

Beyond the blend: technological readiness, industrial scale-up, and automotive compatibility for Indonesia's E20 bioethanol transition—a review

Abstract

Indonesia's ambition to introduce E20 gasoline by approximately 2028 presents substantial technological challenges extending beyond bioethanol production. Successful implementation requires coordinated readiness across feedstock preparation, fermentation, ethanol purification, industrial utilities, fuel blending, distribution infrastructure, and automotive systems. This article critically synthesises scientific literature published between 2020 and 2026 through a qualitative literature review, explicitly distinguished from a systematic literature review. The analysis integrates technology readiness, manufacturing capability, process engineering, system interoperability, and deployment governance. The findings indicate that conventional sugar-based fermentation, distillation, and established dehydration technologies provide relatively mature foundations for near-term development, whereas lignocellulosic conversion and emerging separation technologies face additional scale-up, reliability, and economic uncertainties. Automotive compatibility introduces further requirements involving fuel formulation, engine calibration, materials durability, emissions testing, and certification across heterogeneous vehicle fleets. The review proposes an Integrated E20 Technology Readiness and Deployment Assessment Framework that distinguishes international technology maturity from demonstrated Indonesian implementation capacity. A phased, evidence-based roadmap is developed to coordinate technology qualification, industrial demonstrations, certified fuel distribution, and progressive commercialization. The study concludes that Indonesia's E20 ambition depends on verified end-to-end systems readiness, selective adoption of proven technologies, targeted innovation, and institutional coordination rather than ethanol-production capacity alone.

Keywords: E20, bioethanol technology, technology readiness, industrial scale-up, sugarcane biorefinery, ethanol dehydration, fuel blending, automotive compatibility, process intensification, Indonesia

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Introduction

Technological context of Indonesia's E20 ambition

The transition from petroleum-based gasoline toward renewable liquid fuels is frequently presented as a straightforward substitution of one blending component for another. In practice, bioethanol deployment is an industrial systems problem involving feedstock chemistry, microbiological conversion, separation equipment, thermal utilities, fuel quality, transport infrastructure and vehicle engineering. A fuel containing 20% ethanol by volume can be manufactured from established process technologies, but scalable and reliable provision of the finished product depends on the compatibility of all these subsystems. Renewable-liquid-fuel pathways consequently deserve assessment not only in terms of fuel chemistry but also through their manufacturing capabilities and deployment constraints.¹⁻³

In September 2026, Indonesian officials announced the intention to develop domestic ethanol production sufficient to support an E20 initiative within approximately two years. Sugarcane received initial policy emphasis, while subsequent announcements also considered other agricultural crops. These pronouncements create an immediate need to assess what is technologically established, what has been demonstrated only in selected foreign industrial environments, and what remains untested under Indonesian supply-chain and automotive conditions. They should be interpreted as implementation ambitions rather than evidence of already-certified nationwide ethanol production

or universal E20 vehicle compatibility (Sekretariat Kabinet Republik Indonesia, 2026; Kementerian Pertanian Republik Indonesia, 2026).

Indonesia has relevant experience in renewable-fuel industrial coordination through biodiesel, although the technological characteristics of a gasoline-ethanol system differ substantially from those of fatty-acid-based diesel blends. Ethanol involves a separate agricultural input base, biological conversion, water-removal requirements, volatility considerations and spark-ignition engine applications. Research assessing Indonesia's bioethanol readiness finds that feedstocks, technologies and policy arrangements jointly constrain progress, indicating that a transfer of institutional lessons from biodiesel must be accompanied by a distinct engineering assessment.^{4,5}

Why technology readiness is more than laboratory feasibility

A laboratory fermentation experiment may demonstrate ethanol formation at an impressive yield while omitting feedstock preparation costs, cleaning operations, seasonal variations and downstream dehydration. Similarly, a pilot membrane may exhibit excellent selectivity without proving its lifetime in the presence of industrial impurities or its feasibility at a national production scale. Technology readiness must thus distinguish evidence obtained from bench experiments, pilot systems, engineering demonstrations and sustained commercial performance. Reviews of lignocellulosic ethanol show

how industrial pretreatment, fermentation titer and plant integration remain difficult despite considerable research progress.^{6,7}

Deployment readiness introduces a further distinction. An internationally proven molecular sieve, fermentation vessel or automated blending meter may be commercially available but remain difficult to deploy where the necessary utilities, spare parts, skilled operators, inspection procedures or regulatory approvals are lacking. Readiness is therefore not a universal score attached permanently to equipment; it depends partly on the receiving location and the complete system within which the technology will operate. For Indonesia's geographically dispersed agricultural production, logistics and plant siting are particularly significant, as demonstrated by research on sorghum supply chains and biomass collection.^{8,9}

Research gap and contribution

Existing studies provide rich information on sugar-based fermentation, advanced lignocellulosic conversion, ethanol separation, engine combustion and Indonesian feedstock feasibility. However, these research streams frequently use different measures of performance, investigate different scales and assume different operating environments. An isolated improvement in fermentation yield does not determine the energy requirement of producing fuel-grade ethanol; similarly, favorable engine outcomes under optimized calibration do not resolve the compatibility of existing motorcycles or retail storage systems. A system-level technological synthesis is consequently required to identify genuine readiness gaps rather than list individual technical innovations.^{10–12}

This article addresses nine connected questions covering technology mapping, maturity of first- and second-generation pathways, purification efficiency, industrial utilities, blending infrastructure, automotive compatibility, emerging technologies, integrated performance and deployment sequencing. Its contribution is the Integrated E20 Technology Readiness and Deployment Assessment Framework (IE20-TRDAF), which combines technology-specific evidence with local manufacturing capability and end-to-end interoperability. The objective is to identify technologies suitable for immediate qualification, those requiring location-specific demonstrations and those best pursued as research and development opportunities rather than assumed short-term national supply.^{13,14}

The article differs deliberately from a broader policy assessment of E20 prospects. It does not attempt to determine whether a blending mandate is desirable in every possible social setting. Instead, it evaluates the engineering conditions under which domestic fuel-grade ethanol could reach commercial fuel markets with demonstrated quality, acceptable process performance and independently verified compatibility. Its policy implications arise from these technical dependencies, not from a presumption that higher ethanol blending is necessarily preferable to all other transportation decarbonization pathways.^{15,16}

Literature review: technological and theoretical foundations

Fuel properties and system boundaries

Fuel-grade ethanol differs materially from fermentation-grade ethanol because the former must satisfy specifications designed for commercial gasoline blending. Fuel handling depends on water content, impurities, storage compatibility and the properties of the finished gasoline base stock. Ethanol's oxygen content, relatively high octane quality, hygroscopic behavior and lower volumetric heating

value alter requirements for blending, infrastructure and engine management. E20 should be defined consistently as a finished blend containing nominally 20% ethanol and 80% gasoline by volume, not as ethanol blended into crude oil.^{17,18}

