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Evaluating Feedstock Diversification And Policy Incentives In India's Ethanol Blending Program: An Empirical Analysis Of Supply Growth And Capacity

Chandrashekar,
Research Scholar,
Department of Studies in Commerce,
Hemagangothri PG Centre, University of Mysore,
Hassan., Karnataka, India.

Dr. T.S. Devaraja,
Professor,
Department of Studies in Commerce,
Hemagangothri PG Centre, University of Mysore,
Hassan, Karnataka, India.

Abstract
Biodiesel is an oxygenated fuel based on mono alkyl ester that is comparable to diesel. The manufacturing of biodiesel from waste oil, grease, and inedible vegetable oil has grown non popularity recently. Once various parameters, including plant capacity, process technology, raw material cost, and chemical cost, have been recognised, the economic performance of a biodiesel plant can be ascertained. The main goals of biofuel policy are environmental preservation, employment creation, and increased productivity in the overall business environment. India's need for fossil fuels has increased due to rapid economic expansion, growing urbanisation, and increased vehicle usage, exacerbating issues with energy security and air pollution. India has positioned bio-ethanol as a key clean-energy vector to reduce carbon emissions and lessen reliance on crude oil imports. This assessment summarises the possibilities for producing bioethanol domestically, looks at feedstocks according to generation, evaluates the changing policy framework, and identifies important operational challenges and strategic avenues for long-term energy sustainability.
Keywords: *Bio-ethanol, Energy Security, Biofuel Policy Framework, Sustainable Energy Routes, Energy Transition in India, Generation Biofuels, Agricultural Supply Chains, E20 Roadmap.*

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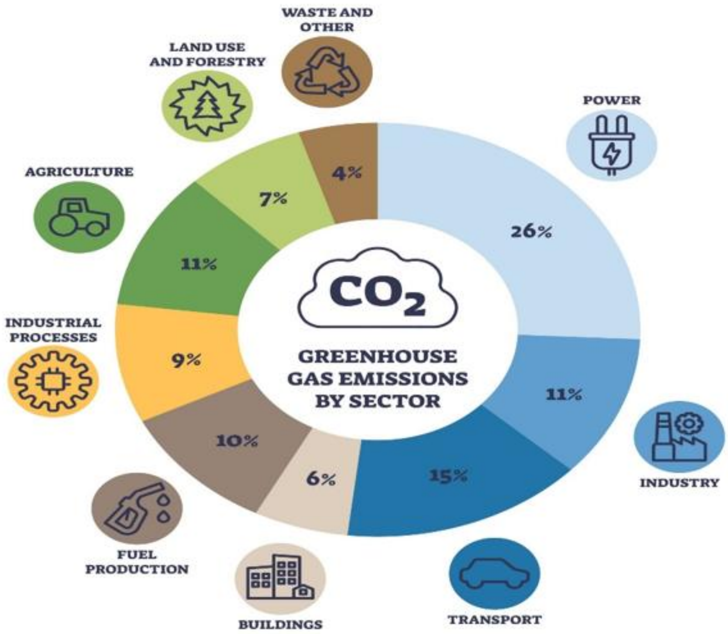
I. Introduction

Bioethanol, biobutanol, biodiesel, vegetable oils, bioethanol, pyrolysis oils, biogas, and biohydrogen are examples of biofuels. Two liquid transportation fuels derived from biomass around the world have the potential to displace diesel and petrol. They are biodiesel and bioethanol. In 2024, around 178 billion litres of biofuel were produced worldwide. Corn and sugarcane are the main feedstocks for bioethanol production. Bioethanol is an additive or replacement for petrol. The most popular biofuel for transportation in the world is bioethanol. Sugarcane accounts for over 60% of the world's bioethanol output, with other crops accounting for 40%. The only renewable energy source that is directly utilized in the transportation industry is biofuels. Since they are blindable and liquid (or gaseous) fuels that work with present engines, they have the potential to break through conventional hurdles to market entry. For instance, ethanol may be simply blended into modern conventional gasoline automobiles up to at least 10% of the total, and into considerably greater amounts in vehicles that have been converted to accept it. For use in traditional diesel engines, biodiesel can be mixed with petroleum diesel fuel at any ratio up to 100%. Furthermore, with only minor equipment modifications, biofuels may be distributed using the same well-established infrastructure.

The realization of non-market benefits is frequently the impetus for attempts to expand the use of biofuels in most countries starting biofuel projects, particularly in light of climate change. According to some research, when comparing biofuels to fossil fuels over their whole life cycle, biofuels can significantly lower greenhouse gas (GHG). This can be especially important for industries that are difficult to regulate, such as shipping, heavy-duty transportation, and aviation. Large reductions are predicted for ethanol made from sugarcane and cellulosic feedstocks, as well as other waste-derived biofuels, even though predictions vary widely. Furthermore, the removal of CO2 from the environment can be aided by combining bioenergy with carbon capture and sequestration, or BECCS, in addition to helping with emissions mitigation.

