

COMPARATIVE LIFE CYCLE ASSESSMENT AND TECHNO-ECONOMIC ANALYSIS OF ETHANOL BLENDS IN GASOLINE AND DIESEL

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Ethanol blending; life cycle assessment; techno-economic analysis; gasoline; diesel; biofuels; transport decarbonization; sustainability.

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Abstract

The transition toward low-carbon transport fuels has intensified global interest in ethanol blending as an immediately deployable strategy for reducing petroleum dependence, greenhouse gas emissions, and urban air pollution. This study presents a comparative life cycle assessment and techno-economic analysis of ethanol blends at 10%, 20%, and 30% volumetric substitution levels, hereafter referred to as E10, E20, and E30, in gasoline and diesel applications. The analysis is performed under a cradle-to-grave approach as it includes the cultivation of the feedstock, ethanol production, blending, distribution, combustion, and end use performance. The study is a comparative analysis of 1st generation ethanol pathways (sugarcane molasses, corn) and emerging lignocellulosic ethanol pathways, in particular for South Asia. The techno-economic component examines the cost of production, retrofits to existing infrastructure, fuel economy impacts, material compatibility, and policy support mechanisms in the presence of different ethanol prices and subsidy policy structures. Results show that ethanol-gasoline blends can lead to measurable reductions in life-cycle greenhouse gas emissions, particularly when sugarcane- and molasses-based ethanol is produced using efficient cogeneration systems. Ethanol-diesel emulsions in turn have measurable reductions in particulate matter and smoke with issues regarding phase stability, lubricity, and cetane. While both E20 and E30 offer greater decarbonization potential, they also demand a multi-year program of upgrading the infrastructure, managing fuel quality, and targeted policy support, with E10 being the least disruptive pathway. When ethanol blending is part of a larger policy framework that embraces a sustainability perspective and considers land-use changes, water-ethanol trade-offs, and rural livelihoods, it can play a significant role in achieving transport decarbonization.

1. INTRODUCTION

Transportation sector is the largest energy consumer and accounts for 24% of energy-related CO₂ emissions in 2023 (International Energy Agency [IEA], 2024). In the context of increasing climate demands and energy security threats, ethanol blending in traditional fuels has emerged as a viable option that can be scaled, to create a low-carbon alternative. Bioethanol made from biomass feedstocks like sugarcane, corn, and lignocellulosic sources can achieve lifecycle GHG (Greenhouse Gas) reductions from 20% to 60% compared to fossil fuels, depending on the feedstock and production efficiency (Chakraborty et al., 2025; Shakoor et al., 2025). Ethanol blending regulations have been proliferating worldwide with Brazil having E27 gasoline, the United States having E10 as standard, and India pushing towards E20 (NITI Aayog, 2021; IEA, 2024). The regional mandates are E5 to E10 with Vietnam planning to reach E10 in 2026, the Philippines to reach E10 (voluntary) in 2026 and Indonesia to reach E10 (mandatory) in 2028 (ChiniMandi, 2026; U.S. Grains Council, 2025). The benefits of blending ethanol include higher octane ratings for improved combustion efficiency, reduced carbon monoxide and particulate emissions with complete oxidation, and increased domestic bioenergy supply chains (NREL, 2022; Kumar et al., 2024). Ethanol programmes can provide dual benefit for developing countries, where petroleum import bill is more than \$20 billion every year, to reduce import dependency and also stimulate rural economy. The Ethanol Blending Programme in India has reached 12% Ethanol Blending capacity by 2024, saving \$4 billion in foreign exchange and creating 1.2 million farm jobs (Kumar et al., 2024). The National Ethanol Policy (2023) is also set to achieve additional 10% blending by 2027, with the government benefiting from the surplus production of sugarcane.

However, there are numerous challenges with blending ethanol. Blending increases with a corresponding reduction in energy density of 5–12% and may cause higher fuel consumption, and ethanol is hydrophilic, which can aggravate corrosion in older fuel system components

(NREL, 2022). Life cycle assessments show that sugarcane ethanol shows a negative value (-50 gCO₂eq/MJ), requiring significant amounts of irrigation, while cellulosic pathways show better values, but have not yet reached commercialization (Chakraborty et al., 2025; Shakoor et al., 2025). Ethanol-diesel emulsions (E-diesel) achieve 25-40% GHG reductions for heavy-duty fleets, but face challenges of phase separation and lubricity issues (NREL, 2022).

1.1 Research Gap

Most recent research focuses on ethanol-gasoline blends instead of systematic gasoline-diesel comparisons, limited to E10-E30 blends and different feedstocks (Chakraborty et al., 2025). Research tends to focus on developed countries (US, Brazil) and does not adequately capture the challenges faced at the infrastructural and economic level in less developed countries in South Asia (Kumar et al., 2024; NITI Aayog, 2021). The scope of techno-economic evaluations is typically limited to cost and benefits and often does not capture other sustainability dimensions like water-energy-land nexuses, or define thresholds for commercial viability of subsidies (Shakoor et al., 2025). There are also few studies that focus on how international standards (e.g. ISO 14040/14044) harmonize LCA methods for biofuels at a regional level (ISO, 2006; Green NCAP, 2023).

1.2 Objectives

This study pursues the following objectives:

1. Comparative cradle to grave life cycle assessment (LCA) for E10, E20, and E30 gasoline and diesel blends spanning primary feedstocks.
2. Techno economic viability assessment, quantifying break even ratios and fiscal incentives for South Asian contexts.
3. Development of an evidence based policy architecture for ethanol blending acceleration.

2. Literature Review

2.1 Ethanol Feedstocks and Production Pathways

Ethanol production primarily utilizes first-generation feedstocks including sugarcane, corn,

and molasses, alongside emerging second-generation lignocellulosic sources. This is because sugarcane ethanol is the predominant bioenergy in tropical economies, producing 70-90 L/tonne and with lifecycle GHG savings of 61% compared to gasoline thanks to efficient Bagasse cogeneration (Chakraborty et al., 2025). A common fermentation process in temperate areas is the conversion of corn starch into ethanol, which produces around 380 L/tonne of ethanol per tonne of corn grain and leads to GHG reductions ranging from 19-43% from conventional gasoline depending on the amount of nitrogen fertilizer applied and the type of energy source used (Kumar et al., 2024). In India and Pakistan, the molasses-based process is used, which results in lower yields (250 l/tonne), and different levels of sustainability depending on the efficiency of the sugar milling process in the upper stream of the production chain (NITI Aayog, 2021).