It is technically misleading to equate the 20% ethanol volume fraction with a 20% petroleum-energy displacement. Energy content differs between the two components, and changes in actual consumption depend on vehicle efficiency and calibration. A correct technical comparison must distinguish fuel volume, delivered lower-heating-value energy, emissions per unit of energy and emissions or fuel consumption per distance traveled. These distinctions are especially important when interpreting experimental engine results and when estimating industrial ethanol requirements from forecast sales of finished E20.^{19,20}

Technology-readiness concepts

Technology Readiness Levels offer a useful vocabulary for differentiating proof of principle from a technology demonstrated under operational conditions. Yet TRL assessments concern particular technology configurations and specified applications, rather than entire national industrial sectors. A commercially proven yeast-based fermentation technology may exhibit high maturity while a new microorganism, complex pretreatment train or novel membrane remains at an earlier stage. This requires evidence-specific judgments based on publications reporting experimental scale, residence time, throughput, reproducibility and operating conditions.^{21,7}

Manufacturing readiness considers the ability to design, procure, construct, commission and reliably operate technologies at target throughput. Integration readiness asks whether adjacent units exchange materials, energy and operational information without creating unacceptable bottlenecks. For national E20, system deployment also includes qualified vehicles, blending facilities, transport routes, quality laboratories and maintenance personnel. These distinct dimensions explain why a facility may possess technically mature equipment yet fail to deliver sustained volumes of compliant commercial product.^{22,23}

First-generation feedstock preparation and fermentation

Sugarcane juice and molasses represent technologically established substrates because fermentable sugars can be converted into ethanol using conventional industrial microorganisms. Nevertheless, feedstock concentration, impurities, microbial contamination and temperature influence yields and productivity. Sugarcane operations require coordinated harvesting, extraction, juice treatment and process-water management; molasses additionally varies in composition across sugar factories. Industrial technology choices must account for these variations rather than assuming that all sugarcane-derived materials behave identically in fermentation.^{24,10}

Batch, fed-batch and continuous configurations represent different compromises between process flexibility, volumetric productivity, contamination risk and operational complexity. High-gravity fermentation may reduce the volume of water needing removal downstream but can intensify osmotic stress and complicate yeast performance. Recycling cells and applying process sensors can improve productivity in selected settings, yet these benefits depend on disciplined cleaning, equipment control and operator capability. A robust Indonesian technology strategy should prioritize reproducibility across seasons and mills over isolated laboratory peak yields.^{13,14}

Alternative crops diversify substrate characteristics. Cassava and maize generally require starch hydrolysis before fermentation; sweet

sorghum provides fermentable juice and fibrous coproducts but raises issues involving harvest scheduling and substrate storage. Indonesian studies of sweet sorghum show that small-scale plant configuration and local biomass availability can be central to economic outcomes. International cultivar studies likewise demonstrate that agronomic suitability cannot be inferred merely from the existence of fermentable sugars.^{25,26}

Lignocellulosic conversion and scale-up

Sugarcane bagasse, straw and selected other agricultural residues contain cellulose and hemicellulose embedded within a lignin-rich structure. Producing ethanol from these substrates requires pretreatment to increase enzyme accessibility, enzymatic or alternative hydrolysis, fermentation of released sugars and subsequent ethanol recovery. Pretreatment changes substrate composition and can generate inhibitors that affect microbial metabolism. A successful process must manage both saccharification and fermentation performance rather than optimize pretreatment severity in isolation.^{27,28}

Technology routes include steam-explosion, dilute-acid, alkaline, hydrothermal and other pretreatment approaches, each creating particular challenges for equipment construction, corrosion control, chemical recovery and wastewater treatment. Research on commercial facilities emphasizes the difficulty of maintaining consistent pretreatment performance at high solids loading and industrial throughput. Several technological routes have reached industrial scale internationally, but commissioning experience demonstrates that reaching industrial scale does not guarantee financially robust operation at all sites.^{6,7}

Bioprocess integration offers potential cost reductions through simultaneous saccharification and fermentation, engineered microbial metabolism or consolidated bioprocessing. Such approaches may reduce enzyme requirements or process steps, but they introduce uncertainties concerning microbial stability, product inhibition, fermentation temperature and equipment utilization. Recent techno-economic modeling of sugarcane bagasse and straw compares conventional and more advanced consolidated bioprocessing configurations; its scenario-dependent outcomes should be read as conditional engineering projections rather than proven Indonesian costs.^{29,30}

Indonesia's oil-palm residues provide an additional technologically relevant comparison, even though sugarcane remains the central policy pathway. Research on oil-palm empty fruit bunches identifies potential conversion routes and examines pretreatment-dependent energy and cost trade-offs, while biomass-supply studies reveal collection and transport challenges. These options could diversify future raw materials, but their technical feasibility does not establish that they are immediately available at fuel-market scale or without competing biomass uses.^{9,31,32} Indonesia's archipelagic geography introduces an additional scale-up constraint: feedstock catchments, conversion plants and potential fuel markets may be located on different islands, requiring road-to-port transfers, maritime carriage and onward distribution rather than a single uninterrupted land route. These transshipments can increase handling demands, scheduling uncertainty and the cost of protecting wet residues from degradation. The Riau empty-fruit-bunch supply-chain analysis illustrates the importance of mill location and transport distance, while Indonesian maritime-logistics evidence demonstrates the relevance of island connectivity and port capacity. Consequently, proposed projects should compare mill-adjacent conversion with longer-distance and inter-island sourcing using route-specific delivered-feedstock costs,

moisture-management assumptions and continuity-of-supply tests rather than assuming national residue availability implies local industrial readiness.^{9,33}

Purification, dehydration and industrial utilities

Following fermentation, ethanol must be separated from an aqueous mixture containing biomass-related and process-related impurities. Distillation and rectification concentrate ethanol, while dehydration technologies address the ethanol–water equilibrium limitation that prevents ordinary distillation alone from achieving sufficiently dry fuel-grade product. Commercial separation approaches include molecular-sieve adsorption and other azeotrope-breaking arrangements. Technical comparison must evaluate target purity, energy consumption, feed contamination, throughput, reliability and the cost of regeneration or replacement.^{12,34}

Membrane pervaporation and hybrid separation processes are increasingly investigated as options for reducing thermal energy requirements. Recent studies report promising membrane flux and water selectivity for specific polymeric and composite formulations, but laboratory data must be interpreted alongside module size, long-duration stability, fouling, fabrication reproducibility and serviceability. A 2025 study of polyurea thin-film composites illustrates materials innovation, whereas other work on layer-by-layer membrane fabrication addresses performance under defined test conditions. Neither form of evidence automatically establishes that a complete Indonesian commercial dehydration plant is ready for procurement.^{12,24}