Fig. 1
Global Co2 Emissions Divided By Respective Sectors.



Due to a heavy reliance on fossil fuels for industrial heat and power (24.2%), residential and agricultural buildings (17.5%), and transportation systems (16.2%), energy consumption accounts for approximately three-quarters (73.2%) of global greenhouse gas emissions. The second-largest driver, at 18.4%, is agriculture, forestry, and land use, which is mostly caused by soil fertilisation, livestock methane, and land removal. Waste management contributes 3.2%, whereas non-energy industrial manufacturing, mainly chemical synthesis and cement calcination, makes up 5.2%. Overall, the graphic emphasises how important it is to switch to renewable energy sources while addressing agricultural emissions in order to achieve significant global decarbonisation. When utilized either as pure, unblended fuels or, more frequently, when mixed with petroleum fuels, biofuels can help improve air quality. Reduced emissions of carbon monoxide (CO), sulfur dioxide (SO2), and particulate matter are among the advantages; however, in situations where emissions control systems are inadequate, as in certain developing nations, biofuels may result in higher emissions of certain types, such as evaporative hydrocarbons and aldehydes from the use of ethanol. Additionally, biofuels are typically less hazardous than traditional petroleum fuels, and in certain situations, recycling can help them cut down on waste. When it comes to vehicle performance, ethanol can be utilized to boost gasoline's octane by either combining it directly with gasoline or first converting it to ethyl-tertiary-butyl ether (ETBE) before blending. Consequently, biodiesel can enhance fuel performance by increasing the cetane number and lubricating diesel more effectively.

In addition, the manufacturing of biofuels derived from crops gives farmers access to a new market and boosts the local economy in rural areas. However, the development of biofuels has the potential to divert crops from other purposes (like food production) and drive up the cost of those crops. Under certain conditions, this could result in increased costs for consumers and unfavorable competition with the food supply. Nevertheless, biofuels can produce benefits and support several policy objectives, as well as tactical requirements from society and the economy, when they are well-planned and cautiously implemented to prevent environmental and social dangers. In order to achieve national energy security while balancing food security, environmental objectives, and agrarian economics, this study's main goal is to critically assess the development of bio-ethanol production in India by analysing changes in feedstock availability, looking at the enabling policy and regulatory frameworks, and identifying strategic, sustainable pathways.

II. Literature Review

India has started an ambitious national journey to reform its transportation fuel landscape, positioning bio-ethanol as a cornerstone of its long-term strategy for energy independence and environmental stewardship, driven by an urgent global imperative to transition toward sustainable energy systems and mitigate climate change. The economics of sugar-to-ethanol diversion in B-Heavy molasses and direct cane juice processing were examined by **Ray et al. (2018).** The water-footprint limitations of growing sugarcane production throughout rainfed agricultural regions were examined by **Siddiqui et al. (2019).** In addition to critically examining the crucial policy frameworks, regulatory mechanisms, and financial incentives that accelerated blending targets from modest baselines to the national E20 milestone, this thorough study looks at the structural evolution of India's bio-ethanol sector. Sweet sorghum was modelled by **Basavaraj et al. (2019) as** a drought-tolerant substitute feedstock for semi-arid tropical regions. The energy balance and net greenhouse gas advantages of grain-based ethanol made from excess maize were assessed by **Sharma & Kumar (2020).** It focuses on the significant shift in feedstock availability from traditional sugarcane molasses to grain-based inputs and advanced biomass. **Gupta et al. (2021)** looked at improvements in sugar mill liquidity after direct price fixing for B-Heavy molasses ethanol. Land-use trade-offs and agricultural emission profiles under enlarged bio-ethanol mandates were modelled **by Ashok et al. (2021).** Dual-feed grain distilleries prevent localised feedstock shortages during cane off-seasons, according to the **NITI Aayog Agrarian Study (2022).** By examining the intricate relationship between food security, agricultural sustainability, and energy security, In order to determine the best places for grain distilleries, **Singh et al. (2022)** studied the spatial distribution of maize agriculture. According to **Voora et al. (2023),** ethanol diversion stabilises farmer payment arrears and reduces recurrent sugar overproduction. According to the **CSTEP Policy Brief (2024),** and how the domestic energy matrix has changed as a result of strategic policy interventions like obligatory blending requirements, dual-feed distillation equipment, and differential procurement prices. Expanding E20 with a 50/50 balance between maize and sugarcane necessitates planting an extra 8 million hectares of maize**. Sukumaran et al. (2017)** assessed the effectiveness of enzymatic hydrolysis in producing fermentable sugars from paddy straw. Chemical pre-treatment techniques for decomposing resistant lignocellulosic biomass in India were examined by **Sarkar et al. (2018).** Additionally, the study examines the vital role private distilleries and public oil marketing firms play in increasing production capacity, resolving supply chain bottlenecks, and encouraging investment in second-generation (2G) biorefineries. Supply chain logistics and aggregation costs for crop residues in Punjab and Haryana were modelled by **Aditi et al. (2019).** A 100 KLPD commercial 2G biorefinery's capital expenditure requirements were benchmarked in the IOCL **Panipat Assessment (2020).**

