Asia Pacific Academy of Science Pte. Ltd.

Sustainable Social Development 2026, 4(5), 8803.
https://doi.org/10.23812/ssd8803

Article

Policy pathways for higher ethanol blending in India: Advancing pollution mitigation, energy security, and agricultural linkages through the ethanol blended petrol program

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CITATION

Kumar A, Shaikh R, Palav M, et al. Policy pathways for higher ethanol blending in India: Advancing pollution mitigation, energy security, and agricultural linkages through the ethanol blended petrol program. Sustainable Social Development. 2026; 4(5): 8803. https://doi.org/10.23812/ssd8803

ARTICLE INFO

Received: 13 June 2026
Revised: 28 July 2026
Accepted: 31 July 2026
Available online: 1 September 2026

Abstract: India's Ethanol Blended Petrol Program (EBPP) is the largest and one of the most successful biofuel blending programs undertaken by an emerging economy. Since its inception in 2003 and subsequent restructuring under each of the National Policies on Biofuels, the program has evolved into a significant initiative to reduce greenhouse gas emissions associated with transportation fuels. This paper analyzes the program's development from relatively low levels of blending to achieve 20 percent blended petrol across all oil marketing companies' outlets by the end of December 2025. It uses a four-dimensional framework to assess the program's impact; namely: Energy Security, Environmental Performance, Economic Outcomes and Equity. The results demonstrate that the program has generated significant foreign exchange savings of approximately Rs. 1910 billion (USD 23 billion), crude oil substitution of approximately 31 million metric tons, and a cumulative reduction in CO_2 emissions of approximately 93.1 million metric tons since FY14–15 through May 2026. In addition, farmers and ethanol suppliers have been paid a total of approximately Rs. 1620 billion since FY14–15, demonstrating a tangible rural income transfer mechanism. Additionally, this paper analyzes the recent policy direction announced by the central government in June 2026, in which the Ministry of Consumer Affairs, Food & Public Distribution stated that the Government will extend the Excise Duty Waiver for 100 Octane Petrol to all formulations up to E30. The paper is a novel attempt to highlight a major sustainable social development policy initiative of the Indian government.

Keywords: ethanol blending; energy security; biofuel policy; E20; decarbonization; rural economy

1. Introduction

India is dependent upon foreign-sourced petroleum to an extent that is perhaps the single most damaging vulnerability to its national economic framework. For it purchases the majority of its crude oil and refined petroleum products from abroad, subjecting the treasury to two major, interrelated stresses: Volatility in global commodity pricing and ongoing pressure on the Current Account Deficit (CAD). In 2020–21, the total volume of petroleum product imports was 185 million metric tons, costing US$ 55 billion, according to data provided in the NITI Aayog Roadmap for ethanol blending. Therefore, India is amongst the largest importing countries in the world, which has implications far beyond simple Balance of Payments calculations into areas of strategic autonomy and macroeconomic resilience [1,2].

Urban air quality in Indian metropolitan cities is becoming an increasingly significant public health issue, as is the case in secondary cities. Three major components contribute to these poor air quality issues, including carbon monoxide, unburnt hydrocarbon emissions, and particulate matter due to vehicular emissions, especially in congested urban areas. As a result of the last two decades of rapid growth in the use of passenger cars and motorcycles in urban areas, vehicle density has increased dramatically. These two factors (chronic import dependence and acute air quality problems) have created a singular, consistent policy problem. In order to address the policy problem of chronic import dependence and acute air quality problems, the government of India implemented the ethanol blended petrol program, or EBP program, which is intended to provide a domestic supply of renewable liquid fuels to be blended into gasoline and delivered throughout the country via the same distribution system currently used by the petroleum industry [3,4].

