution, vehicle compatibility, and credible economic arrangements. The principal challenges concern the scale and sustainability of feedstock supply, competition with sugar and other agricultural uses, capital requirements, fuel-system compatibility, lifecycle emissions, water demand, and institutional coordination. These challenges interact and may amplify one another when investments are poorly sequenced or environmental and social safeguards are inadequate. International experience demonstrates that rapid blending expansion is possible under supportive policies, but it also illustrates the risks associated with resource competition, distorted incentives, and insufficient sustainability governance.

The article recommends an integrated and adaptive implementation strategy based on verified agricultural productivity, diversified feedstocks, coordinated industrial investment, representative automotive testing, transparent pricing, and comprehensive environmental safeguards. A phased rollout should be governed by independently verifiable readiness milestones rather than an unconditional national deadline. Public investment and industrial incentives should be linked to measurable outcomes, while smallholder participation, land rights, and food security should be embedded within programme governance. Future research should develop Indonesia-specific spatial land-suitability assessments, detailed ethanol supply-demand models, project-level techno-economic evaluations, lifecycle-carbon inventories, and representative vehicle-fleet compatibility studies. Additional analysis should examine the relative performance of sugarcane, molasses, cassava, sorghum, and agricultural residues under regional production conditions. The longer-term success of E20 should ultimately be evaluated through its contribution to energy security, environmental sustainability, economic efficiency, and inclusive development rather than through the achievement of a blending percentage alone.

References

1. Bonenkamp, T.B., Middelburg, L.M., Hosli, M.O., Wolffenbuttel, R.F. (2020). From bioethanol containing fuels towards a fuel economy that includes methanol derived from renewable sources and the impact on European Union decision-making on transition pathways. Renewable and Sustainable Energy Reviews, 120, 109667.
2. Cherwoo, L., Gupta, I., Flora, G., Verma, R., Kapil, M., et al. (2023). Biofuels an alternative to traditional fossil fuels: A comprehensive review. Sustainable Energy Technologies and Assessments, 60, 103503.
3. Rial, R.C. (2024). Biofuels versus climate change: Exploring potentials and challenges in the energy transition. Renewable and Sustainable Energy Reviews, 196, 114369.
4. Setiawan, I.C., Indarto, D. (2021). Quantitative analysis of automobile sector in Indonesian automotive roadmap for achieving national oil and CO_2 emission reduction targets by 2030. Energy Policy, 150, 112135.
5. Prasad, S., Yadav, K.K., Kumar, S., Pandita, P., Bhutto, J., et al. (2024). Review on biofuel production: Sustainable development scenario, environment, and climate change perspectives—A sustainable approach. Journal of Environmental Chemical Engineering, 12(2), 111996.
6. Wirawan, S.S., Solikhah, M.D., Setiapraja, H., Sugiyono, A. (2024a). Biodiesel implementation in Indonesia: Experiences and future perspectives. Renewable and Sustainable Energy Reviews, 189, 113911.
7. Wirawan, S.S., Setiapraja, H., Sugiyono, A., Ibadurrohman, I.A., Nitamiwati, N.P.D., et al. (2025). Assessing the readiness to implement bioethanol-blended fuel in Indonesia. Biomass and Bioenergy, 201, 108112.
8. Sekretariat Kabinet Republik Indonesia (2026). Pemerintah Siapkan Produksi E20 Dalam Dua Tahun, Tebu Jadi Sumber Etanol. 16 September. Available at: https://setkab.go.id/pemerintah-siapkan-produksi-e20-dalam-dua-tahun-tebu-jadi-sumber-etanol/
9. Kementerian Pertanian Republik Indonesia (2026). Mentan Amran Gaspol Bioetanol, 2 Juta Hektare Tebu, Singkong, Jagung untuk Kemandirian Energi. 21 September. Available at: https://pertanian.go.id/news/view/8162
10. Kumar, G., Padhy, R., Das, D., Narayana, S.A. (2024). Ethanol fuel blending program in India: Analysis of environmental, economic, and policy aspects using system dynamics approach. Journal of Advanced Transportation, 2002187.
11. Ayodele, B.V., Alsaffar, M.A., Mustapa, S.I. (2020). An overview of integration opportunities for sustainable bioethanol production from first- and second-generation sugar-based feedstocks. Journal of Cleaner Production, 245, 118857.