The second generation pathways from agricultural residues (corn stover, bagasse) and energy crops offer a potential production of 300-500 L/tonne of ethanol with lower land consumption, but with enzymatic hydrolysis and fermentation costs that are still too high on a large scale (Shakoor, Shafiq, & Ashraf, 2025). Cellulosic ethanol production costs are anticipated to fall to the 0.45-0.60 USD/L range by 2030, based on favourable policy and technology scenarios, with first generation ethanol production costs expected to range from 0.35-0.50 USD/L (National Renewable Energy Laboratory [NREL], 2022). In recent years, maize

has been recognized as a promising feedstock option for ethanol production in India, with the target of achieving 20% blending by 2025-26 and 30% by 2030 (National Academy of Agricultural Sciences, 2024).

2.2 Engine Performance Characteristics of Ethanol Blends

Ethanol has a high octane (RON 108) property, which provides improved knock resistance, allowing for more aggressive spark timing and modestly higher power gain of 1-3% at E10-E20 concentrations in gasoline engines (NREL, 2022). However, lower energy density (21.1 MJ/L compared to 32 MJ/L for gasoline) results in 1-4% volumetric efficiency losses, and some advantages of lean-burn capabilities (Kumar et al., 2024). Brake thermal efficiency is highest at E20 (2-5% efficient improvement) followed by a decrease because of the possibility of phase separation.

Micro-emulsification is used for enhancing cetane of E-diesel that decreases NO_x by 10-20% and particulates by 30-50%, but increases BSFC by 5-10% due to oxygen dilution (Chakraborty et al., 2025). Due to cold-start problems and injector wear, lubricity additives are required in fuels above E15 (NREL, 2022). Recent research on diesel-ethanol emulsions has reported 10-20% NO_x reduction and 30-50% reduction in particulate emissions, with an increase in brake specific fuel consumption and emulsifier stability sensitivity (PMC, 2025).

Table 2.1: Performance metrics by blend ratio (meta-analysis, n = 25 studies; Chakraborty et al., 2025; NREL, 2022; Kumar et al., 2024).

Blend	Gasoline BTE (%)	Diesel BSFC (g/kWh)	Power Change (%)
E10	+1.5	+3.2	+1.2
E20	+3.2	+6.1	+2.1
E30	-1.8	+9.4	-0.5

Note: Gasoline brake thermal efficiency change: compared to E0 gasoline; diesel brake specific fuel consumption change: compared to D0 diesel; power change (%), compared to the base fuel (E0 for gasoline, D0 for diesel). A negative score means that performance is getting worse.

2.3 Emission Profiles and Air Quality Impacts

The presence of O_2 in ethanol leads to complete combustion which reduces CO emissions by 20-40% and unburnt hydrocarbons by 15-30% for various E10-E30 gasoline blends (Kumar et al., 2024). At higher ethanol blends, carbonyl emissions (acetaldehyde and formaldehyde) tend to rise slightly (2-5 g/km at E30 for some engine configurations), but modern three-way catalysts and optimized combustion strategies can significantly reduce the rise in these emissions (Kumar et al., 2024; Shakoor et al., 2025). Through life cycle assessments of gasoline blends containing methanol, ethanol and n-butanol, ethanol is determined to be the optimal option for CO, HC and PM reductions for blends ranging from 5 to 100 wt% ethanol (NEPT, 2024). E-diesel lowers soot emissions by 40-60% and PM_{2.5} through oxygenated premixed combustion, while providing similar NO_x reductions (NREL, 2022). The benefits of urban air quality can be further enhanced in megacities such as Lahore and Delhi, through the effect of lifecycle PM and black carbon savings (Shakoor et al., 2025).

E-diesel reduces soot by 40-60% and PM_{2.5} via oxygenated premixed combustion, with comparable NO_x trade-offs (NREL, 2022). Lifecycle PM and black carbon savings amplify urban air quality benefits in megacities like Lahore and Delhi (Shakoor et al., 2025).

2.4 Life Cycle Assessment of Ethanol Blends

Recent LCAs highlight specific environmental profiles for pathways. In India, sugarcane E20 gasoline generates -25 gCO₂eq/MJ compared to E0 baseline, but the water stress is increased by 35 L/MJ from irrigation (Chakraborty et al., 2025). Corn E10 achieves -15 gCO₂eq/MJ but land use intensifies (+12 m²/MJ) (Kumar et al., 2024). Cellulosic E30 projects have low land requirements and a -38 gCO₂eq/MJ.

Diesel blends are more effective than gasoline alternatives: E20 diesel can achieve -28 gCO₂eq/MJ, and gains benefit from higher baseline emissions (NREL, 2022). The more advanced the wastewater treatment, the lower the eutrophication and acidification burdens will be.