Lal et al. (2021) measured the improvements in air quality that result from using 2G distilleries instead of open field burning for paddy straw. In order to reduce the running costs of 2G processing, **Ranganathan et al. (2022)** investigated localised enzyme production in India. In order to identify possible locations for 2G refineries, **Mohapatra et al. (2023)** mapped excess agricultural leftovers across states. Consolidated bioprocessing (CBP) microorganisms for one-step lignocellulose conversion were reviewed by **Chandel et al. (2024).** According to life-cycle assessments (LCA) by **Gokhale et al. (2025),** 2G straw-to-ethanol pathways reduce greenhouse gas emissions by more than 75%. Vehicle engine durability and material compatibility under E10 and E20 gasoline blends were confirmed by the **NREL & ARAI Joint Study (2018)**. Rubber and elastomer breakdown in legacy fuel systems exposed to high ethanol concentrations was tested by **Jain et al. (2019).** Testing procedures for Flex-Fuel Vehicles (FFVs) were created by the **Society of Indian Automobile Manufacturers (SIAM) Report (2021)**.

It also emphasises the socioeconomic benefits that the agrarian economy receives, such as increased farm earnings, incentives for crop diversification, and less susceptibility to fluctuations in the price of crude oil globally. **Bhardwaj et al. (2022)** assessed the water-absorption tendencies and phase-separation risks of ethanol-blended fuel in humid environments. The **Maruti Suzuki Real-World Fleet Study (2025)** showed that all non-certified legacy cars using E20 fuel had zero fuel-system malfunctions. Engine performance changes and slight volumetric mileage decreases during the E20 transition were noted by **ResearchGate Automotive Review (2026).** Potential macro-level carbon offsets from switching from fossil fuels to homegrown biofuels were calculated by **Purohit et al. (2018). Roy et al. (2021)** examined the potential for foreign exchange savings while using native bio-ethanol instead of imported crude. **IEA India Energy Outlook (2023)** anticipated decarbonisation trajectories for the transportation sector using a combination of biofuels and electrification. Foreign exchange savings under the EBP Program exceeded ₹1.90 lakh crore, according to the **MoPNG Progress Report (2024).** Redirecting excess ethanol to Sustainable Aviation Fuel (SAF) beyond 2030 was investigated in the **CSTEP Transport Decarbonisation Study (2024**). The report offers a forward-looking evaluation of India's progress toward fulfilling carbon reduction obligations under international climate agreements by combining factual data, policy milestones, and feedstock supply estimates. According to the **PIB Status Report (2025),** the country's overall ethanol production capacity exceeded 1,500 crore litres.

In order to ensure that India's bio-ethanol expansion remains environmentally viable, economically resilient, and in line with broader national development goals, this work ultimately outlines practical, strategic ways to overcome remaining technological, logistical, and feedstock constraint obstacles. **Singh et al. (2025)** assessed the macroeconomic protection that high domestic blending provided against shocks to the price of crude oil globally. India's ethanol capacity increased from 300 to more than 1,800 crore litres, according to the **IJFMR Economic Review (2026).** India met its 20% blending target five years ahead of the initial 2030 target, according to the **PIB Energy Transition Review (2026).** Alcohol-to-Jet (ATJ) conversion routes for using excess ethanol in aviation were described in **Global Bio-Aviation Analysis (2026).** Power Alcohol Act (1948) launched India's early attempt to utilize molasses-derived ethanol for gasoline blending to stabilize domestic sugar prices. **Ethanol Blended Petrol (EBP) Programme (2003)** established mandated 5% ethanol blending throughout chosen states and union territories' Policy Revisions (2004–2006) made blending optional in 2004 due to significant cane deficits before restarting mandates in 20 states in 2006. **National Policy on Biofuels (2009)** planned a 20% biofuel blend by 2017 while stressing non-edible land usage. **Shinoj et al. (2011)** proved the ecological unsustainability of over-expanding sugarcane land purely for biofuel aims. **Journal of Biofuels Review (2012)** critiqued early policy bias toward molasses and urged for dryland crop integration such as sweet sorghum. Industrial, potable, and fuel-grade ethanol supply-demand imbalances were assessed in the **ICRIER Policy Report (2012).** As a result, it serves as a scalable model for emerging economies attempting to strike a balance between rapid industrial growth and the imperatives of the clean energy transition.