12. Melendez, J.R., Mátyás, B., Hena, S., Lowy, D.A., El Salous, A. (2022). Perspectives in the production of bioethanol: A review of sustainable methods, technologies, and bioprocesses. Renewable and Sustainable Energy Reviews, 160, 112260.
13. Wirawan, S.S., Sugiyono, A., Nitamiwati, N.P.D., Widiyanti, P.T., Romelan, R., et al. (2025b). Integrated supply chain optimization model for sorghum-based bioethanol industry on a small scale: Case study in East Java Province, Indonesia. Bioresource Technology Reports, 29, 102051.
14. Hiloidhari, M., Haran, S., Banerjee, R., Rao, A.B. (2021). Life cycle energy–carbon–water footprints of sugar, ethanol and electricity from sugarcane. Bioresource Technology, 330, 125012.
15. Duden, A.S., Verweij, P.A., Kraak, Y.V., Van Beek, L.P.H., Wanders, N., et al. (2021). Hydrological impacts of ethanol-driven sugarcane expansion in Brazil. Journal of Environmental Management, 282, 111942.
16. iu, X., Kwon, H., Wang, M. (2023). Life cycle greenhouse gas emissions of Brazilian sugar cane ethanol evaluated with the GREET model using data submitted to RenovaBio. Environmental Science & Technology, 57(32), 11814–11822.
17. Boly, M., Sanou, A. (2022). Biofuels and food security: Evidence from Indonesia and Mexico. Energy Policy, 163, 112834.
18. Azad, V.K., De, K., Majumder, S. (2024). Ethanol blending and its environmental impacts: A case study of India. Energy for Sustainable Development, 79, 101385.

19. Jha, C.K., Stevanović, M., Das, P., Dietrich, J.P., Mosnier, A., et al. (2026). India's biofuel blending policy presents serious trade-offs with land use, nitrogen emissions and food security. PLOS ONE, 21(7), e0351419.
20. Lundberg, L., Cintas Sanchez, O., Zetterholm, J. (2023). The impact of blending mandates on biofuel consumption, production, emission reductions and fuel prices. Energy Policy, 183, 113835.
21. Jain, S., Kumar, S. (2024). A comprehensive review of bioethanol production from diverse feedstocks: Current advancements and economic perspectives. Energy, 296, 131130.
22. Wirawan, S.S., Solikhah, M.D., Widiyanti, P.T., Nitamiwati, N.P.D., Romelan, R., et al. (2024b). Unlocking Indonesia's sweet sorghum potential: A techno-economic analysis of small-scale integrated sorghum-based fuel grade bioethanol industry. Bioresource Technology Reports, 25, 101706.
23. Setiawan, H., Hermawan, E., Adiarso, A., Setiadi, S., Saputra, H., et al. (2024). Optimized supply chain of empty fruit bunches as feedstocks for second generation bioethanol production. Case Studies in Chemical and Environmental Engineering, 10, 100950.
24. Tse, T.J., Wiens, D.J., Reaney, M.J.T. (2021). Production of bioethanol—A review of factors affecting ethanol yield. Fermentation, 7(4), 268.
25. Barua, S., Sahu, D., Sultana, F., Baruah, S., Mahapatra, S. (2023). Bioethanol, internal combustion engines and the development of zero-waste biorefineries: An approach towards sustainable motor spirit. RSC Sustainability, 1, 1065-1084.
26. Shirazi, S.A., Abdollahipoor, B., Windom, B., Reardon, K.F., Foust, T.D. (2020). Effects of blending C3–C4 alcohols on motor gasoline properties and performance of spark ignition engines: A review. Fuel Processing Technology, 197, 106194.
27. Waluyo, B., Setiyo, M., Saifudin, Wardana, I.N.G. (2021). Fuel performance for stable homogeneous gasoline-methanol-ethanol blends. Fuel, 294, 120565.
28. Rimkus, A., Pukalskas, S., Mejeras, G., Nagurnas, S. (2024). Impact of bioethanol concentration in gasoline on SI engine sustainability. Sustainability, 16(6), 2397.