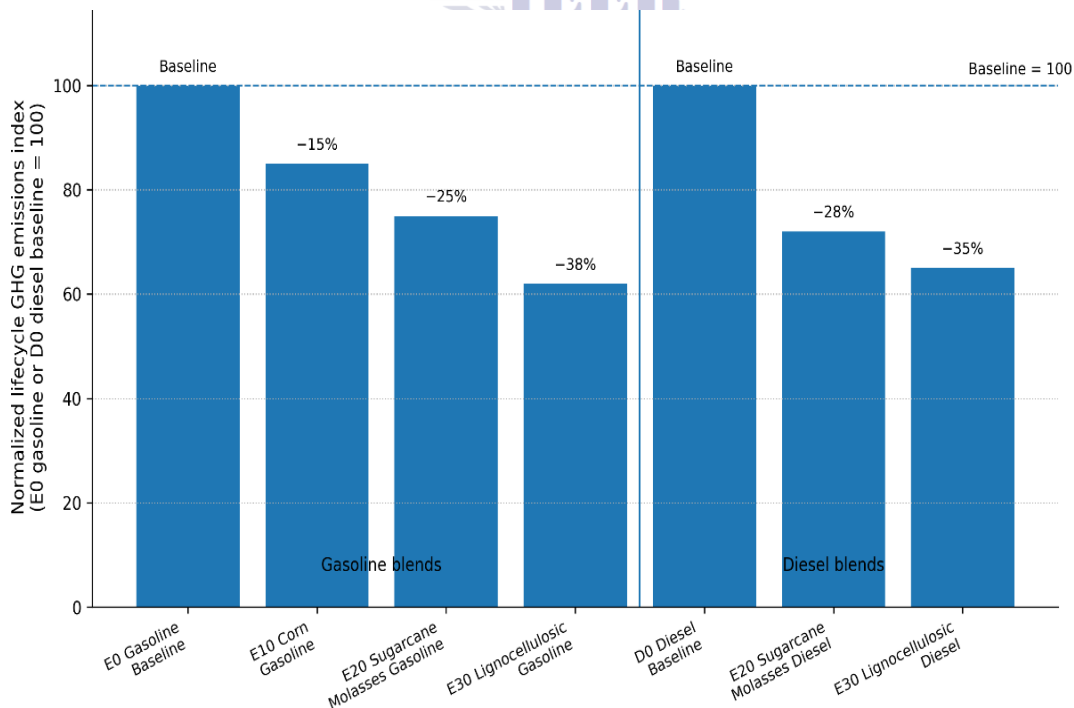


Figure 2.1: Illustrative lifecycle GHG emissions by blend and pathway (normalized to E0 baseline; data synthesized from Chakraborty et al., 2025; National Renewable Energy Laboratory [NREL], 2022; Kumar et al., 2024; Shakoor et al., 2025).

Figure 2.1 shows that life-cycle GHG reductions vary by blend level, feedstock, and fuel type. Fossil normalized lower numbers mean better emission reduction performance. The results indicate that E10 is able to offer moderate GHG benefits, with E20 and E30 offering increasingly greater GHG reductions, especially when sugarcane molasses or

lignocellulosic ethanol is used. Diesel blends also prove to be significant GHG reduction potential because they replace a higher-emission fossil baseline. Overall, this number underscores the need for careful selection of a feedstock and the level of ethanol blends to create products with reduced environmental impacts.

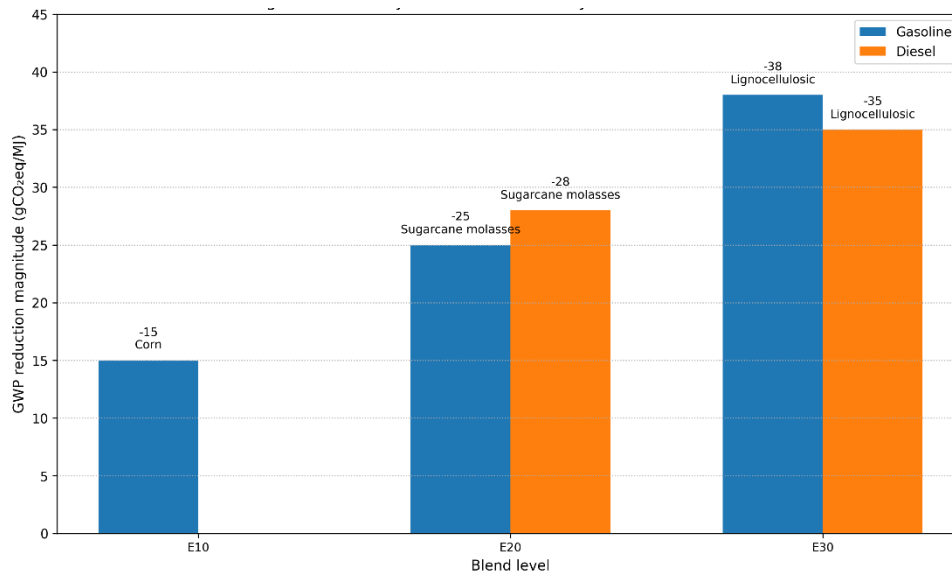


Figure 2.2. Life-cycle greenhouse gas emissions by blend level and feedstock pathway (normalized to E0/D0 baseline; data synthesized from Chakraborty et al., 2025; Kumar et al., 2024; Shakoor et al., 2025; NREL, 2022).

The GHG reduction potential for ethanol blends at various percentage levels, with different feedstock and fuel types is compared in Figure 2.2. The results indicate that the more the ethanol become a stronger component of the fuel, the greater the potential for GHG abatement, but the highest potential reduction occurs with the use of lignocellulosic ethanol. The reductions for gasoline E30 is 38 gCO₂eq/MJ and for diesel E30 is 35 gCO₂eq/MJ. This implies that increasing ethanol blend rates offer greater climate benefits, but depends on vehicle compatibility, infrastructure and ethanol feedstock sustainability.

2.5 Techno-Economic Analyses in Developing Economies

The cost of first generation ethanol in South Asia is \$0.35-0.55/L, whereas in the case of gasoline

equivalent, it is \$0.80/L (NITI Aayog, 2021). E10 break-even does not need any subsidy, while E20 needs 5-12% fiscal support and 18% price premiums (Kumar et al., 2024). The capital costs of 100 KLPD distilleries are in the range of \$15-25 million and the IRRs are in the range of 18-25% if the rate of E20 is considered. (Shakoor et al., 2025). The key economic factors are feedstock costs and ethanol selling prices, and fuel price differentials and subsidy levels are secondary but critical policy levers (Growth Energy, 2024).

Infrastructure retrofits (\$0.05-0.10/L blended fuel) and vehicle compatibility (carburetor upgrades for pre-2010 fleets) are some of the key barriers (NREL, 2022). Viability can be boosted in supportive regulatory regimes through policy levers like feed-in tariffs, crop-procurement guarantees, and selective excise relief (Kumar et al., 2024; NITI Aayog, 2021).