The EBP program has a unique architecture when compared to an individual objective-based (subsidy / procurement) program. It is a multi-objective mechanism that will provide for the three primary objectives of: Energy security via crude oil substitution, economic development via rural income generation & agricultural value addition, and environmental improvement via cleaner combustion at the point of use. The program’s growth path over the last decade demonstrates the operationalization of this multi-objective design at large-scale. From only 38 crore liters of ethanol available during ethanol supply year 2013–14, which represented approximately 1.5 % blending, the program grew to 173.03 crore liters and 5.00 % blending during ethanol supply year 2019–20 and subsequently rapidly increased to 408.09 crore liters and 10.02 % blending during ethanol supply year 2021–22, exceeding the program’s own 10 % target [5,6]. Ethanol supply surpassed 1000 crore liters, achieving a blending level of 19.24 % by ethanol supply year 2024–25 [5], and by December 2025, achieved formal compliance with the 20 % blending goal for the entire program [7]. As such, the program’s expansion is one of the fastest and most sustainable deployments of blended fuels on record within major economies; as such, there is a need for significant analytical attention in order to reflect the program’s size and complexity.

Although the program has had significant success, there are many gaps in analysis for the EBP Program. There are many studies that provide an overview of the program’s development, mostly with descriptive information, or examine each dimension individually (feedstock economies, environmental impacts, supply chain logistics), but none examine all four dimensions together. This study addresses this void by applying a 4E framework comprising four dimensions: Energy Security, Environment, Economics, and Equity. By using this framework to analyze verified parliamentary and official data, we will be able to conduct an integrated analysis that previous studies could only do one dimension at a time or only review the program overall [8–10]. Its specific contribution is to integrate verified policy outputs and their cross-dimensional trade-offs in one empirical framework, rather than reproduce a descriptive program chronology or a single-outcome assessment.

The study investigates three specific research goals. Research goal O1: To evaluate the development of India's EBP Program (Energy Blending Program) policy framework since its inception in 2003 through the implementation of E20 and the developing regulatory framework for E22–E30, as well as the pathways through which each successively developed policy instrument impacted program results. Research Goal O2: To determine quantitative results on three distinct factors: Energy security; economic; environmental performance via verified statistics from governmental documents including parliamentary records; cabinet decisions; official governmental publications; thus, establishing the credibility of the empirical analysis based upon verifiable evidence and not modeling predictions. Research Goal O3: To outline structural barriers that limit the ability to scale blending ratio to greater than E20 and provide evidence-based recommendations for policies that will address these structural barriers in light of India's current institutional and market realities.

Two main hypotheses guide the research methodology for this paper. H1: The increasing levels of ethanol blended into fuels in India, facilitated through a coordinated effort by multiple government ministries and an active policy approach to diversify the sources of biomass (feedstocks) that can provide the base for these blends has enhanced energy security and also significantly reduced greenhouse gas emissions from transportation related activities in ways that would not have been possible through incremental increases in fuel economy standards during the time period under study. H2: Sustainable expansion of the level of blending beyond E20 is dependent upon simultaneous intervention across all three interdependent constraints identified as necessary to achieve blending at high levels: The ability of the existing vehicle fleet to operate using higher concentrations of ethanol than E10; the availability of sufficient amounts of sustainable feedstocks that are suitable for conversion into alcohol for use in transportation fuels; and mechanisms for farmers to receive reasonable incomes from their production of biofuels crops.

The rest of this article is divided into the following sections. In section two, we will review the EBP Program's policy structure. The first part of that section will cover the EBP program's legislative history starting at the time it was established by the national policy on biofuels (2018) through to its extension to allow for a larger number of blends up to the end of June 2026. In section three, we will apply the 4E framework to quantify results for all dimensions of analysis. In section four, we will analyze changes in feedstocks and the structural changes occurring in India's evolving biofuel feedstock base. We will examine how these changes have influenced, or will influence, India's ability to expand beyond E20. Some of those factors include the need for vehicles to be compatible with E85 and other ethanol fuels, which can be blended at different ethanol percentages, and the development of infrastructure that supports the use of flexible-fuel vehicles. In section five, we will make policy recommendations based upon our analysis. Finally, section five presents the conclusions and policy recommendations.