29. López-Ortega, M.G., Guadalajara, Y., Junqueira, T.L., Sampaio, I.L., Bonomi, A., et al. (2021). Sustainability analysis of bioethanol production in Mexico by a retrofitted sugarcane industry based on the Brazilian expertise. Energy, 232, 121056.
30. Guimarães, C.E.C., Neto, F.S., de Castro Bizerra, V., do Nascimento, J.G.A., Valério, R.B.R., et al. (2023). Sustainable bioethanol production from first- and second-generation sugar-based feedstocks: Advanced bibliometric analysis. Bioresource Technology Reports, 23, 101543.
31. Elias, A.M., Gargalo, C.L., Farinas, C.S., Gernaey, K.V. (2024). Production of phosphate biofertilizers as a booster for the techno-economic and environmental performance of a first-generation sugarcane ethanol and sugar biorefinery. Journal of Cleaner Production, 471, 143400.
32. Nazli, R.I. (2020). Evaluation of different sweet sorghum cultivars for bioethanol yield potential and bagasse combustion characteristics in a semiarid Mediterranean environment. Biomass and Bioenergy, 139, 105624.
33. Sharma, B., Larroche, C., Dussap, C.G. (2020). Comprehensive assessment of 2G bioethanol production. Bioresource Technology, 313, 123630.
34. Chen, J., Zhang, B., Luo, L., Zhang, F., Yi, Y., et al. (2021). A review on recycling techniques for bioethanol production from lignocellulosic biomass. Renewable and Sustainable Energy Reviews, 149, 111370.
35. Aghaei, S., Karimi Alavijeh, M., Shafiei, M., Karimi, K. (2022). A comprehensive review on bioethanol production from corn stover: Worldwide potential, environmental importance, and perspectives. Biomass and Bioenergy, 161, 106447.
36. Afedzi, A.E.K., Parakulsuksatid, P. (2023). Recent advances in process modifications of simultaneous saccharification and fermentation (SSF) of lignocellulosic biomass for bioethanol production. Biocatalysis and Agricultural Biotechnology, 54, 102961.
37. Chauhan, S.J., Patel, B., Devliya, B., Solanki, H., Patel, H.D. (2024). Recent advancement in production of bioethanol from waste biomass: A review. Clean Technologies and Environmental Policy, 26, 3739-3759.
38. Vasilakou, K., Nimmegeers, P., Billen, P., Van Passel, S. (2023). Geospatial environmental techno-economic assessment of pretreatment technologies for bioethanol production. Renewable and Sustainable Energy Reviews, 187, 113743.
39. Jabbarzadeh, A., Shamsi, M. (2025). Designing a resilient and sustainable multi-feedstock bioethanol supply chain: Integration of mathematical modeling and machine learning. Applied Energy, 377, 123794.
40. Gomes, B.F.M.L., Vaz Júnior, S., Gurgel, L.V.A. (2024). Production of activated carbons from technical lignin as a promising pathway towards carbon emission neutrality for second-generation (2G) ethanol plants. Journal of Cleaner Production, 450, 141648.
41. Kim, Y., Kim, W.I., Min, B., Seo, J., Lee, K. (2022). Experimental investigation of combustion characteristics of ethanol–gasoline blended fuel in a T-GDI engine. Applied Thermal Engineering, 208, 118168.
42. Liu, S., Lin, Z., Zhang, H., Fan, Q., Lei, N., et al. (2023). Experimental study on combustion and emission characteristics of ethanol-gasoline blends in a high compression ratio SI engine. Energy, 274, 127398.
43. Kumar, T.S., Ashok, B. (2023). Corrosion behaviour analysis of SI engine components for ethanol-gasoline blends in flex fuel vehicular application. Fuel Processing Technology, 240, 107574.
44. Iodice, P., Amoresano, A., Langella, G. (2021). A review on the effects of ethanol/gasoline fuel blends on NOx emissions in spark-ignition engines. Biofuel Research Journal, 8(4), 1465-1480.
45. Cao, Y., Zhao, H., Zhang, S., Wu, X., Anderson, J.E., et al. (2024). Impacts of ethanol blended fuels and cold temperature on VOC emissions from gasoline vehicles in China. Environmental Pollution, 348, 123869.
46. Patel, K., Singh, S.K. (2024). Environmental sustainability, energy efficiency and uncertainty analysis of agricultural residue-based bioethanol production: A comprehensive life cycle assessment study. Biomass and Bioenergy, 191, 107439.