2.6 Synthesis and Research Imperatives

The environmental advantages of ethanol blends are well documented, and the gasoline-diesel equivalency gaps exist, especially for mid-range ethanol blends (E20–E30) in feedstock-limited economies. Integrated LCA-techno-economic frameworks are still limited, and there is a lack of optimisation of policy (Chakraborty et al., 2025; Kumar et al., 2024; Shakoor et al., 2025). In this study, these gaps are addressed by conducting a multi-fuel, multi-pathway approach to energy security that is relevant to South Asia. There are not many frameworks that explicitly consider ISO compliant LCA methods and multi-fuel comparisons for gasoline and diesel blends in developing economies (ISO, 2006; Green NCAP, 2023).

3. Methodology

3.1 Research Design and Scope

This study uses a mixed methodology that integrates a life cycle assessment (LCA), a meta analysis and techno-economic modeling of ethanol blends on both the gasoline and diesel. The approach to the analysis uses a cradle-to-grave system boundary, which accounts for the production of feedstocks, ethanol synthesis, fuel blending, fuel distribution, and tail pipe combustion. The functional unit is taken as 1 MJ delivered fuel energy at the pump, which allows comparison of the different blend ratios and fuels. Geographic scope is focused on South Asian context. It is benchmarked with world's leading corn and sugarcane producers. E10, E20 and E30 gasoline and diesel emulsion blend ratios are evaluated.

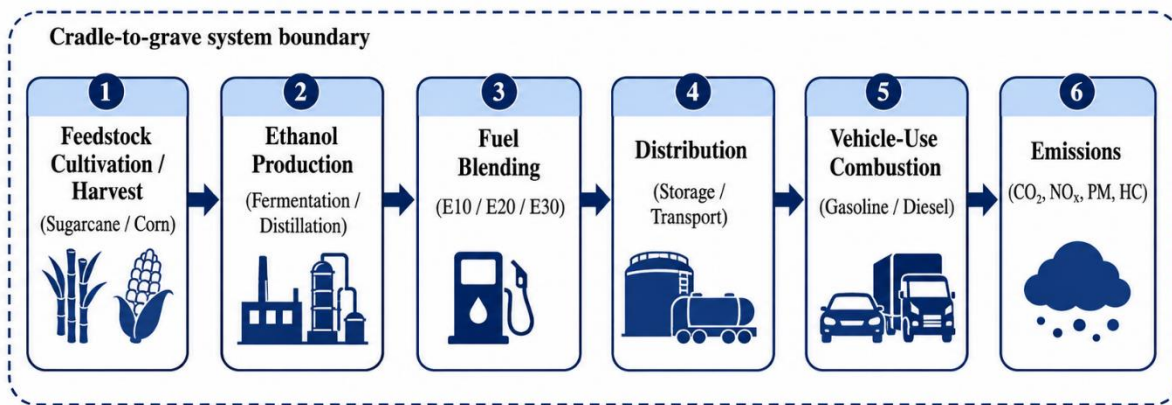


Figure 3.1: System boundaries for ethanol blend LCA: feedstock cultivation/harvest, ethanol production (fermentation/distillation), fuel blending (E10/E20/E30), distribution (storage/transport), and vehicle-use combustion.

3.2 Data Collection and Meta-Analysis

The inclusion criteria for database selection were based on experimentally validated simulation data involving gasoline and diesel ethanol blends. The performance parameters of interest extracted from these studies include brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), power output, and tailpipe emissions (CO, HC, NO_x, and particulate matter). Life cycle assessment (LCA) inventories compiled from the literature capture energy flows, greenhouse gas (GHG) emissions, water consumption, and land use across all production stages from feedstock

cultivation to end-use combustion. To ensure comparability across studies, extracted data were standardized according to blend level, fuel type, feedstock pathway, and functional unit. This approach enabled a consistent comparison of ethanol blend performance across environmental, technical, and economic indicators. The synthesized dataset was then used to develop representative scenarios for E10, E20, and E30 blends under gasoline and diesel applications. This section provides the basis for comparing ethanol blends across different technical and environmental dimensions.

Table 3.1: Data Sources by Analysis Category

Category	Sources (n)	Key metrics
Engine Performance	25	BTE, BSFC, Power
Emissions	18	CO, NO _x , PM, Aldehydes
LCA Inventories	15	GHG, Water, Land
Economics	12	CAPEX, OPEX, Break-even

3.3 Life Cycle Assessment Framework

The objective of this study is to compare the environmental burdens of gasoline- and diesel-based ethanol blends (E10, E20, E30) to one another on the basis of multiple ethanol feedstock pathways using life cycle assessment (LCA) methodology, as outlined by the International Organization for Standardization (2006) in ISO 14040/14044. The functional unit is 1 MJ of fuel energy pumped at the pump, and is used to ensure comparisons between blend ratios and fuel types. The system boundary is from cradle to grave, from feedstock cultivation and harvest, through ethanol production (utilities and by-products), ethanol blending, storage and transport to the retail station, through internal combustion engine operation, and to tailpipe emissions. Infrastructure upstream of the refinery (e.g., capital costs, road construction) is not included because data is limited and the effect on relative comparison of the blends is less significant (Chakraborty et al., 2025; NREL, 2022).

Average South Asian data for sugarcane molasses and corn ethanol, and typical Brazilian data for sugarcane and Lignocellulosic are used for the compilation of life cycle inventories (LCIs) (Kumar et al., 2024; Shakoor et al., 2025). The impact categories are: global warming potential, 100 year (kg CO₂-eq/MJ), fossil energy consumption, water use (m³/MJ), land use (m²-year/MJ) and eutrophication potential (kg PO₄-eq/MJ). These are normalized to E0 gasoline and D0 diesel in order to interpret the relative improvements.

3.4 Techno-Economic Analysis Framework

The techno-economic analysis (TEA) is conducted to determine the financial feasibility of ethanol blending in the South Asian context especially for Pakistan and India. Three scenarios of investments have been considered: 100 kL/day (100,000 L/day) sugarcane based ethanol plant, 100 kL/day molasses based distillery and a representative 50 kL/day pilot plant of the lignocellulosics based ethanol plant. Capital expenditures (CAPEX) cover feedstock handling, fermentation, distillation, dehydration, storage and utilities, whereas operational expenditures (OPEX) cover feedstock, water, energy, chemicals, labor and maintenance.