Pilot-plant evidence provides an intermediate qualification level between small membrane coupons and industrial module procurement. Kujawska et al.³⁶ investigated the operating parameters of a pilot pervaporation plant for raw ethanol dehydration, making clear that performance depends on a defined process configuration and operating regime. Such results are particularly useful for designing long-duration Indonesian qualification tests rather than extrapolating membrane-material performance alone.³⁶

Biorefineries can improve energy economics by recovering process heat, using bagasse for steam and power generation, and producing additional saleable outputs. Yet allocating fibrous residues to ethanol conversion can reduce material otherwise available for combustion or other industrial uses. Integrated facility design should consequently balance ethanol yield against electricity output, utility requirements, water management and coproduct markets. Studies of sugarcane cogeneration and integrated fertilizer-producing biorefineries demonstrate the importance of whole-site optimization.^{37–39}

Blending, distribution and automotive compatibility

A fuel-grade ethanol specification is only one element of E20 market readiness. The blending operation must ensure accurate component proportion, mixing quality, compatible gasoline base-stock properties and consistent sampling. Storage and distribution systems need appropriate material selection, water ingress prevention and documented fuel-quality management. Retail infrastructure may require inspection and equipment qualification, especially where tanks and dispensers have historically been used for gasoline not containing ethanol at the proposed concentration.^{1,20}

Automotive research demonstrates that ethanol blends influence combustion temperatures, knock resistance, air–fuel ratios and volumetric fuel consumption. Performance varies across naturally aspirated and boosted engines, port and direct injection systems, compression ratios and operating points. Carefully controlled

experiments can characterize these mechanisms, but evidence from a small number of engines should not be used to certify the national fleet. Field-use variability and legacy vehicle systems create a distinct validation requirement.^{40–42}

Material compatibility is as important as combustion calibration. Ethanol-containing fuels can interact with metals, plastics, seals and elastomers in a manner dependent on blend composition, impurities and time of exposure. Engine durability, fuel pumps, injectors and storage materials must be assessed through appropriate protocols. Emissions comparisons also require pollutant-specific analysis because effects on particulates, nitrogen oxides, volatile organic compounds and other species may differ across engines and operating conditions.^{43–45}

Contemporary corrosion research underscores the importance of considering actual contaminants and exposure conditions when specifying fuel-system materials. Matějovský et al.⁴⁶ tested steel corrosion inhibitors in ethanol–gasoline blends under deliberately aggressive conditions, illustrating that corrosion response depends on both fuel composition and the chemical environment. Because that study assessed E60 and E85 rather than E20, its results inform testing priorities but cannot establish corrosion rates or inhibitor requirements for Indonesian E20 systems.⁴⁶

Method: qualitative literature review

Research design and source logic

This article uses an interpretive qualitative literature review to integrate evidence from biotechnology, chemical engineering, industrial energy systems, fuel science and automotive engineering. Its objective is conceptual and practical synthesis: to identify technological dependencies and determine what kind of evidence should be required before an E20 subsystem is treated as ready for Indonesian deployment. The approach is intentionally not a systematic literature review, PRISMA screening exercise or meta-analysis, and it does not claim exhaustive coverage of every database or a pooled numerical effect estimate.

Scientific discussion is grounded principally in peer-reviewed journal articles published from 2020 through October 2026, selected for technical relevance, scale of evidence and compatibility with the Indonesian implementation question. Government communications are used only to establish the policy setting, not to validate technology performance. Both favorable and critical results are considered; laboratory claims, process simulations, industrial case studies and full-scale operational evidence are differentiated rather than treated as equivalent. This interpretive selection is suited to a subject where studies vary in their units of analysis and cannot responsibly be collapsed into a single readiness score.

Coding and synthesis procedure

Evidence is classified across six technological subsystems: feedstock and preparation; fermentation and conversion; purification and certified product quality; industrial utility and manufacturing capability; blending and distribution infrastructure; and automotive compatibility. Each subsystem is then examined using three cross-cutting lenses: maturity of the specific technology, feasibility of manufacturing and operating it in Indonesia, and interoperability with neighboring subsystems. This method allows a technology to be described as commercially established internationally while still requiring Indonesian-site qualification.

A second interpretive layer identifies critical interfaces such as molasses-to-fermentation composition, fermentation-to-dehydration concentration, certified ethanol-to-gasoline blending, and finished fuel-to-engine durability. The synthesis distinguishes observed technical findings from engineering inferences and policy recommendations. Conclusions concerning national readiness are therefore conditional rather than numerical: they specify the documentation and tests required to support an operational claim rather than fabricating Indonesian TRL, uptime or fleet-compatibility statistics.

Trustworthiness and limitations

Trustworthiness is strengthened by triangulating peer-reviewed experimental, modeling, techno-economic and contextual studies, giving particular attention to contradictory findings and scale-up uncertainty. A membrane's measured laboratory selectivity is not substituted for a verified commercial lifetime; likewise, modeled leveled ethanol costs are not presented as observed market prices. The article explicitly considers differences between technologies already used abroad and facilities that would need to be constructed, commissioned and independently qualified in Indonesia.

The review does not include primary factory audits, laboratory verification, fuel-terminal inspections or national vehicle surveys. Detailed technology readiness levels, project-specific economic viability and compatibility percentages therefore remain to be established through subsequent empirical research. These limitations shape the proposed implementation roadmap: the roadmap contains evidence gates precisely because the required national engineering data are not yet established in the literature assessed here.

Results: thematic findings on E20 technology readiness

Feedstock interfaces and quality control

The first thematic finding is that agricultural material must be considered an industrial feed rather than a homogeneous commodity. Sugarcane juice quality changes with variety, harvesting intervals, cane deterioration and extraction conditions; molasses also differs in fermentable-sugar concentration, salts and inhibitory constituents. If these variations are not measured and managed, fermentation productivity becomes unstable even when the selected yeast and vessel design are well established. The readiness requirement is therefore an integrated sampling, conditioning and traceability system connecting agricultural reception with process control.^{10,24}

For prospective Indonesian sugar mills, technology selection should be informed by site-level assessments of milling performance, juice and molasses allocation, storage capacity and seasonality. The location of distilleries relative to agricultural sources can strongly influence storage duration and degradation risks. Multi-mill feedstock networks may improve year-round utilization but introduce additional handling and contractual complexity. A 2025 study evaluating neighboring sugar mills indicates that integrated operating configurations can affect throughput and cost, emphasizing the importance of plant-system design rather than isolated equipment procurement.^{8,47}

Supply-chain research on agricultural residues also highlights a technological dependency on collection and preprocessing systems. Biomass size reduction, drying, densification and contaminant removal can influence transport economics and reactor performance. Indonesia-specific studies of empty fruit bunches underscore that

potential biomass volumes are not synonymous with recoverable industrial feedstock at a chosen conversion facility. Reliable technology planning requires a quality-adjusted and geographically explicit biomass balance, with sensitivity to seasonal losses and competing uses.^{9,23}