47. Guarenghi, M.M., Garofalo, D.F., Seabra, J.E., Moreira, M.M., Novaes, R.M., et al. (2023). Land use change net removals associated with sugarcane in Brazil. Land, 12(3), 584.
48. Declerck, F., Hikouatcha, P., Tchoffo, G., Tédongap, R. (2023). Biofuel policies and their ripple effects: An analysis of vegetable oil price dynamics and global consumer responses. Energy Economics, 128, 107127.
49. Machimu, G.M. (2024). Next steps for smallholder sugarcane

contract farmers in developing countries: A review. Social Sciences & Humanities Open, 9, 100865.
50. Das, P., Jha, C.K., Saxena, S., Ghosh, R.K. (2024). Can biofuels help achieve sustainable development goals in India? A systematic review. Renewable and Sustainable Energy Reviews, 192, 114246.
51. Ismail, F.B., Al-Bazi, A., Aboubakr, I.G. (2022). Numerical investigations on the performance and emissions of a turbocharged engine using an ethanol-gasoline blend. Case Studies in Thermal Engineering, 39, 102366.
52. Yu, J., Zhou, F., Fu, J., Yan, J., Zhang, L., et al. (2024). Effects of dual injection strategies on combustion, heat-work conversion process and emissions of a spark ignition engine fuelled with E20 blends. Journal of the Energy Institute, 112, 101498.
53. Suresh, D., Porpatham, E. (2024). Influence of high compression ratio on the performance of ethanol-gasoline fuelled lean burn spark ignition engine at part throttle condition. Case Studies in Thermal Engineering, 53, 103832.
54. Zhao, L., Wang, X., Wang, D., Su, X. (2020). Investigation of the effects of lean mixtures on combustion and particulate emissions in a DISI engine fueled with bioethanol-gasoline blends. Fuel, 260, 116096.
55. Liu, Z., Sun, P., Du, Y., Yu, X., Dong, W., et al. (2021). Improvement of combustion and emission by combined combustion of ethanol premix and gasoline direct injection in SI engine. Fuel, 292, 120403.
56. Zhao, Z., Yu, P.D.X., Huang, Y., Shi, W., Guo, Z., et al. (2022). Experimental study on combustion and emission of an SI engine with ethanol/gasoline combined injection and EGR. Journal of Cleaner Production, 331, 129903.
57. Siddique, M.B.M., Khairuddin, N., Ali, N.A., Hassan, M.A., Ahmed, J., et al. (2021). A comprehensive review on the application of bioethanol/biodiesel in direct injection engines and consequential environmental impact. Cleaner Engineering and Technology, 3, 100092.
58. Bathala, R., Hrishikheshan, G., Rajkumar, S., Jeyaseelan, T. (2024). Experimental investigation, ANN modeling, and TOPSIS optimization of gasoline-alcohol blends for minimizing tailpipe emissions of a motorcycle. Energy, 293, 130698.
59. Suhartini, S., Rohma, N.A., Mardawati, E., Hidayat, N., Melville, L. (2022). Biorefining of oil palm empty fruit bunches for bioethanol and xylitol production in Indonesia: A review. Renewable and Sustainable Energy Reviews, 154, 111817.
60. Priadi, H., Awad, S., Villot, A., Andres, Y., Purwanto, W.W. (2024). Techno-enviro-economic analysis of second-generation bioethanol at plant-scale by different pretreatments of biomass from palm oil waste. Energy Conversion and Management: X, 21, 100522.
61. Bahar, A.H., Riayatsyah, T.M.I., Nadia, C.I.S., Silitonga, A.S., Sebayang, A.H., et al. (2025). Life cycle cost of bioethanol bioeconomy of sugarcane bagasse in Indonesia. Industrial Crops and Products, 237, 122161.
62. Buthelezi, A.S., Chetty, M., Mohammadi, A.H. (2025). Techno-economic assessment of biofuels production from sugarcane bagasse. Energy Science & Engineering, 13, 4270-4286.
63. Sant'Anna, M. (2024). How green is sugarcane ethanol? The Review of Economics and Statistics, 106(1), 202-216.

Copyright: ©2026 Loso Judijanto. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.