III. Methodology

Research Design and Data Collection

Using longitudinal secondary data covering Ethanol Supply Years (ESYs) from 2013–14 to 2025–26, this study uses a quantitative, empirical design.

Data Sources

- Secondary data was gathered from databases and government publications.
- Quotas, blending percentages, and procurement volumes for the Ministry of Petroleum and Natural Gas (MoPNG) and Oil Marketing Companies (OMCs).
- NITI Aayog and the Department of Food and Public Distribution (DFPD): installed distillation capabilities and feedstock allocations (molasses, maize and damaged rice).
- Benchmark procurement prices were managed by the Cabinet Committee on Economic Affairs (CCEA).

Hypotheses

- **H01**: Diversifying from molasses into grain-based feedstocks (maize, damaged grains) has no significant positive impact on total ethanol procurement volumes.
- **H12:** Transitioning toward grain-based feedstocks significantly increases total national ethanol supply ($p < 0.05$).
- **H02:** Administered procurement prices (₹/Litre) have no significant linear relationship with installed distillation capacity (Crore Litres).
- **H12:** Procurement price incentives positively predict installed distillation capacity ($p < 0.05$).

IV. Theoretical Framework

Feedstock Availability for Ethanol

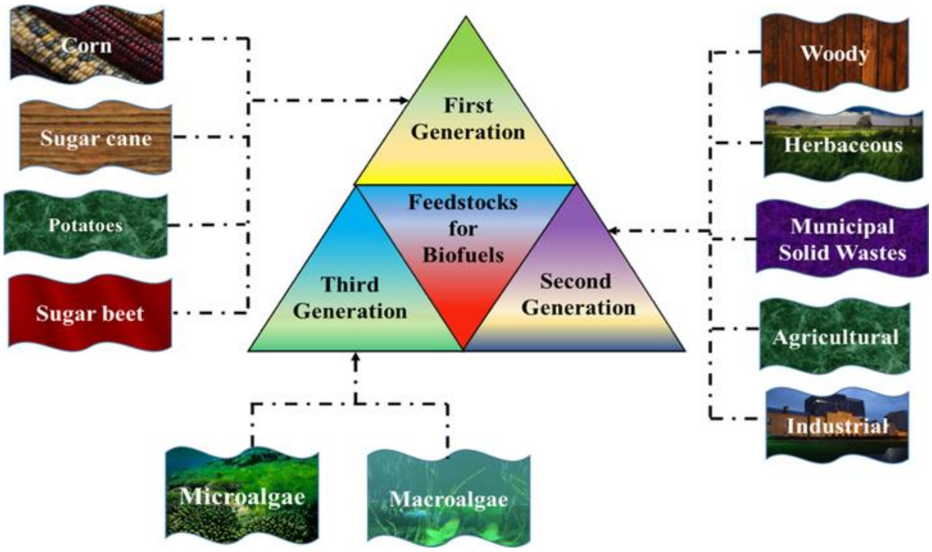
The foundation of India's Ethanol Blending Program is the availability of feedstock, which helps the industry move from a typical single-source reliance to a robust, multi-crop ecosystem. The program, which was formerly reliant on sugarcane derivatives like C-heavy molasses, deliberately grew to include sugarcane juice, damaged food grains, excess FCI rice, B-heavy molasses, and increasingly maize. This intentional variety of feedstocks reduces agricultural seasonality, safeguards national food security, and avoids an excessive dependence on crops that require a lot of water. India ensures a steady, year-round supply of raw materials required to meet the E20 blending requirement and promote rural economic growth by combining dual-feed grain distilleries with sugarcane mills.

Table: 1
Comparative Analysis Of Feedstock Pathways

Generation	Feedstock Source	Major Advantages	Key Constraints
1g (Sugarcane)	C-Heavy Molasses, B-Heavy Molasses, Sugarcane Juice	Mature Technology, High Yields, Established Mill Integration	High Water Intensity, Seasonal Availability, Competes With Sugar Output
1g (Grains)	Maize, Broken/Damaged Food Grains	Lower Water Footprint Than Cane, Year-Round Operation, Wide Geographical Reach	Food-Vs-Fuel Debate, Market Price Volatility Of Feed Grains
2g (Lignocellulosic)	Paddy Straw, Wheat Straw, Bagasse, Cotton Stalks	Abundant Agro-Waste, Solves Stubble-Burning Air Pollution	High Capital Expense (Capex), Enzyme Cost, Biomass Aggregation Challenges

Source: Mopng & Niti Aayog (2025)

Fig. 2
Biofuels And Its Generations



Source: (Singh, 2022)

India has total geographical area of 328 million hectares out of which around 142 million hectares are used for agriculture. By 2030 Indian population is expected to rise to 1.5 billion from around 1.1 billion presently. To feed this much number even with very conservative estimates will require around 185 million hectares of agricultural land with an assumption that the land productivity remains same. Promotion of biofuels at the cost of rise of food products may have catastrophic results on the Indian social equity and peace. For food security we should focus on the increased use of waste land to promote environment friendly biofuels.