2. Materials and methods

2.1. Research design

This study uses a combination of secondary data analysis and policy document reviews to assess the performance of India's ethanol-blending program across a variety of measures. No original data were collected from first-hand sources. The decision to use these methodologies is consistent with the nature of the research question: Because the program's performance has been documented in official government data, parliamentary records, and technical documentation, there is sufficient detail in those reports to allow for both qualitative and quantitative evaluation. Secondary data analysis is a commonly employed methodology in energy policy studies and is consistent with the analytical focus of this Journal. By using this methodology, comparisons can be systematically made across ESYs and across goals/objectives of the program that would be complicated or confounded by survey responses if it were used to evaluate a program implemented at the national level [8,11,12].

2.2. The 4E analytical framework

The research uses an integrated, four-dimensional approach to analyze program outputs by grouping them into the categories of Energy Security, Environment, Economics, and Equity. These dimensions represent the different types of policy goals and outcomes that each output represents. Energy security is concerned with reducing India's crude oil imports and the accompanying foreign exchange loss. For every liter of ethanol generated through domestic production, it reduces the amount of crude oil required for imports. As such, through the years of ESY 2014–15 to May 2026, a total of about 31 million metric tons of crude oil was substituted [13]. The environmental dimension examines both the reductions in lifecycle greenhouse gases as well as tailpipe emissions. This includes reductions in carbon monoxide (CO), hydrocarbons (HC), and net CO_2 throughout the entire life cycle of a fuel [14,15]. The economic dimension encompasses all farmer incomes, rural capital circulation, and distillery investments, which have been quantified as a cumulative payment of over Rs. 162,000 crores to farmers and suppliers since ESY 2014–15 [13]. The equitable distribution dimension asks how program benefits are shared among the three main groups: Smallholder sugarcane producers, cooperative sugar mills, and large organized distilleries.

This framework works well for multi-objective biofuels policy evaluations, as the Indian Program has never been based on a single objective. The 4E framework does not allow any one dimension to overshadow the others, thereby enabling the discovery of contradictions (for example,) between stated objectives of energy security and the equitable distribution of benefits [11,16]. Its novelty lies in testing whether gains in one dimension coexist with constraints or distributional weaknesses in the others, using a common evidence base.

2.3. Data sources

The research draws upon five categories of source materials. Parliamentary documentation from the Sansad Portal (Unstarred Questions) that are Ministerially verified includes: Ministers personally guarantee the accuracy of their responses to questions posed by both the Lok Sabha and the Rajya Sabha [5–7]. Thus, they can be treated as official statistics. Official press releases from the Ministry of Petroleum & Natural Gas, NITI Aayog, and the Ministry of Consumer Affairs, Food & Public Distribution (via the Press Information Bureau) contain aggregate performance information and policy announcements [13,17,18]. The NITI Aayog's road map for ethanol blending in India 2020–25 [1] will serve as a foundation for assessing performance against an established target. BIS notifications documenting changes to fuel specifications, including the BIS notification dated 14 May 2026 for IS 19850: 2026 (E22–E30 blends) [13], provide the supply context for our analysis. The literature referenced includes peer-reviewed sources that provide context for claims regarding lifecycle assessment and feedstock conversion dynamics [19,20].

2.4. Analytical approach

When similar statistical data from different types of sources appear to be consistent with one another, it is assumed that the most current government response is the authoritative one, because responses to parliament go through ministerial review and represent the most up-to-date information available at the administrative level. The use of triangulation among all three categories of sources cross-validated important data: Although PIB releases (volume data) [13] were independent of parliamentary responses (volume data) [5,6], these two sets of data support each other in their depiction of trend over time and thereby increase the degree of confidence that can be placed in the reported data. Sources were retained when they provided a defined ESY, unit, reporting date, and identifiable issuing authority; peer-reviewed studies were used for technical interpretation rather than to overwrite official program totals. Conflicts were resolved by matching the reporting period and unit, then preferring the latest ministerially verified value. CAGR was calculated as (ending value / beginning value) ^ (1 / years)-1; Sen slope as the median of pairwise annual slopes; and HHI as the sum of squared feedstock percentage shares.