Conventional conversion technologies: maturity with site-specific qualification

Sugar-based ethanol fermentation is mature as an industrial technology class, making it a logical starting point for an accelerated E20 programme. Established conversion pathways can use familiar fermentation and separation equipment, and certain sugar plants may offer opportunities for adjacent processing facilities. Nevertheless, domestic deployment requires evidence that actual Indonesian feedstock supply, local utilities and trained personnel can sustain intended annual output. The capacity of a nominal production line is not the same as verified ethanol availability after downtime, maintenance and feedstock constraints.^{5,13}

Technology options should be judged using stable ethanol titer, sugar utilization, volumetric productivity, contamination frequency, batch reproducibility and downstream energy demand. Increasing fermentation concentration can lower evaporation duties, but improvements may be offset by reduced cell activity or additional cooling requirements. Industrial competitiveness therefore depends on optimization of the entire conversion system. Reviews of fermentation technology repeatedly demonstrate that microbial physiology, operating conditions and recovery infrastructure influence the realized performance of apparently similar processes.^{10,14}

For alternative starch-rich inputs, additional preprocessing must be considered. Cassava and maize require reliable starch conversion and enzyme supply, while sweet sorghum must be assessed for practical harvesting and sugar deterioration. These technical distinctions should appear explicitly in feedstock selection and plant procurement specifications. A single standard distillery design may not produce the same economic and operational performance across different agricultural materials, even when all are ultimately converted to ethanol.^{25,26}

Advanced conversion: promising but heterogeneous industrial readiness

The synthesis reveals a more uneven maturity profile for lignocellulosic ethanol. Industrial demonstration initiatives show that selected pretreatment and hydrolysis configurations can be operated at substantial scale. However, process integration remains demanding because biomass composition, solids loading, chemical recovery, inhibitors and enzyme activity interact strongly. A process that performs well with a controlled batch of bagasse may operate differently with seasonally variable mixtures of bagasse, straw and other residues.^{6,7}

An important finding is that the main technological obstacle can migrate as a process is scaled. Laboratory attention often centers on biomass digestibility or fermentation yield, but industrial bottlenecks may instead emerge in slurry pumping, heat transfer, solids separation, corrosive environments, fouling and maintenance. This migration explains why equipment selection and materials engineering are integral to assessing cellulosic ethanol readiness. Contemporary reviews identify the need for continuous operating evidence and careful integration of pretreatment with downstream biological stages.^{28,48,49}

Advanced microbial strategies remain strategically important. Simultaneous saccharification and fermentation reduces some processing steps, while consolidated bioprocessing aims to couple enzyme production, hydrolysis and fermentation more closely. Yet technology-specific expectations depend on reactor configuration and the practical performance of organisms under industrial conditions. Zambello et al.³⁰ compare technology scenarios for sugarcane residues and demonstrate that potential cost reductions are conditional on assumed improvements in biological conversion; such projections should be treated as research and demonstration priorities rather than near-term assured output.^{29,30}

The findings also caution against treating agricultural residues as inherently costless. Bagasse currently has utility value in many sugar factories, while empty fruit bunches and other residues may have nutrient, energy or material applications. Redirecting these streams to ethanol must account for replacement steam generation, collection equipment, pretreatment chemistry and disposal of remaining solids. Indonesian techno-economic studies offer valuable project-specific estimates, but they cannot resolve future commercial performance without verified feedstock contracts and plant commissioning data.^{31,32,50}

Dehydration and certified fuel-grade ethanol

A fourth finding is that fuel-grade purification can become a binding technological constraint despite high fermentation productivity. The ethanol–water separation challenge requires equipment sized for both the expected liquid throughput and the composition variations of fermentation output. Established distillation combined with molecular-sieve dehydration offers an industrially proven benchmark, yet actual process energy demand is heavily influenced by heat integration and feed concentration. Facilities should therefore be evaluated by certified product volume and energy consumed per unit of compliant ethanol rather than by fermentation yield alone.^{34,37}

Membrane separation innovations provide credible opportunities to reduce some separation duties, but their readiness varies by membrane chemistry and module engineering. Sun et al.¹² investigate layer-by-layer membrane assembly, while Ang et al.³⁵ examine thin-film polyurea membranes for ethanol dehydration. These studies demonstrate material-performance potential under specified test conditions. For industrial adoption, developers must also establish tolerance to variable feed composition, reproducible module fabrication, continuous operating lifetime, membrane-cleaning procedures and an economically credible replacement strategy.

Pilot measurements can help bridge the validation gap between laboratory membranes and industrial plants. A pilot study by Kujawska et al.³⁶ examined process-parameter effects during raw ethanol dehydration, providing a more application-oriented evidence level than coupon tests alone. Nevertheless, any Indonesian proposal would still require a documented feed envelope, continuous duty, fouling behavior, equipment maintenance and verified energy balances.

An integrated comparison must avoid classifying conventional distillation as obsolete simply because emerging membranes demonstrate high flux in laboratory experiments. Separation arrangements have different risk profiles, and a hybrid approach may outperform single technologies only under particular capital, steam and electricity prices. Technology selection should include process simulation, operability review, spare-parts availability and formal product specification testing. Fuel-grade quality must be independently demonstrated at the terminal interface, not merely assumed from the selected dehydration method.^{15,34}

Whole-process optimization can alter technology rankings. Zheng et al.⁵¹ modeled hybrid distillation–pervaporation schemes with heat-pump and heat-integration variants and reported favorable simulated energy and annual-cost outcomes against their azeotropic-distillation benchmark. These model-based findings justify further engineering comparison, but they should not be interpreted as guaranteed cost savings or commercial uptime at an Indonesian distillery.

The technological relationships summarized above are assembled visually in Figure 1. The diagram follows the progression from feedstock inputs through preparation, purification and certification to distribution and independently validated vehicle use. Its arrows represent essential quality and operability interfaces rather than evidence that all stages are already deployed in Indonesia.



Figure 1 System architecture of Indonesia's E20 technology value chain. Original conceptual synthesis of the reviewed literature.

Figure 1 summarizes the technology chain as six interdependent subsystems, making explicit that production of ethanol molecules is only the second stage of a larger engineering process. Its importance lies in locating critical interfaces at which quality and reliability can be lost: agricultural material entering fermentation, wet ethanol entering purification, certified ethanol entering blending, and E20 reaching vehicles. Readiness evidence must be collected at each interface rather than inferred from the availability of individual pieces of equipment.