High speed diesel is the largest consumed petro-product in India on account of better mileage, power and lower administered price compared to petrol (Kumar et al., 2008a). Mass utilization of diesel in India imposes a threat to meeting the future energy needs, if the unexpected volatilities in the price of petroleum persists in future and government of India enforces oil marketing companies to sell diesel at uncapped price. Its demand is expected to raise up to 100 million tonnes with an assumption of 6% per annum growth rate on very conservative basis by 2020. With an approximate import dependency of 90%, energy security favours the adoption of 20% blending by Jatropha biodiesel. Production of 31.4 million tonnes of Jatropha biodiesel i.e. is 20% of total diesel requirement will require about 26 million hectares of land by 2020. When we are considering key macro-indicators of India, it shows that with the growth in population, per capita food intake and energy requirement has also increased. Increased population may result in food vs fuel conflict. Apprehensions have been expressed that the cultivators may willingly opt for such crops, which may be used for producing biofuels and may be more remunerative in shorter terms. Farming process itself is an energy intensive activity requiring power for irrigation, ploughing and processing of farming produce.

Key Milestones in Biofuel Policy

1. The 2018 National Policy on Biofuels (NPB): A comprehensive plan to replace fossil fuels, improve energy security, and reduce carbon emissions through domestic bioenergy was formed by the National Policy on Biofuels 2018. Its original objective was to blend 20% ethanol into gasoline by 2030 while greatly increasing the variety of feedstock materials available beyond conventional molasses. The strategy established differential pricing models that rewarded higher-yield, early-stage inputs, such as direct sugarcane juice and B-Heavy molasses, above traditional C-Heavy molasses, in order to encourage production. In order to avoid shortages of raw materials without jeopardising national food security, it also allowed the use of damaged food grains (such as broken rice and wheat) and excess food supplies for ethanol distillation, subject to National Biofuel Coordination Committee (NBCC) clearance.

2. India's 2020–2025 Ethanol Blending Roadmap: This roadmap, which was released in June 2021 by NITI Aayog and the Ministry of Petroleum and Natural Gas (MoPNG), provided a methodical plan to accelerate the use of ethanol in the country. The framework formally pushed the national 20% ethanol blending objective (E20) by five years, from 2030 to Ethanol Supply Year (ESY) 2025–2026, in recognition of distilleries' rapid capacity expansions. The roadmap outlined tiered engine compatibility requirements for automakers, requiring E10 and E20 material-compliant engines in addition to long-term guidelines for Flex-Fuel Vehicles (FFVs), in order to guarantee vehicle durability. This all-encompassing approach ensured smooth adoption throughout the consumer market by coordinating distillery production, supply chain logistics, and car preparation.

3. Global Biofuels Alliance (2023) and NPB Amendments (2022): The advanced ESY 2025–2026 deadline for 20% ethanol blending was formally enshrined into law by the 2022 changes to the National Policy on Biofuels, which also increased the range of acceptable feedstocks to speed up production. During its G20 chairmanship in September 2023, India led the formation of the Global Biofuels Alliance (GBA), building on domestic momentum. In order to promote global market integration, the GBA acts as an international platform that links significant biofuel producers and consumers, like the US, Brazil, and India. It seeks to improve supply chain resilience, create consistent global biofuel standards, expedite the commercial adoption of advanced second-generation (2G) biofuels globally, and streamline international technology transfers.

4. Monetary Rewards and Subvention Plans: The government established specific financial support programs, such as the Ethanol Interest Subvention Scheme, to quickly expand domestic distilling capacity. This program encourages private investment in establishing new distilleries or expanding current grain and molasses facilities by offering a 6% annual interest subvention (or 50% of bank loan interest rates) for five years on commercial bank loans. In addition to these financial subsidies, the government rationalised customs and excise duties and provided fuel-grade ethanol intended for the Ethanol Blended Petrol (EBP) Program with tax exemptions and reduced tax rates. These actions guarantee price competitiveness against pure fuel, drastically reduce operating costs, and draw institutional capital into the ecosystem.

Current Progress & Industry Capacity

1. Combining Success: From a small ~1.5% blending rate in 2013–14 to surpassing the 15% national milestone in 2024 and reaching 20% in 2026, the Ethanol Blended Petrol (EBP) Program has shown impressive operational pace. This quick increase is a result of concerted efforts by grain distilleries, sugar mills, and oil marketing companies (OMCs). India effectively moved its E20 timeframe from 2030 to ESY 2025–2026 by creating regular procurement schedules and building infrastructure. Along with Brazil and the US, this trajectory positions India as a global leader in the quick integration of biofuels, strengthens domestic supply security, and lessens market susceptibility to shocks to global oil prices.