2.5. Limitations

Three limitations are acknowledged. Relying on government data may understate challenges encountered during program implementation at the ground level. Examples include supply chain disruptions, delayed payments to farmers, and localized shortages of feedstocks not reported as part of the aggregate reports from ministers. The public has no feedstock price data for ESY 2025–26. Thus, there is limited economic data for this year's supplies. There is no primary survey data for farmer income impacts. Therefore, the payment figure of Rs. 1.62 lakh crore [13] cannot be broken down based on farm size, cooperative membership, or region. The annual policy series is small and may exhibit serial dependence and structural breaks; consequently, the Mann-Kendall, Sen slope, and Spearman results are interpreted as descriptive trend evidence rather than causal estimates. HHI measures feedstock concentration, not competition among suppliers or resilience by itself.

3. Key policy developments and empirical outcomes

3.1. Evolution of the EBP programme architecture

India's ethanol blending program (EBP) has gone through several legislative and administrative-driven policy changes over a period of twenty-plus years. Each new iteration reflected on the shortcomings of previous iterations and therefore demonstrated an increasingly bold vision for national biofuels policy. Initially in 2003, the EBP was formally launched as a five percent ethanol blend for nine states and four union territories; this provided an initial model for how state-level coordination would occur among sugar mills, distilleries, and Oil Marketing Companies (OMCs). In the end, the original design of the program had very limited supply elasticity, and the various purchasing methods were highly decentralized, which resulted in the mandated levels being met infrequently [11,16,21].

The national policy on biofuels of 2009 offered a wider view, in that it set out an indicative target of 20 % biofuels blending by 2017 and stressed that the program would utilize non-food feedstocks to protect the program from food security issues. The 2017 target was never met due to a lack of adequate distillation capacity and the limited feedstock definition; however, the national policy provided a normative foundation for future action. In 2018, a new structural configuration occurred when the government released the national policy on biofuels 2018 (NPB 2018). NPB 2018 increased the number of acceptable feedstocks into the biofuels system by including surplus food crops, and revised the E20 blending target to 2030. The key function of NPB 2018 was to create the National Biofuel Coordination Committee (NBCC) under the Ministry of Petroleum and Natural Gas (MoPNG) as the top-level Inter-Ministerial Coordinating Body, and Oil Marketing Companies (OMCs) were assigned responsibility for all of the operational aspects of the biofuels program, including sourcing of feedstocks, blending and logistics for distributing blended fuels [11,21,22].

In June 2021, there was a significant increase in momentum when the NITI Aayog, together with MoPNG, released a comprehensive plan to project a total ethanol demand of 1016 crore liters once 100 % of E20 is deployed and to accelerate the timeline to be achieved by 2025–26 [1]. The above-mentioned report was a policy framework to guide the next phases of growth. The E10 blend was rolled out in the entire mainland of India in April of 2022, and amendments were made to NPB 2018 in the same time frame to formalize the accelerated E20 timeline [5]. The E20 deadline was met by December 2025, and by early 2026, all of India's mainland Oil Marketing Companies (OMCs) had switched to selling E20 [7]. The regulatory border now extends well past E20 as the BIS has just issued IS 19850: 2026, which outlines the specifications for E22, E25, E27, and E30 blends of fuel [13], and on 10 June 2026 the government announced that it would extend its previously announced exemption from excise tax for these higher blends so that consumers are not taxed twice on the ethanol portion [13]. The NBCC continues to play a coordinating role in ensuring this pace of progress, bringing stakeholders from agriculture, food processing, petroleum, and finance into common working forums. **Table 1** and **Figure 1** showcase these developments.