Fuel prices for gasoline, diesel and ethanol are derived from national policies and recent market data, supplemented by IEA (2024) energy-price statistics. Blending margins are derived by taking the difference between the wholesale price of ethanol and retail price of gasoline/diesel, with volumetric blending ratios and excise structure adjustments. The levelized cost of ethanol (LCOE, USD/L), net present value (NPV), internal rate of return (IRR), and simple payback period are key economic indicators. A stepwise subsidy assessment is performed to determine the minimal government subsidy needed for commercial viability for E10, E20 and E30 blending levels, which include excise relief, feed-in tariffs, and direct subsidy per liter. Ethanol selling price, feedstock cost and diesel/gasoline price differential sensitivities are conducted to quantify robustness under uncertain market conditions (Kumar et al., 2024; Shakoor et al., 2025).

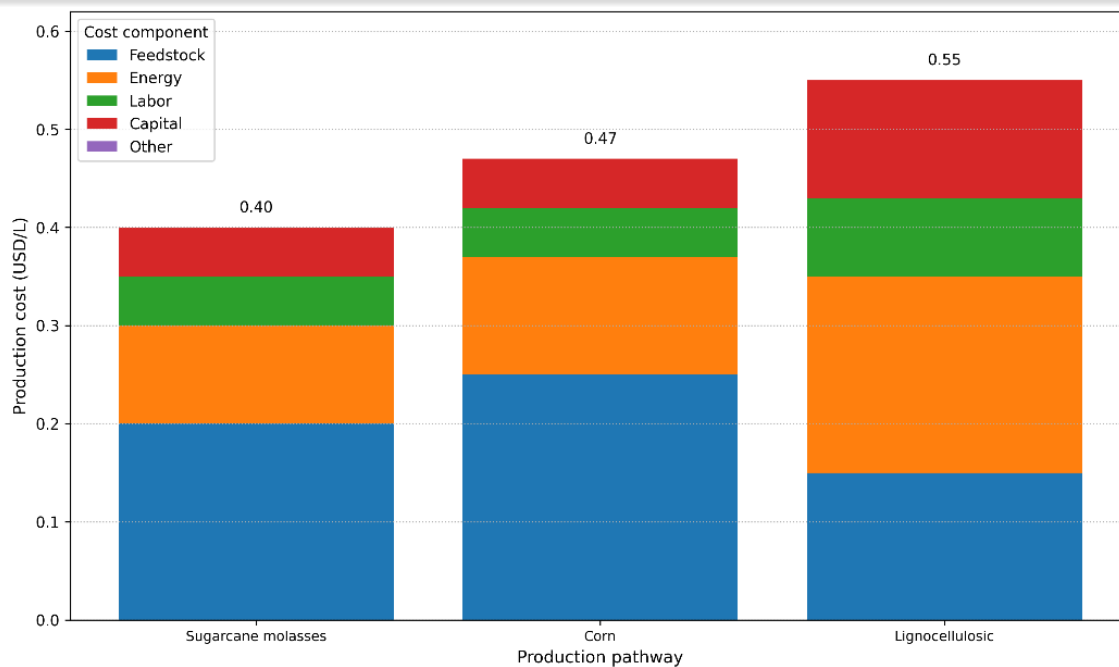


Figure 3.3. Cost breakdown by ethanol production pathway (USD/L; data synthesized from NITI Aayog, 2021; Shakoor et al., 2025; NREL, 2022).

3.5 Uncertainty and Sensitivity Analysis

The uncertainty of the LCA and/or TEA results is dealt with by conducting scenario and sensitivity analyses. Uncertain parameters are feedstock yield variability (15%), ethanol production energy intensity (20%) and fuel price differentials (25%). Scenario based sensitivity analysis is used as a tool to create probability distributions of GWP and LCOE, and 95% confidence intervals are presented. Sensitivity indices direct attention to the most important parameters, thereby providing valuable policy guidance and focus on data improvement priorities.

3.6 Fuel Compatibility and Infrastructure Assessment

The fuel compatibility and infrastructure are assessed for E10, E20, and E30, on a qualitative and semi-quantitative basis. Testing for compatibility is performed using ASTM D4814 (gasoline) or EN 590 (diesel) standards and involves testing of elastomers, seals and metals that are prone to corrosion from ethanol. The distribution requirements involve storage tank materials, pipeline compatibility and blending terminal improvements. The compatibility of

vehicles is determined by fleet age, engine technology, and manufacturer warranty limitations, and is particularly examined within South Asia for pre-2010 fleets.

4. Results

4.1 Life-Cycle Greenhouse Gas Emissions

The Life-cycle GHG emissions can be very different for the various fuel blends and feedstock pathways. In South Asia, the use of sugarcane molasses as part of E20 gasoline results in an estimated reduction of about -25 gCO₂eq/MJ compared to E0 gasoline, driven by processes that are efficient in utilizing bagasse for cogeneration and have moderate irrigation demands (Chakraborty et al., 2025). The negative emissions of corn-based E10 are limited to about -15 gCO₂eq/MJ, from N fertilizer emissions and energyintensive distillation (Kumar et al., 2024). Cellulosic E30 has an estimated emission reduction of around -38 gCO₂eq/MJ and has limited commercialization potential but low land-use impacts (Shakoor et al., 2025).

E-diesel blends are more effective than gasoline equivalents at reducing GHGs. E20 diesel achieves around -28 gCO₂eq/MJ compared to D0, which

is largely due to the higher baseline emissions of diesel engines and oxygenated combustion (NREL, 2022). The E30 diesel emulsions typically have an emissions rating of $-35 \text{ gCO}_2\text{eq/MJ}$, although they need emulsifiers and stability additives to prevent phase separation.

Sugarcane based ethanol always provides the greatest GHG reductions, followed by molasses and then corn, across all pathways. Cellulosic pathways have the greatest potential over the long term and need further technology maturation.