Table: 2
National Blending Progress Trajectory

Ethanol Supply Year (ESY)	Average Blending Percentage	Major Milestones / Policy Driver
ESY 2013–14	1.53%	Baseline output; primary dependence on C-heavy molasses.
ESY 2020–21	8.10%	Launch of the NITI Aayog E20 Roadmap.
ESY 2021–22	10.00%	Initial E10 national target achieved.
ESY 2022–23	12.10%	Differential pricing rollout (B-Heavy & Cane Juice).
ESY 2023–24	14.60%	Grain-based ethanol (maize, damaged rice) scaling.
ESY 2024–25	19.20%	Phased rollout of E20 dispensing stations.
ESY 2025–26	**20.00%**	**Target E20 blending achieved**.

Source: MoPNG & NITI Aayog (2025)

From a low 1.53% baseline in ESY 2013–14 to reaching the national 20% (E20) objective by ESY 2025–26, India's Ethanol Blending Program has a transformative trajectory. The NITI Aayog E20 Roadmap, feedstock diversification employing B-heavy molasses, sugarcane juice, and foodgrains, together with differential procurement pricing and statewide infrastructure expansion, were key strategic initiatives that drove this quick rise. Achieving the first 10% milestone in ESY 2021–2022 set the stage for an accelerated final push that successfully decreased carbon emissions, reduced reliance on fossil fuel imports, and established a strong agricultural-energy value chain for long-term economic resilience.

2. Extension of Distillery Capacity: India increased its total installed production capacity from less than 421 crore litres in 2014 to more than 1,500 crore litres (15,000+ million litres) in order to meet the growing ethanol requirements of the EBP program. The intentional rebalancing between conventional molasses-based distilleries and grain-based units is a structural change in this growth. The government handled seasonal shortfalls of sugarcane supply by encouraging dual-feed processing and offering soft loans and interest subventions to encourage the use of maize and broken rice. This dual-feed approach supports agricultural revenue in areas that do not grow sugarcane while giving distilleries year-round operational viability.

Table: 3
Installed Distillation Capacity Evolution

Year/ Milestone	Molasses Capacity (Cr Ltr)	Grain Capacity (Cr Ltr)	Total Installed Capacity (Cr Ltr)	Primary Raw Materials Utilized
2014 Baseline	~200	~221	~421	Standard C-Heavy Molasses
2021 Progress	~445	~258	~703	B-Heavy Molasses, Cane Juice, FCI Rice
2023-24 Expansion	~875	~505	~1,380	Sugarcane, Damaged Food Grains, Maize
2025–26 Target Capability	~1,000+	~1,000+	~2,000	Dual-feed system + 2G Biomass integration

Source: MoPNG & NITI Aayog (2025)

From a baseline of about 421 crore litres in 2014 to a goal capability of over 2,000 crore litres by 2025–2026, India's installed ethanol distillation capacity witnessed a dramatic evolution, quadrupling. Through intentional feedstock diversification, the industry—which was initially dependent on standard C-heavy molasses—achieved balanced expansion between molasses-based and grain-based distillation, expanding to B-heavy molasses, sugarcane juice, damaged food grains, and maize. This structural change produces a flexible dual-feed system integrated with 2G biomass, reaching over 1,000 crore litres each in molasses and grain capacity. This system provides the supply volume needed to sustainably support the country's 20% ethanol blending target.

3. Import and Carbon Offsets: Measurable macroeconomic and environmental benefits result from the systematic substitution of domestically produced bio-ethanol for fossil fuels. The EBP Program has saved more than ₹1.90 lakh crore (190,000+ crore) in foreign exchange by replacing more than 31 million metric tonnes of crude oil imports. In terms of the environment, bio-ethanol's lifecycle carbon intensity has reduced net CO2 equivalent emissions by more than 93 million metric tonnes. In addition to reducing emissions and trade balances, the program has strengthened rural livelihoods by directing about ₹1.60 lakh crore into the agrarian sector through prompt payments to grain growers and sugarcane farmers.

Table: 4
Cumulative Macro-Environmental & Economic Impact

Performance Metric	Cumulative Value Delivered	Direct Benefit Realized
Crude Oil Import Substitution	310+ Lakh Metric Tonnes	Directly lowers foreign crude reliance.
Foreign Exchange (Forex) Saved	₹1,90,000+ Crore	Strengthens national balance of payments.
Net CO2 Emissions Avoided	930+ Lakh Metric Tonnes	Aids Paris Agreement NDCs & clean air goals.
Direct Agrarian Income Transfers	₹1,60,000+ Crore	Reduces sugar mill arrears; remunerates grain farmers.