Table 1. Key policy and regulatory milestones in India's ethanol blended petrol programme (2003–2026).

Year	Policy / milestone	Key provision	Implementing body
2003	EBP Programme launch	5 % blending mandate; 9 states and 4 UTs from January 2003	MoPNG / OMCs
2009	National Policy on Biofuels 2009	Indicative 20 % target by 2017; non-food feedstock emphasis; NBCC established	MNRE / NBCC
2018	National Policy on Biofuels 2018	20 % by 2030; food grain feedstocks permitted; NBCC moved under MoPNG	MoPNG / NBCC
June 2021	NITI Aayog Roadmap	Target advanced to 2025–2026; 1016 Cr L demand at E20; E10 by April 2022	NITI Aayog / MoPNG
April 2022	E10 pan-India rollout	E10 petrol available at all OMC outlets nationally	MoPNG / IOC / BPCL / HPCL
2022	NPB 2018 Amendment	E20 target formally advanced to 2025–2026; expanded feedstock permissions	MoPNG / NBCC
April 2023	E20 vehicle compatibility mandate	New vehicle models required to be E20 compatible	MoPNG / MoRTH
December 2025	E20 target achieved	20 % blending achieved nationally; all mainland OMC outlets dispensing E20	MoPNG / OMCs
May 2026	BIS IS 19850: 2026 issued	Technical specifications for E22 / E25 / E27 / E30 ethanol-blended petrol	Bureau of Indian Standards
10 June 2026	Excise duty waiver E22–E30	Waiver notified to prevent double levy on higher blend petrol	Ministry of Finance / MoPNG
Target: December 2027	FFV retail outlet rollout	500 FFV outlets by December 2026; 5000 by December 2027 (advisory)	MoPNG / OMCs

Sources: NITI Aayog / MoPNG [1]; National Policy and amendment sources [11,21,22]; MoPNG, BIS and parliamentary records [5–7,13,18]

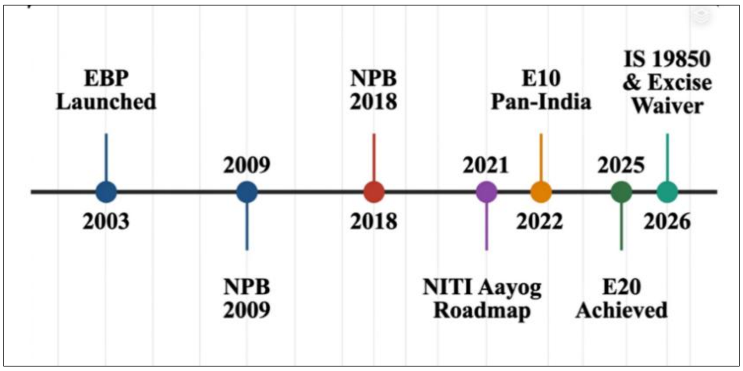

Figure 1. Chronological policy milestones in India's ethanol blended petrol programme, 2003–2026.

Sources: Authors' chronology from NITI Aayog / MoPNG [1], national-policy sources [11,21,22], and MoPNG / BIS / parliamentary records [5–7,13,18]