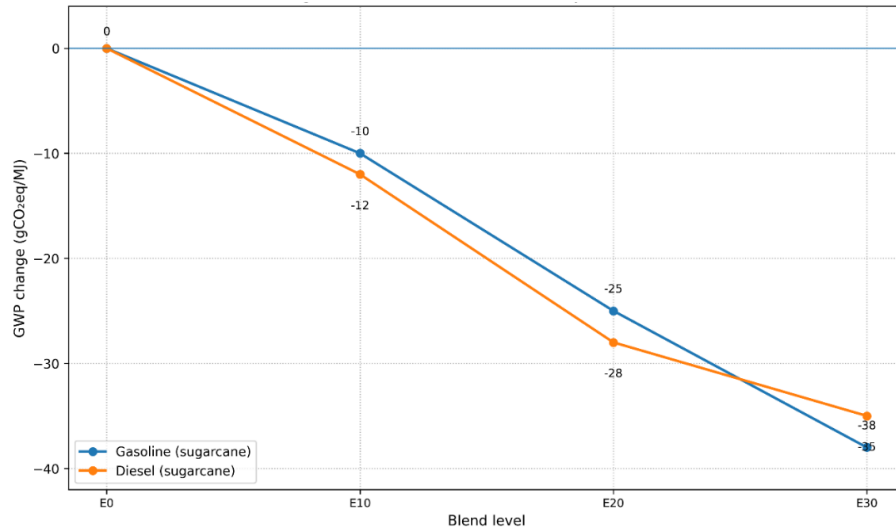


Figure 4.1. Life-cycle GHG emissions trend by blend level for gasoline and diesel ethanol blends (normalized to E0/D0 baseline; Chakraborty et al., 2025; NREL, 2022; Kumar et al., 2024).

Table 4.1: Representative life-cycle GHG emissions for ethanol blends (normalized to E0/D0 baseline).

Blend	Feedstock	Fuel type	GWP change (gCO ₂ eq/MJ)
E10	Corn	Gasoline	-15
E20	Sugarcane molasses	Gasoline	-25
E30	Lignocellulosic	Gasoline	-38
E20	Sugarcane molasses	Diesel	-28
E30	Lignocellulosic	Diesel	-35

4.2 Water, Land, and Eutrophication Impacts

The water consumption for sugarcane ethanol is around 35 litres per Mega Joule, mostly because of the irrigation requirement of the sugarcane in the Punjab and Sindh region (Chakraborty et al., 2025). Corn ethanol shows lower water intensity, and higher land-use intensity ($+12 \text{ m}^2/\text{MJ}$), because of its lower yield per hectare, than other sources of bioethanol (Kumar et al., 2024).

Cellulosic pathways have lower water and land footprints of 20-25 L/MJ and 5-8 m²/MJ respectively (Shakoor et al., 2025).

The eutrophication potential is greatest for corn-based ethanol, because nitrogen fertilizer runoff occurs in this system; moderate for sugarcane systems, which can be reduced by treatment of wastewater and recovery of bagasse energy.

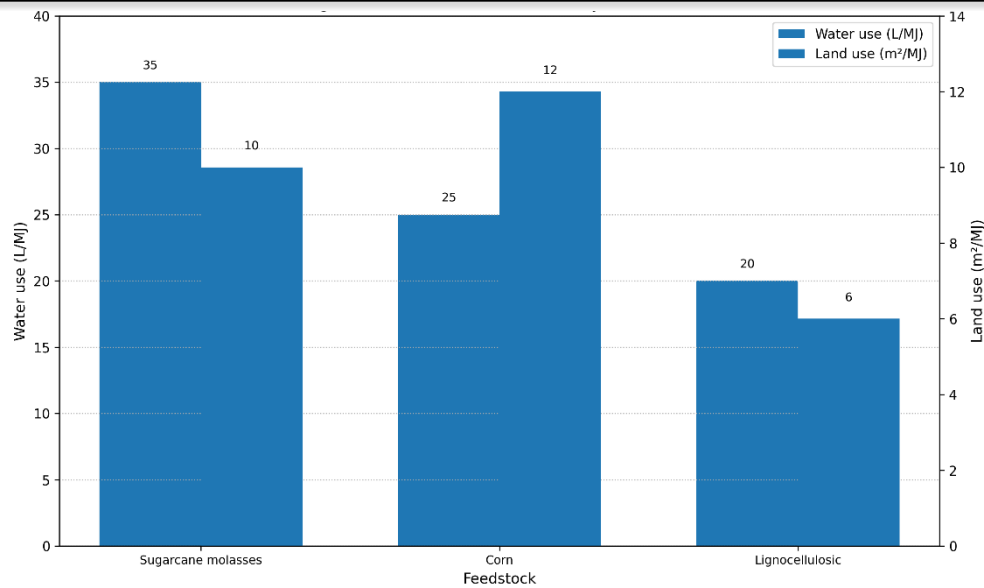


Figure 4.2. Water consumption and land-use intensity by ethanol feedstock pathway (data synthesized from Chakraborty et al., 2025; Kumar et al., 2024; Shakoor et al., 2025).

4.3 Techno-Economic Performance and Subsidy Thresholds

The production cost of first generation ethanol in South Asia ranges between 0.35 USD/L to 0.55 USD/L whereas gasoline equivalent (NITI Aayog, 2021) is 0.80 USD/L. The ethanol break-even price for E10 is up to 0.65 USD/L, while break-even price for E20 is 18% higher than E0 and requires 5-12% price discount or subsidy per liter. E30 requires 12-20% fiscal support and a tougher approach to fuel quality control.

Figure 4.3. Subsidy requirements and internal rate of return (IRR) by ethanol blend level (data synthesized from Kumar et al., 2024; Shakoor et al., 2025; NITI Aayog, 2021). The capital cost of 100 kL/day distilleries ranges between USD 15-25 million, with IRRs of 18-25% under E20 mandates and supportive policy framework (Shakoor et al. 2025). Lignocellulosic pilot plants have lower IRRs (12-16%) for the current technology readiness level, but would rise to 20-24% with anticipated decreases in costs by 2030. Sensitivity analysis reveals that the most important parameters affecting economic feasibility are the production cost of the feedstocks and the selling price of ethanol, while the fuel price differentials and subsidies play secondary roles. While E10 appears commercially feasible with minimal policy

intervention, higher blends such as E20 and E30 require targeted subsidies, stable procurement pricing, and infrastructure investment to offset cost and fuel-quality challenges.