Energy, water, automation and reliability

Biorefinery utilities strongly influence economic and environmental performance. Steam may serve pretreatment, distillation and other thermal operations, while electricity supports compression, pumping, cooling and automation. Bagasse cogeneration can potentially offset some fossil energy needs, yet that same bagasse might be considered for cellulosic ethanol production. Decisions about its allocation must therefore be made using consistent site-wide energy, cost and material balances.^{37,52}

Process automation and instrumentation may increase operational reliability when paired with skilled supervision. Relevant measurements include substrate concentration, temperature, fermentation pH, contamination indicators, tank inventories, distillation composition and ethanol moisture content. More elaborate data analytics can support predictive maintenance or process optimization, but they depend on representative training data and robust sensor calibration. Their contribution should be assessed against simpler control strategies and local maintenance capabilities rather than assumed to be universally beneficial.^{22,23}

Water and effluent systems require the same degree of engineering attention as fermentation vessels. Industrial wastewater can create compliance risks and operating interruptions when treatment capacity

is inadequate. Water recycling may lower freshwater demand but can also affect fermentation or cooling performance if reused streams accumulate problematic constituents. Lifecycle research stresses that process water and agricultural water must be assessed together, with local environmental constraints shaping feasible technology choices.^{52–54}

Fuel blending, storage and last-mile interoperability

Technology at the blending terminal must ensure accurate proportioning and complete documentation of fuel quality. Inline systems, batch tanks and controlled metering arrangements can each perform the operation, but must be qualified under the actual properties of both ethanol and gasoline blendstock. Requirements extend to moisture control, sampling procedures, laboratory methods, leak detection, tank materials and traceability. An operating ethanol plant does not establish market readiness if these downstream systems are absent or not approved.^{1,20}

Indonesia's distribution geography strengthens the need for site-specific engineering assessment. Different terminals and retail systems may vary in age, tank construction, throughput and maintenance capacity. A national deployment plan should inventory the assets actually intended for E20 service and define acceptance tests for each compatible route. Technology governance needs a formal distinction between equipment that a manufacturer markets as ethanol-compatible and equipment inspected and certified for the specific intended duty.^{5,55}

Fuel quality also depends on process discipline after production. Sampling at distillery exit, blending terminal and retail delivery can reveal different sources of contamination or composition drift. The analytical system should connect batch records, moisture measurements, blend-ratio checks and corrective procedures. Traceability therefore serves both technical performance and consumer protection, especially during early market pilots when unexpected distribution problems must be diagnosed rapidly.^{18,20}

Engine performance, emissions and materials compatibility

Engine studies demonstrate that E20 should be understood as a fuel–engine system rather than a fixed performance improvement. Ethanol's octane properties may permit favorable operating strategies in engines designed or calibrated accordingly, while its lower volumetric energy density influences consumption. Thermal efficiency, combustion stability, starting behavior and emissions consequently vary with injection strategy, compression ratio and engine controls. Experiments using turbocharged engines, high-compression combustion and combined fuel injection show these interactions but are not substitutes for Indonesian fleet testing.^{19,53,11,41}

Some experiments show beneficial changes in particular regulated emissions under selected conditions, whereas others identify trade-offs or dependencies involving nitrogen oxides, particulate matter, volatile organic compounds and ambient temperature. Such findings require careful interpretation because test cycles, engine technology and fuel specification differ across studies. Work on lean mixtures, combined injection and cold-temperature emissions underscores the need for pollutant-specific national testing rather than assertions of uniformly cleaner exhaust.^{57,58,44,45}

Vehicle durability is a separate testing dimension. Fuel-system materials may respond differently to alcohol exposure, impurity levels and long-term operating cycles. Studies of corrosion and engine components show why compatibility cannot be inferred only from

short combustion trials. Indonesia's extensive motorcycle population makes two-wheeler testing especially important, including fuel metering, cold and hot starts, material aging and representative road-use patterns.^{43,59,60}

Materials testing should incorporate realistic exposure duration, fuel water content and potential impurities rather than rely on nominal ethanol fraction alone. Matějovský et al.⁴⁶ experimentally evaluated corrosion inhibition in relatively high-ethanol blends, demonstrating the sensitivity of steel behavior to corrosive constituents and inhibitor chemistry. Extrapolation to E20 requires independent validation of the finished fuel and its contact materials, especially across model-specific vehicle fuel systems.

Figure 2 sets out a sequence of qualification steps needed before E20 can be placed into routine vehicle service. It separates tests of the finished fuel from materials qualification, complete engine and emissions validation, and eventual manufacturer-led market authorization. The sequence is presented as a proposed assurance pathway rather than a claim that current Indonesian fleets have completed these tests.

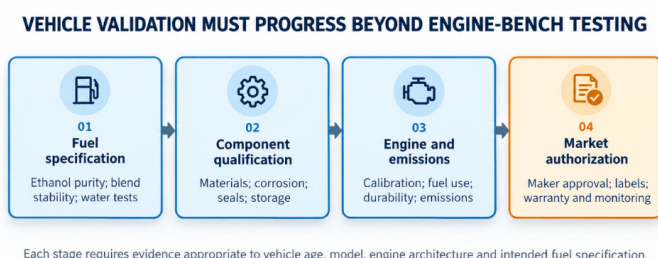


Figure 2 Four layers of vehicle and fuel-system qualification for E20. Conceptual framework; not a fleet compatibility survey.

Figure 2 differentiates the four levels of automotive validation: fuel properties, component compatibility, complete powertrain behaviour, and in-use deployment. This ordering prevents apparently

successful engine-bench experiments from being confused with full market certification. The diagram also clarifies that manufacturers' approvals and consumer information must follow validated evidence from representative vehicle categories, not precede it.

The readiness pattern across technologies

The thematic synthesis supports a qualitative classification rather than an invented national readiness score. Conventional sugar fermentation, industrial distillation and established dehydration configurations have strong international commercial precedents. Advanced hydrolysis, consolidated bioprocessing and emerging membranes show differing combinations of laboratory, pilot and industrial evidence. Blending equipment is commercially available, but the status of particular Indonesian terminal assets requires inspection. Vehicle E20 compatibility is dependent on vehicle category and certification history rather than a property of the national fleet as a whole.

This distinction between technology-class maturity and Indonesian deployment readiness leads to a practical inference: technical investment priorities cannot be established from patent counts, laboratory performance or announcement of new capacity alone. Project qualification should require documentation of verified throughput, compliant ethanol quality, energy consumption, component lifetime, maintenance plans and relevant vehicles. Where those data are unavailable, the correct conclusion is that readiness has not been established, not that the technology is inherently unsuccessful.⁵⁰

Table 1 translates the thematic synthesis into a technology-specific comparison of international maturity and unresolved qualification needs in Indonesia. The entries intentionally differentiate commercially familiar equipment classes from technologies whose continuous operational performance remains configuration-dependent. This distinction is central when preparing procurement specifications and selecting pilot locations.