3.2. Blending targets and achieved performance

The overall volume trends for the EBP program have shown some of the most successful examples of supply-side scale-up in India's energy industry. In the fiscal year 2019–20 (ESY), the total blended volume was 173.03 crore liters. This corresponds to a blending percentage of 5.00 % [6]. From this point forward, the program experienced rapid growth: In FY 2020–21 (ESY), the total blended volume was approximately 302.40 crore liters, representing a blending percentage of 8.10 %. Although it missed its goal of reaching an 8.50 % blending percentage, it met its blending percentage goal by less than half of one percent [5,6]; FY 2021–22 (ESY) saw an increase to 408.09 crore liters blended at a rate of 10.02 %, or slightly above its goal of 10.00 % [5,6]; and FY 2022–23 (ESY) showed further increases in both volume (to approximately 506.40 crore liters blended) and blending percentage (to 12.06 %) as well as achieving its goal of being over 10.00 % [5,6]. The trend has also continued in FY 2023–24 (ESY); at that time, 672.49 crore liters were blended at a blending percentage of 14.60 % [5,6], and in FY 2024–25, more than 1,000 crore liters were blended at a blending percentage of 19.24 % [5]. On 15 December 2025, the E20 threshold was officially passed [7]. Early in 2026, all retail locations in mainland India would offer E20 fuels [7]. A yearly listing of volumes and blending percentages is provided in **Table 2**.

Table 2. Year-wise performance of India's ethanol blended petrol (EBP) pogramme.

ESY	Ethanol spplied (Crore L)	Blending ahieved (%)	Target (%)	Key milestone
2013–2014	38.00	~1.5	Indicative	EBP operational; fragmented supply
2019–2020	173.03	5.00	Indicative	EBP scaled nationally
2020–2021	302.40	8.10	8.5	Highest blending level at that point
2021–2022	408.09	10.02	10.0	E10 target achieved ahead of schedule
2022–2023	506.40	12.06	Indicative	NPB 2018 amended; E20 formally advanced
2023–2024	672.49	14.60	Indicative	E20 rollout commenced at select outlets
2024–2025	>1000.00	19.24	Indicative	E20 pan-India; near-target performance
2025–2026	Accelerated rollout	20.00 (December 2025)	20.0	E20 achieved; IS 19850: 2026 issued

Sources: Parliamentary and MoPNG programme statistics [5–7]; targets from NITI Aayog / MoPNG [1].

Three types of policy tools were behind the transition from stagnation to long-term growth. First, Long-Term Off-Take Agreements (LTOAs) between Oil Marketing Companies (OMCs) and distilleries removed uncertainty about demand, thereby enabling investments in distilling capacity over time. Second, the interest subsidy scheme under the Ministry of Petroleum & Natural Gas (MoPNG) provided cheap loans to the distilleries, removing the capital cost constraint on the part of sugar mills wanting to develop or expand their own ethanol production unit. Third, an administered pricing mechanism based upon the type of feedstock and annual revision by the cabinet ensured that the required level of price certainty existed for the long term capacity building. Therefore, the combination of assured off-take, subsidized capital, and stable prices formed a comprehensive infrastructure for investment promotion which was missing from previous stages of the program [1,18,23–25]. **Table 2** and **Figure 2** present these initiatives.

3.3. Energy security and economic outcomes

The large-scale economic impacts from scaling up the EBP program can be measured in several areas. Foreign Exchange Savings were generated by the ESB program from FY 2015 through May 2026, exceeding Rs. 191,000 crores as domestically produced ethanol was substituted for imported crude oil [13]. The amount of crude oil physically replaced during this time frame was approximately 31 million metric tons [13], which provides context for India's import dependency and the strategic value of domestic biofuels. At the current levels of E20 established, the program is estimated to generate an additional $4 billion annually in foreign exchange savings, or about Rs. 30,000 crore [1]. This represents a direct reduction in the Current Account Deficit (CAD) related to petroleum imports and reduces exposure to International Crude Price Volatility.