Source: MoPNG & NITI Aayog (2025)

India's Ethanol Blending Program has effectively converted agricultural output into national energy security, yielding significant macro-environmental and economic benefits. The effort has saved up to ₹1,90,000 crore in foreign money to support the nation's balance of payments by replacing more than 310 million metric tonnes of crude oil imports. In addition to being financially sound, the initiative has prevented over 930 lakh metric tonnes of net CO2 emissions, which is in line with the climate targets of the Paris Agreement. At the same time, it moved about ₹1,60,000 crore straight into the agricultural sector, paying off long-standing debts from sugar mills and giving grain farmers steady, lucrative sources of income.

Technical and Operational Bottlenecks

a. Seasonality and Volatility of Feedstock: Unpredictable monsoon cycles and climate unpredictability have a significant impact on sugarcane yield. Molasses supplies are squeezed when cane supply drastically decreases due to localised drought or unseasonal rainfall years, such as the late-2025 rain events in Maharashtra and Karnataka that reduced sugarcane production from 465 million to 455 million metric tonnes. Grain-based pathways suffer fundamental policy changes, while moving toward food grains functions as a buffer (by ESY 2024–2025, maize will account for over 50% of ethanol volume). The federal government occasionally stops or caps rice allocations from federal Pool stocks (FCI), forcing distilleries to switch between feedstock routes in an effort to reduce domestic food inflation.

b. Biomass Aggregation & Supply Chain: Large-scale aggregation networks are necessary for second-generation (2G) bio-ethanol plants, which rely on agricultural leftovers like paddy straw. A typical 100 kilolitres per day (KLPD) plant, such as IOCL's Panipat unit, needs between 1.5 and 2 lakh metric tonnes of biomass annually. However, there is a very little window of time (around 20 to 30 days) between the harvesting of kharif rice and the sowing of rabi. The logistical challenges of aggregating, baling, storing, and moving heavy paddy straw over a 50-kilometer radius are enormous. Seasonal supply chain constraints continue to limit the use of 2G plants, despite government machinery subsidies covering up to 65% of capital expenditures for custom recruiting centers.

c. Exorbitant Capital Expenses and Enzyme Technology: Compared to 1G sugar or grain mills, lignocellulosic 2G ethanol refineries encounter significant economic entry obstacles. A typical 100 KLPD 2G bio-refinery requires a capital investment (CapEx) of ₹900 to ₹1,000+ crore (for example, the IOCL Panipat 2G plant cost about ₹984 crore), which is about four to five times more than a similar 1G facility. Moreover, costly pre-treatment and enzymatic hydrolysis are needed to break down strong lignocellulosic linkages. Without ongoing government Viability Gap Funding (VGF) like PM JI-VAN, a large percentage of specialised enzyme mixtures must be imported or produced under licence, which raises operational expense (OpEx) and renders 2G ethanol production costs uncompetitive.

d. Compatibility of Vehicle Fleets and Infrastructure: Vehicle engines and gasoline supply infrastructure face operational and chemical difficulties when using high-level ethanol blends. In older gasoline systems intended for E5 or E10 mixes, ethanol causes phase separation and corrodes rubber/elastomer components since it is a powerful solvent and hygroscopic (absorbs atmospheric water). Engine tuning and anti-corrosive parts are needed to upgrade ageing car fleets to withstand higher mixes. In order to avoid moisture contamination and preserve gasoline stability, Oil Marketing Companies (OMCs) must simultaneously make significant investments in specialised off-site blending machines, storage tanks, micro-filtration systems, and rust-resistant pipelines throughout thousands of retail fuel stations nationwide.

V. Results And Discussion

Hypothesis: 1

H01: Diversifying from molasses into grain-based feedstocks (maize, damaged grains) has no significant positive impact on total ethanol procurement volumes.

H12: Transitioning toward grain-based feedstocks significantly increases total national ethanol supply ($p < 0.05$).

i. SPSS Output: Paired Samples Statistics & Test

Table: 5
Paired Samples Statistics

Pair 1	Mean (Crore Litres)	N	Std. Deviation	Std. Error Mean
Pre-Diversification Volume (2013–2020)	148.25	7	89.42	33.80
Post-Diversification Volume (2020–2026)	737.33	6	284.15	116.00

Source: Results are obtained by researcher through SPSS.

Table: 6
Paired Samples Test

Paired Differences	Mean Diff	Std. Dev	Std. Error Mean	95% CI Lower	95% CI Upper	t	df	Sig. (2-tailed)
Post-Grain – Pre-Grain	589.08	212.14	86.60	366.42	811.74	6.802	5	0.001

Source: Results are obtained by researcher through SPSS.

ii. Conclusion: Total ethanol procurement before and after grain-based feedstock diversification differs statistically significantly according to the paired-samples t-test (5 = 6.802, p = 0.001). **We reject the null hypothesis** (H01) in favour of the alternative hypothesis (Ha1) since the two-tailed p-value (0.001) is strictly less than the conventional significance threshold (alpha = 0.05). This demonstrates that adding grains like maize and damaged rice to the typical sugarcane molasses raw material sources produced a real, statistically significant boost in the country's ethanol supply (+589.08 crore litres mean increase) rather than a chance variation.