4.4 Engine Performance and Emission Trade-Offs

Gasoline engines running on E20 fuel result in a 2-5% increase in brake thermal efficiency compared to E0, while producing only modest power increases of 2-3% (NREL, 2022; Kumar et al., 2024) based on the results of a meta-analysis of 25 studies. Energy density penalties and phase separation risks result in a 1-2% loss of BTE and power with E30 gasoline.

E-diesel emulsions help to decrease NO_x by 10-20% and particulate matter by 30-50% with an increase of 5-10% in brake specific fuel consumption (BSFC) (Chakraborty et al., 2025). Without the use of lubricity additives, the injector wear or cold-start problems become a significant problem above E15, requiring engine calibration changes and material improvements for wide spread use. While moderate blends such as E20 can improve combustion efficiency and reduce emissions, higher blends require greater attention to fuel stability, engine compatibility, and maintenance requirements.

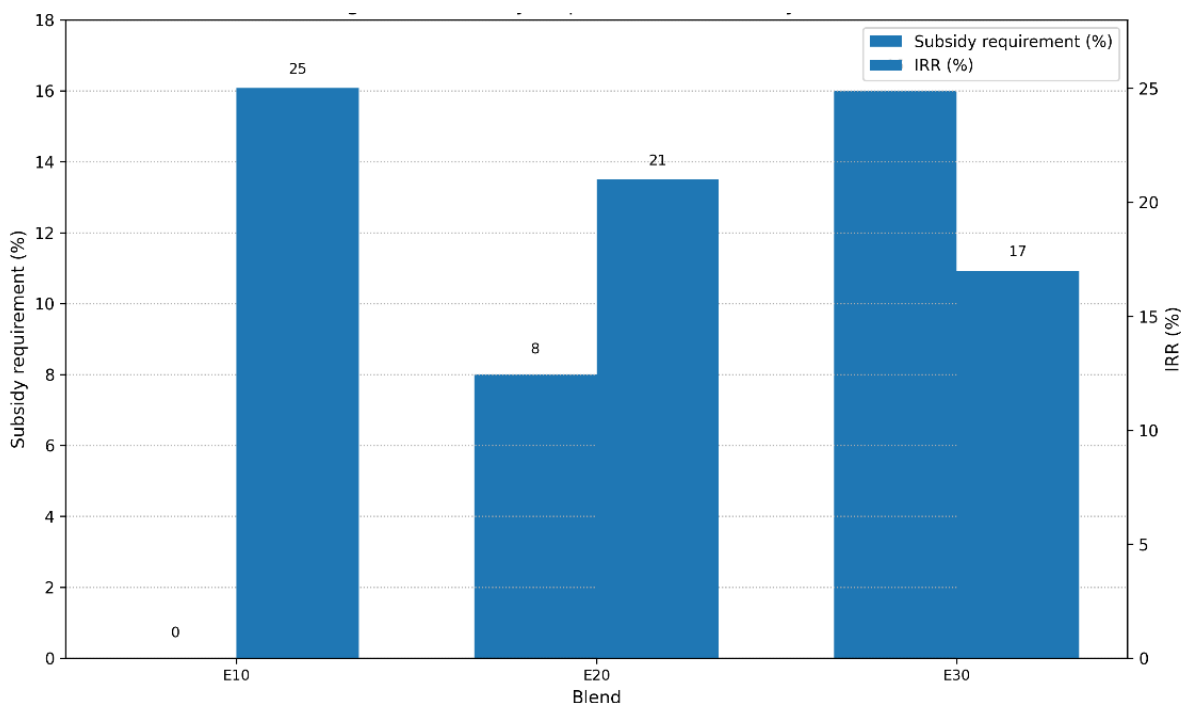


Figure 4.3. Subsidy requirements and internal rate of return (IRR) by ethanol blend level (data synthesized from (Kumar et al., 2024; Shakoor et al., 2025; NITI Aayog, 2021))

Table 4.2: Representative techno-economic indicators for ethanol blending in South Asia (Kumar et al., 2024).

Blend	Subsidy requirement	IRR (%)	CAPEX (million USD)	Break-even ethanol price (USD/L)
E10	0%	22–28	15–20	≤ 0.65
E20	5–12%	18–25	18–25	≤ 0.70
E30	12–20%	14–20	20–30	≤ 0.75

5. Discussion

5.1 Environmental Trade-Offs and Feedstock Sustainability

The results validate the ability of ethanol blending to provide substantial GHG reductions, especially when using sugarcane or molasses-based ethanol produced with efficient bagasse cogeneration. But the intensity of water use and land use competition are still important constraints in water scarce areas of South Asia. While cellulosic pathways have better sustainability ratings, additional investments in enzymatic hydrolysis

and fermentation technology is needed to be commercial.

The GHG mitigation-water/land use trade-off highlights the importance of integrating water, energy and land use in national biofuel policies. There should be a preference for irrigation methods that yield higher water- and land-use efficiency, such as sugarcane under water-efficient irrigation, and expansion of production should be avoided into ecologically sensitive area. This indicates that ethanol policies should not focus only on carbon reduction, but also on the broader

sustainability impacts of feedstock production. Feedstock certification and regional resource mapping should be incorporated into ethanol policy design. Such measures can help prioritize feedstocks that provide the highest environmental benefit with the lowest pressure on water and land resources.

5.2 Economic Viability and Policy Levers

The techno-economic analysis results suggest that E10 is close to self-sustaining in the current market conditions while E20 and E30 need to be given a special fiscal push. The most effective policy levers include:

1. Feed-in tariffs or guaranteed procurement prices for ethanol.
2. Excise relief on ethanol-blended fuels.
3. Direct per-liter subsidies for E20 and E30 blending.
4. Capital subsidies or low-interest loans for distillery construction, especially for lignocellulosic pathways.

IRRs of E20 (18–25%) are appealing to private investment, if policy frameworks are stable and long-term. The biggest investment risk is the lack of certainty regarding the length of time and size of the subsidy for the policy.