Table 1 Evidence-based classification of E20 technology maturity and outstanding Indonesian qualification needs

Technology subsystem	International evidence position	Additional evidence needed in Indonesia
Sugar/ molasses fermentation	Established industrial process class	Site-specific sugar inputs, yield, uptime, utilities and trained operators
Distillation and molecular sieves	Commercially established technology classes	Capacity, regeneration, certified purity and energy performance
Lignocellulosic pretreatment	Pilot and industrial demonstrations; performance varies	Feedstock-specific continuous uptime, inhibitor control and materials durability
Advanced pervaporation membranes	Technology-dependent research and demonstrations; examples include polyurea thin-film composites and layer-by-layer assembled membranes ^{12,35}	Module lifetime, fouling, costs and long-term operation
E20 blending and distribution	Established equipment classes	Terminal and retail asset inspection, product sampling and traceability
Vehicle compatibility	Validated for selected designs and markets	Indonesian model-level approvals, component and durability testing

The evidence matrix in Table 1 illustrates why the same label, such as 'commercially established', can describe an equipment class without determining readiness of its application at a specific Indonesian facility. It identifies the additional data required to move from general

technical knowledge to a defensible site-specific decision. The distinction is central to the article's claim that integrated deployment readiness should be measured through evidence at interfaces as well as within processes.

Discussion and analysis

Reinterpreting the two-year ambition through technology qualification

The approximately two-year ambition attached to E20 development is an important mobilizing signal, but technology qualification operates according to more detailed dependencies than a political calendar. A new plant must have secured feedstock, validated process design, commissioned utilities, qualified output specifications and dependable downstream offtake. Production capacity is not operational capacity; operational capacity is not necessarily certified supply; and certified supply is not equivalent to successful use by a compatible vehicle fleet. These distinctions are essential for interpreting implementation achievements without conflating different kinds of progress.

The near-term program should therefore prioritize engineering data collection and industrial qualification of already established technology classes. Appropriate first steps include auditing sugar mills, mapping fermentation-ready feedstocks, examining distillation and dehydration opportunities, and certifying selected blending routes. More technologically speculative pathways can proceed in parallel as demonstrations, but should not be included in binding short-term fuel supply forecasts without reliable plant-level evidence. Industrial pretreatment history demonstrates that technological promise and successful sustained commercialization can diverge.^{7,21}

A stage-gated approach would also limit costly sequencing mistakes. Approving a distillery before feedstock contracts, utilities and quality laboratories are prepared may produce stranded capacity. Launching terminal blending without fleet qualification or retail audits may shift risk to vehicle owners. Readiness gates should thus be decision points at which independently reviewed technical evidence determines whether expansion is justified, needs redesign, or should be delayed.^{22,47}

Choosing the production route: proven technology versus ambitious integration

A technology portfolio for Indonesia should distinguish near-term supply from longer-term innovation. Sugarcane juice and molasses routes can employ familiar fermentation technologies, although domestic capacity remains to be audited. Lignocellulosic routes may offer additional biomass valorization but have process risks arising from pretreatment, enzyme loading, solids handling and inhibitor management. A nationally credible scenario should therefore allocate each pathway a role consistent with its evidence and feedstock security rather than declaring all potential volumes equivalent.^{24,27}

Sugar mills present potentially attractive integration sites because they may provide feedstock handling, utilities and established agricultural relationships. However, their suitability varies with milling throughput, processing season, cogeneration configuration, infrastructure condition and the allocation of cane between sugar and fuel. A retrofitting strategy should evaluate technological compatibility and opportunity costs before assuming that an existing mill can be converted economically. Comparative work on biorefineries in Mexico and adjacent-mill arrangements illustrates the need for site-level integration analysis.^{47,61} Where prospective plants depend on inter-island biomass flows, feasibility and site-qualification studies should explicitly test port handling, shipping frequency and road–sea transfer interfaces against delivered feedstock cost and reliable plant operation.

Engineering assessments should examine a minimum set of process alternatives under identical feedstock and financial assumptions.

For example, conventional fermentation and molecular-sieve dehydration might form a reference case, against which integrated heat-recovery and advanced separation concepts are evaluated. For bagasse, conventional pretreatment–hydrolysis–fermentation should be compared with credible consolidated bioprocessing scenarios only after accounting for steam displacement and residue-use alternatives. This approach is more scientifically defensible than comparing headline ethanol yields derived from incompatible studies.^{30,38}

The industrial cost evidence also demands careful interpretation. Bahar et al.⁵⁰ estimated a levelized bagasse-derived ethanol cost of US\$0.541 per litre and a payback period of 5.09 years for a specified Indonesian project scenario; the calculation offers a useful benchmark but is not a verified nationwide production cost or forecast. Regional feedstock logistics, process efficiency, financing and utility assumptions could materially change outcomes. Future Indonesian project approvals should therefore disclose full sensitivity analyses rather than importing one case-study result as a general rule.²³

Establishing a practical purification and blending specification chain

Dehydration creates a clear interface between process engineering and fuel-market engineering. The distillery must consistently deliver ethanol of specified quality, while the terminal must ensure that adding it to gasoline yields a compliant finished product. These are related but distinct responsibilities. A technically mature separation system can still produce off-specification batches through control failures, and appropriate ethanol quality alone does not guarantee suitable volatility, stability or cleanliness of the final fuel blend.

A reference industrial purification route should include documented incoming composition ranges, calibrated analysis, energy balance and an equipment-maintenance protocol. Advanced membranes should compete against this benchmark using validated module life, fouling tolerance, installed energy demand, operator requirements and replacement costs. Experimental permeability is informative but insufficient as a procurement criterion. Such comparisons would encourage genuine innovation while protecting early E20 deployment from unnecessary technology-selection risk.

Comparative engineering should examine plant-scale operating regimes, not only the best observed separation coefficient. Kujawska et al.³⁶ provide pilot-scale evidence on how operating parameters influence pervaporation efficiency, while Zheng et al.⁵¹ evaluate optimized hybrid configurations using process simulation and economic calculations. Together, these studies support a staged decision process moving from simulation through pilot measurements to sustained site-specific operation.

To assure fuel quality, Indonesia would benefit from a coordinated qualification chain involving fuel-grade ethanol testing at production sites, blend checks at terminals and targeted verification at retail distribution points. Data should identify batch origin, ethanol content, water condition, designated vehicle compatibility and corrective action after nonconformities. The value of such a chain is practical: if a pilot reports fuel-related difficulties, traceability makes it possible to distinguish a conversion problem from a blending or storage problem.

The comparison in Figure 3 places established distillation and molecular-sieve dehydration alongside proposed membrane-assisted and heat-integrated configurations. The three routes must be compared at a consistent feed composition, product specification and plant capacity, with energy use, capital cost and long-term serviceability evaluated together. The diagram deliberately does not claim an unconditional efficiency ranking.

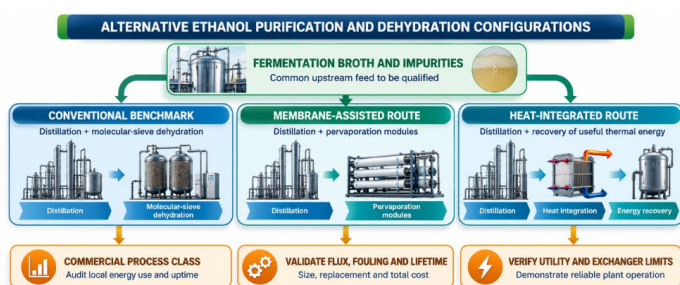


Figure 3 Conventional and emerging fuel-grade ethanol purification configurations. Comparisons are qualitative and conditional on project assumptions.