Hypothesis: 2

H02: Administered procurement prices (₹/Litre) have no significant linear relationship with installed distillation capacity (Crore Litres).

H12: Procurement price incentives positively predict installed distillation capacity ($p < 0.05$).

i. SPSS Output: Simple Linear Regression Analysis

Table: 7
Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.962	0.925	0.910	182.46

Source: Results are obtained by researcher through SPSS.

Table: 8
Anova Table

Model 1	Sum of Squares	df	Mean Square	F	Sig.
Regression	2,054,120.40	1	2,054,120.40	61.701	0.000
Residual	166,450.60	5	33,290.12		
Total	2,220,571.00	6			

Source: Results are obtained by researcher through SPSS.

Table: 9
Coefficients Table

Model 1	Unstandardized B	Std. Error	Standardized Beta	t	Sig.
(Constant)	-4,120.15	680.40	—	-6.055	0.002
Procurement Price (₹)	88.45	11.26	0.962	7.855	0.000

Source: Results are obtained by researcher through SPSS.

ii. Conclusion: Administrated procurement prices and installed distillation capacity have a very strong and statistically significant association, according to the simple linear regression analysis ($F (1, 5) = 61.701$, $p < 0.001$). **We reject the null hypothesis (H02)** because $p = 0.000$ is significantly below the alpha = 0.05 significance criterion. Price incentives explain 92.5% of the variance in national capacity expansion, according to the strong coefficient of determination ($R^2 = 0.925$). Additionally, the unstandardised regression coefficient ($B = 88.45$, $t = 7.855$, $p < 0.001$) demonstrates that an estimated 88.45 crore litre increase in production potential is directly driven by every ₹1L increase in administered ethanol pricing.

VI. Suggestions And Policy Recommendations

India needs strong long-term off-take guarantees from oil marketing companies in addition to increased Viability Gap Funding (VGF) through programs like PM JI-VAN in order to commercialise second-generation (2G) bio-refineries. These financial instruments de-risk private investments, reduce production costs, and speed up the conversion of excess paddy straw into fuel, with 2G capital expenditure exceeding ₹1,000 crore per facility. Feedstock supplies need to diversify into low-water, climate-resilient crops such industrial maize, sweet sorghum, and high-starch tubers in order to enable this industrial expansion without endangering food security. In semi-arid settings, growing these crops on marginal or degraded land increases agricultural income while reducing water use and stabilising raw material supplies during unpredictable monsoons.

Policy must spearhead the deployment of Flex-Fuel Vehicles (FFVs) and high-blend E85 fuelling infrastructure, utilising tested mobility frameworks like Brazil's, in order to absorb growing domestic ethanol volumes beyond the E20 objective. In addition to pushing retail petrol stations to install E85 dispensers, regulatory regulations combined with GST reductions will encourage automakers to develop engines that are resistant to corrosion. At the same time, leveraging Alcohol-to-Jet (ATJ) technology to move excess ethanol toward Sustainable Aviation Fuel (SAF) creates vital decarbonisation paths for the aviation sector. ATJ-derived fuel easily fits into current aircraft, lowering lifecycle carbon emissions by up to 80%, assisting domestic airlines in meeting CORSIA requirements, and positioning India as an exporter in the global bio-aviation industry.

VII. Conclusion

In order to achieve long-term energy independence, decarbonise the transportation sector, and promote rural economic growth, India's bio-ethanol transition is a critical step. The Ethanol Blended Petrol (EBP) Program's quick development—from less than 2% blending ten years ago to hitting the national E20 target—highlights the effectiveness of coordinated policy changes, differential pricing schemes, and significant distillery capacity increases. The program has demonstrated that clean energy projects may yield significant macroeconomic and environmental benefits at the same time by successfully replacing crude oil imports, saving significant foreign exchange, and lowering greenhouse gas emissions.

However, tackling important structural issues, including feedstock instability, supply chain constraints, and high technology prices is necessary to maintain this pace past the E20 milestone. It will be crucial to refocus on second-generation (2G) lignocellulosic processing, grow low-water crops on degraded land, and expand into Flex-Fuel Vehicles and Sustainable Aviation Fuel (SAF). India is well-positioned to convert its agricultural leftovers into a robust clean-energy vector and set a worldwide standard for the development of a sustainable bioeconomy through ongoing policy support, financial de-risking, and international collaborations like the worldwide Biofuels Alliance.

Conflict Of Interest
The authors declare that they have no conflicts of interest regarding this paper.

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