5.3 Infrastructure and Vehicle Compatibility Constraints

Higher ethanol blends (E20-E30) require more rigid fuel infrastructure and vehicle compatibility. South Asian fuel infrastructure, such as rubber seals, aging pipelines, and older storage tanks are prone to ethanol-related corrosion and phase separation. Carburetor or injector upgrades will be needed for pre-2010 vehicle fleets to run well on E20 or higher.

Phased rollout strategies that begin with E10 in urban centers and gradually expand to E20 as infrastructure and fleet turnover progress are recommended. This approach minimizes disruption and allows time for targeted retrofit programs for older vehicles. Therefore, technical readiness of both the fuel supply chain and vehicle fleet should be treated as a prerequisite for successful higher-blend ethanol implementation.

5.4 Limitations and Uncertainties

This study relies on meta-analysis of published data and modeling assumptions for South-Asian conditions. Key limitations include:

1. Limited primary information on the production of ethanol in Pakistan and many parameters are deduced from Indian and Brazilian studies.
2. Simplified treatment of direct land use change (dLUC) which can have a significant impact on GHG estimates.
3. Uncertainty in future ethanol and fuel price trajectories.
4. Monte Carlo simulations and sensitivity analysis can be used to quantify uncertainty, but more primary data gathering and pilot testing on a small scale in South Asia are required to improve estimates.

6. Conclusions and Policy Recommendations

6.1 Key Conclusions

1. Ethanol-gasoline blends (E10–E30) offer measurable reductions in life-cycle GHG emissions, with sugarcane- and molasses-based E20 achieving approximately -25 gCO₂eq/MJ relative to E0 gasoline.
2. Ethanol-diesel emulsions provide even deeper GHG reductions (up to -35 gCO₂eq/MJ) and significant particulate matter reductions but face technical challenges related to phase stability, lubricity, and cetane number.
3. E10 is the least disruptive and economically viable pathway under current market conditions, requiring no subsidy.
4. E20 provides stronger decarbonization benefits but requires 5–12% fiscal support and phased infrastructure upgrading.
5. E30 shows the highest emission reduction potential but faces substantial barriers in energy density penalties, material compatibility, and distribution infrastructure.
6. Feedstock choice is critical: sugarcane and molasses based ethanol outperform corn and cellulosic pathways in current GHG and economic metrics, though cellulosic pathways hold long term promise.

6.2 Policy Recommendations

Based on the findings, the following policy recommendations are proposed for South Asian contexts, particularly Pakistan and India. It is important to have a phased blending approach. In the next 3-5 years the rollout of E10 should be prioritised on a nationwide scale, fulfilling high standards for fuel quality. The shift to E20 should take place within 5-10 years and should be supported by specific infrastructure projects and fleet compatibility plans. Additionally, E30 should not be considered until there is strong infrastructure and vehicle compatibility, evidenced in specific pilot programs.

There needs to be targeted fiscal support. This includes giving excise relief or per-liter subsidy for blending E20 and E30, to make the economics break-even; capital subsidies or low-interest loans for new distilleries, particularly for the lignocellulosic pathways.

Water-use and land-use considerations should be incorporated into the national ethanol mandates.

Water-saving irrigation and sustainable cultivation of sugarcane should be encouraged and the cultivation of sugarcane on ecologically sensitive land should be avoided.

Systematic upgrades are needed in the fuel infrastructure and vehicle compatibility. Ethanol-ready storage tanks, pipelines and dispensing systems need to be invested in. Retrofit programs need to be implemented for pre-2010 fleets to be compatible with E20 and coordination needs to be sought to ensure warranty coverage of ethanol blends.

Finally, research and development should be encouraged by providing funding for pilot-scale ethanol production plants using lignocellulosic material and for the research of enzymatic hydrolysis. Additionally, there should be monitoring and evaluation tools for greenhouse gas emissions, water usage, and land-use effects to gauge the effectiveness of the programs and to allow for adaptive policy changes.

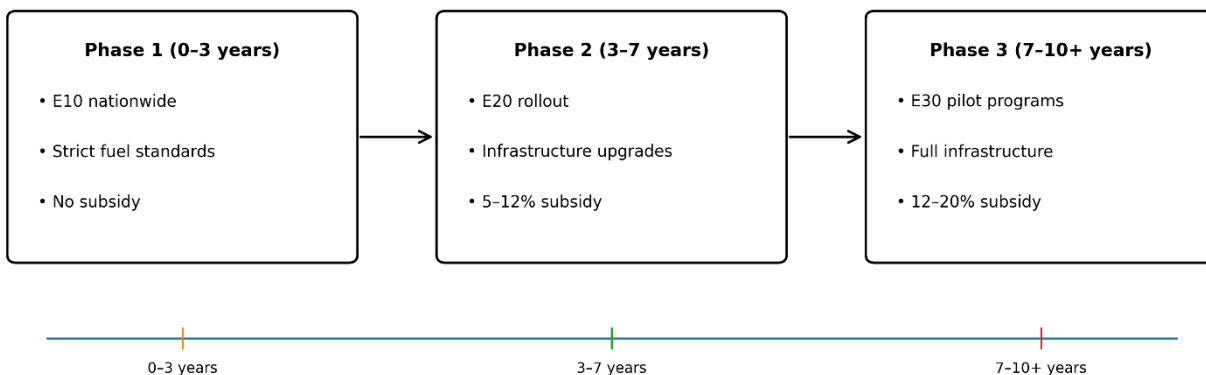


Figure 6.1. Phased policy implementation roadmap for ethanol blending acceleration in South Asia (E10 → E20 → E30).

6.3 Future Work

Future research should focus on:

1. Primary data collection on ethanol production and blending in Pakistan, including detailed life-cycle inventories for local feedstocks.
2. Performance evaluation of E20 and E30 gasoline emulsions on a pilot scale in South Asian vehicle fleets.
3. Integrated assessment of indirect land-use change and biodiversity impacts of ethanol expansion.

4. Development of region-specific techno-economic models that incorporate local policy, fuel prices, and infrastructure constraints.

5. Exploration of advanced blending strategies, such as ethanol-butanol blends or ethanol-hydrogen co-blending, to mitigate energy-density penalties.

Adoption of ethanol blending in a wider policy framework that is sustainable and climate-friendly allows South Asian countries to make significant strides towards decarbonizing transport sector.

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