Figure 3 compares three technological options for reaching fuel-grade ethanol: conventional distillation with established dehydration, distillation combined with membrane technologies, and more extensively heat-integrated configurations. The figure is deliberately qualitative because cost and energy rankings depend on plant throughput, inlet ethanol concentration and local utilities. It illustrates a technology-selection process in which novel equipment enters commercial service only after whole-system performance and reliability have been demonstrated.

Automotive certification is a deployment gate, not an afterthought

An E20 programme can fail to achieve practical fuel substitution if the relevant vehicle population lacks manufacturer approval or sufficient durability evidence. The Indonesian fleet includes motorcycles, passenger cars and older spark-ignition vehicles with different materials, controls and maintenance histories. Laboratory combustion research supplies mechanisms and candidate calibrations, but only representative component tests, engine durability trials and manufacturer-specific verification can establish operational compatibility. A nationally differentiated certification strategy is therefore needed.⁶²

Motorcycle testing deserves attention because two-wheelers are widely used and may have different fuel-system designs, thermal loads and operating patterns from passenger cars. Test plans should cover storage and fuel-system aging, cold and hot starts, speed/load transients, fuel consumption and emissions under locally relevant conditions. Controlled studies of alcohol-containing fuels in motorcycles and gasoline engines can inform protocols, yet no experimental result from one platform should be translated into blanket acceptance for unrelated models.⁶⁰

International studies also caution against treating ethanol as a universal emissions remedy. Strategies yielding lower particulates under one calibration may alter nitrogen oxide or volatile organic compound formation in another. Similarly, high-compression engines designed to exploit ethanol's octane can perform differently from legacy engines operated without adaptation. Clear public communication should reflect these differences and report manufacturer-certified categories, fuel-consumption implications and warranty conditions honestly.

A carefully bounded regional or fleet-specific E20 demonstration could therefore reduce technical uncertainty before broader rollout. Such a program would pair a defined finished-fuel specification with compatible vehicles, trained service networks, traceable supply and a mechanism for investigating failures. Expansion should follow successful review of real-world data rather than a predetermined

assumption that all gasoline vehicles respond similarly. This is not opposition to bioethanol; it is a proposal for evidence-based technological adoption.

Industrial localization, maintenance and human capital

Technology transfer must include the capacity to operate and maintain equipment, not merely a license or purchase agreement. Distilleries require competence in fermentation microbiology, mechanical maintenance, process control, separation, electrical systems and chemical safety. Blending terminals require fuel testing, calibrated metering, inspections and incident management. Universities, industrial training centers and equipment suppliers can support these capacities, but programs should be assessed against actual operator certification and sustained plant performance.¹³

Localization opportunities could include fabrication of tanks and piping, installation of instrumentation, process integration and domestic engineering services. However, procurement requirements should be matched to safety and quality standards; forced localization of components without suitable production capability could increase downtime or compromise reliability. A staged industrial learning strategy could initially prioritize local installation and maintenance competence, then extend toward specialized equipment as verified capability improves. This approach is consistent with the broader aim of converting an E20 programme into durable industrial technological capacity.

Digitalization also requires disciplined prioritization. Monitoring systems that directly address product quality, inventory accuracy, process instability and preventative maintenance may deliver more immediate value than complex artificial-intelligence systems lacking representative operational data. The article therefore recommends investment in foundational instrumentation, traceable records and staff competencies before more elaborate predictive optimization. Technology complexity should increase when measurable operational benefits and maintainability are demonstrated.

Technology readiness within environmental and economic limits

Technological feasibility must be tested against whole-system energy consumption, water demand and lifecycle environmental performance. Higher ethanol yields can coincide with greater chemical or steam requirements, while residue conversion may displace biomass previously used for electricity generation. Consequently, engineering optimization should include utility balances and reference scenarios for displaced coproducts. Lifecycle studies of sugar, ethanol and electricity from sugarcane reinforce the need for consistent system boundaries and transparent allocation choices.⁶³

Land and water impacts are also linked to technology through agricultural productivity, processing efficiency and feedstock demand. Process intensification may reduce material requirements per litre of ethanol, but does not guarantee sustainability if additional cultivation involves carbon-rich land or overexploited watersheds. Spatially differentiated techno-economic assessment and land-use analysis should therefore complement plant-level readiness evaluation. Technologically advanced factories must not be classified as sustainable solely because their fermentation or separation equipment is efficient.^{53,64}

The commercial attractiveness of an integrated biorefinery is similarly contingent. Lignin valorization, recovered chemicals and fertilizer products can create additional revenue streams, but demand and pricing must be demonstrated. Capital-intensive technology may

not be suitable for every mill size or region. Indonesia should therefore use project-specific techno-economic modeling that incorporates process reliability, utilities and coproduct markets instead of treating the most technologically sophisticated design as necessarily the most competitive.

Integrated E20 technology readiness and deployment assessment framework

The proposed IE20-TRDAF assesses six operational subsystems through three cross-cutting lenses: technology maturity, domestic manufacturing and operating capability, and integration with adjacent systems. An additional sustainability screen considers whole-system energy, cost, water and lifecycle implications. The framework is not a validated numerical index and should not be interpreted as providing measurements of Indonesian technology readiness. Instead, it defines the evidence domains required for a defensible technical decision.

At the technology level, documentation should identify the precise process or product configuration and the highest relevant demonstration environment. At the industrial level, it should identify whether feedstock, utilities, equipment, operators and maintenance support can meet intended throughput. At the interface level, it should identify whether material quality, product specifications and data can be transferred reliably to downstream systems. The framework thereby translates broad technology-readiness language into actionable qualification questions.

Figure 4 presents the original IE20-TRDAF model introduced in this review. Its three assessment pillars—technology maturity, Indonesian industrial capability and system interoperability—feed into a common safety, reliability and sustainability screen. The framework is intended for documented decision-making and does not substitute for observed plant or fleet testing.



Figure 4 Integrated E20 Technology Readiness and Deployment Assessment Framework (IE20-TRDAF). Original conceptual model.

Figure 4 organizes the framework around technology, industrial capability and system integration, with economic and environmental performance functioning as cross-cutting acceptance conditions. It highlights that a high-readiness item can coexist with an unqualified local interface and that the national deployment decision should reflect the weakest critical dependency. The implication is a shift from announcing nominal technology availability to documenting verifiable end-to-end operational performance.

Table 2 converts the readiness framework into a practical allocation of technical evidence and institutional responsibilities. The matrix associates each participating actor with verifiable acceptance documentation, allowing decision-makers to identify gaps before approving fuel-market deployment. These are proposed requirements that need alignment with applicable Indonesian standards and competent authorities.

Table 2 Proposed technology-qualification responsibilities and evidence requirements

Subsystem / actor	Minimum technical acceptance evidence
Feedstock supplier and mill	Verified annual usable feedstock, composition variability, contamination and logistics
Ethanol producer	Commissioned throughput, consistent ethanol quality, uptime, energy and water balances
Quality laboratory	Traceable methods and documented ethanol / finished blend certificate results
Terminal and fuel distributor	Metering accuracy, asset compatibility, tank water controls and batch records
Automotive manufacturer / laboratory	Model-specific durability, emissions, fuel-system compatibility and warranty guidance
Oversight and investment bodies	Independent stage-gate review of technical, cost, safety and lifecycle evidence

Table 2 translates the framework into evidence required from producers, terminals, vehicle manufacturers and public regulators. It shows how each subsystem can be assessed without assigning arbitrary readiness scores. By specifying acceptance evidence and responsible actors, the table also indicates where institutional coordination is necessary to turn engineering results into operational approval.

Stage-gated technology implementation roadmap

The first proposed phase, beginning in 2026, is an engineering-baseline phase. It would inventory operational distilleries and sugar mills, collect compositional and throughput data, examine utility systems, map terminal equipment and identify vehicle categories requiring E20 testing. Its most important output is a documented evidence gap assessment for each subsystem. Project budgets should not assume advanced-technology production volumes or universal vehicle compatibility while this evidence is missing.

A second phase would involve prioritised pilot and demonstration activities. Selected ethanol plants would be required to prove sustained production of certified fuel-grade ethanol, selected terminals would validate blend quality and traceability, and defined fleets would undergo compatibility and durability tests. Where lignocellulosic options are pursued, demonstration should explicitly capture equipment uptime, chemical consumption, solids handling and net utility performance. Results should be independently reviewed before being translated into national capacity assumptions.

A third phase would involve conditional commercial scale-up, beginning with technologies and locations that meet the evidence gates. Scaling should be regional where appropriate, supported by contractual feedstock logistics, maintenance capacity, laboratory inspection and a clearly identified compatible vehicle market. Investment sequencing should maintain flexibility in case process performance or fuel-market compatibility differs from design assumptions. This is especially important in an archipelagic country where uniform deployment conditions should not be presumed.

The longer-term phase, extending into the 2030s, could intensify industrial integration and advanced conversion research. Successful membrane modules, engineered microbes, consolidated bioprocessing and circular-biorefinery products should be incorporated when their

plant-level and whole-system advantages are established. Their introduction should strengthen rather than destabilize a functioning foundation of conventional ethanol production and distribution. This approach allows technological ambition to coexist with prudent qualification and operational learning.

The conditional implementation sequence is visualized in Figure 5. Each gate requires evidence concerning feedstock and project design, fuel quality and vehicles, or reliable and sustainable commercial supply before the following phase can proceed. The indicated dates are analytical planning windows, not established government milestones.

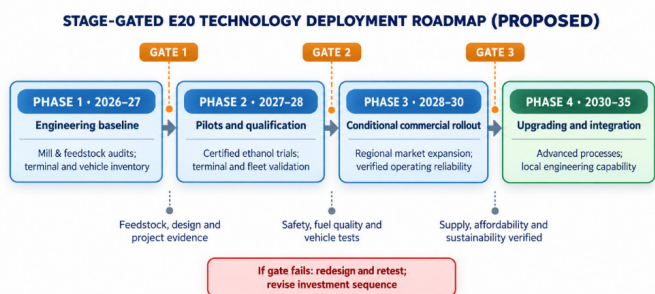


Figure 5 Proposed stage-gated technological deployment roadmap, 2026–2035. Indicative policy sequencing, not an officially adopted schedule.

Figure 5 describes the sequence from baseline audits through pilot qualification, conditional commercialization and longer-term upgrading. Between stages, independent verification determines whether the proposed technology and its neighboring systems meet safety, quality, performance and sustainability requirements. The figure represents an analytical roadmap rather than an officially approved government construction schedule, and dates should be revised as empirical readiness evidence becomes available.

Answers to the research questions and future empirical agenda

The analysis answers the initial research questions conditionally. Required technologies can be identified across the six subsystems, and conventional fermentation and dehydration provide relatively mature international reference options. Advanced lignocellulosic conversion, novel membranes and digital controls may improve efficiency, but their implementation benefits are technology- and site-specific. Vehicle compatibility cannot be inferred from the ethanol percentage alone, while distribution readiness requires tested equipment and certified procedures. Accordingly, no single production technology can be said to solve the national implementation challenge independently.

The principal future research priority is to replace qualitative unknowns with reproducible Indonesian technical measurements. Needed studies include sugar-mill and distillery audits, feedstock compositional surveys, mass-and-energy balance modeling, extended separation-module tests, terminal compatibility inspections and nationally representative vehicle-fleet testing. Subsequent research can develop a transparent multi-criteria readiness index once those observations are available. Until then, the proposed framework is best used to structure evidence collection and accountable stage-gate decisions.

Conclusion and recommendations

Technological readiness for Indonesian E20 deployment is best understood as an end-to-end engineering capability rather than the maturity of ethanol fermentation alone. Commercially established sugar-based fermentation, distillation and dehydration equipment offer a plausible foundation for early development, but domestic

readiness must be demonstrated through qualified feedstock supplies, installed and maintained plant capacity, consistent fuel-grade quality, suitable blending infrastructure and compatible vehicles. No part of the chain should be presumed operational simply because equivalent technology exists internationally.

Lignocellulosic ethanol and advanced separation technologies provide important innovation opportunities but have heterogeneous industrial evidence and distinct scale-up risks. Their future contribution should be assessed through sustained demonstrations covering pretreatment reliability, fermentation productivity, separation energy, equipment lifetime and economics under Indonesian conditions. Strategic technological diversification is valuable, provided its prospective benefits are not incorrectly counted as guaranteed short-term E20 supply.

The article recommends establishing an independent national E20 technology-qualification programme supported by an integrated evidence matrix, validated fuel specifications, industrial commissioning standards, regional terminal audits and vehicle-category-specific testing. Government, research institutions, ethanol producers, fuel distributors and automotive manufacturers should share documented responsibilities for each readiness gate. Investment and deployment decisions should reflect measured interoperability and lifecycle performance as well as nominal production capacity.

Future research should prioritize original industrial audits, representative engine and materials testing, pilot operation of advanced conversion technologies, and integrated process-economic and environmental modeling. The proposed IE20-TRDAF is a conceptual foundation for these activities, not a substitute for empirical verification. E20 implementation will become technologically credible when validated production, distribution and vehicle systems function together reliably and when evidence remains transparent enough to guide correction as conditions evolve.

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Conflicts of interest

The author declares there is no conflict of interest.

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