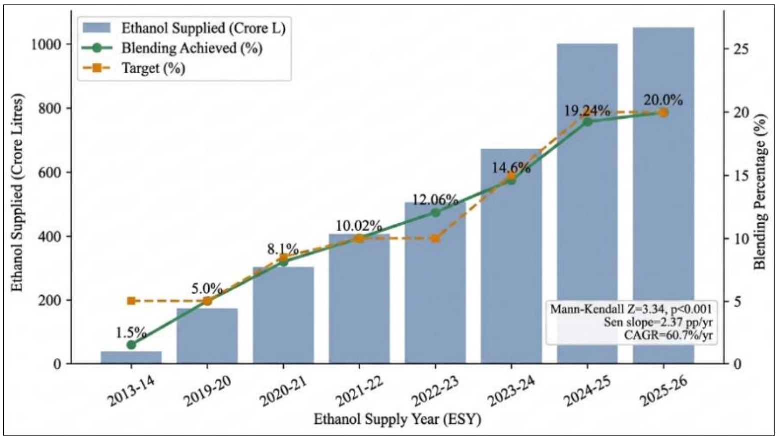

Figure 2. Ethanol supply volume and blending trajectory, ESY 2013–2014 to 2025–2026.

Left axis: Total ethanol supplied to OMCs (crore litres). Right axis: National average blending percentage achieved and official target. Mann-Kendall trend test: $Z = 3.34$, $p < 0.001$. Sen slope = 2.37 percentage points per year. CAGR of ethanol supply = at least 34.7 % per year.
Source: Authors' calculations from the annual values in **Table 2** [1,5–7]; 2025–2026 volume is not used in CAGR because no numeric volume is reported.

The program has produced substantial income inflows into the domestic agriculture economy. Total payments to farmers and ethanol producers from ESY 2014–15 to May 2026 are estimated at over Rs. 1.62 lakh crores [13], an amount that represents the program's impact on monetizing agricultural surpluses as well as, notably, surplus sugar and spoiled grain supplies that would have depressed farm gate prices or required state-supported storage for damaged foods. In describing this structural change, the Government identified it as a new relationship referred to as "Annadata to Urjadata" (from food supplier to energy supplier) to describe the new role of the agricultural sector in the energy supply chain [23]. Correspondingly, installed distillation capacity also grew: It was 1713 crore liters annually by early 2025 [18], of which 242 sugar mills operating distilleries accounted for 788 crore liters annually [26]. This decentralized production system, based in major sugar-producing states, provides a form of decentralized energy generation facility that has significant regional economic multiplier effects.

Procurement pricing for ESY 2024–25 established the price of C-Heavy Molasses (CHM) ethanol at Rs. 57.97 per liter compared to last year's price of Rs. 56.58 per liter [18]. By doing so, it maintained sufficient profit margins for suppliers, which will continue to enable them to invest in their businesses. In addition, the program as a whole adheres to an import substitution model, whereby, rather than transferring domestic capital through petroleum exports to foreign countries, such capital remains within the country and generates income for farmers, distilleries, and logistics companies. As well as aligning with the Atmanirbhar Bharat economic doctrine (self-reliant India), the distribution of benefits across many constituencies, including sugarcane farmers, distillery workers, and refinery employees, has enhanced the political sustainability of the program. **Table 3** states the economic and energy security outcomes of India's EBP program.

Table 3. Economic and energy security outcomes of India's EBP programme (ESY 2014–15 to May 2026).

Indicator	Value	Unit	Source
Foreign exchange savings (cumulative)	More than Rs. 1.91 lakh crore	INR lakh crore	PIB PRID 2271798, MoPNG, 10 June 2026 [13]
Crude oil import substitution (cumulative)	Approx. 31 million metric tons	million metric tons	PIB PRID 2271798, MoPNG, 10 June 2026 [13]
Payments to farmers and suppliers (cumulative)	Rs. 1.62 lakh crore	INR lakh crore	PIB PRID 2271798, MoPNG, 10 June 2026 [13]
Annual forex savings at full E20	US $4 billion (Rs. 30,000 crore)	USD billion / INR crore	NITI Aayog Roadmap 2021 [1]
Installed distillation capacity (early 2025)	1713 crore litres per annum	Crore litres/year	PIB PRID 2097305, MoPNG, 03 Jane 2025 [18]
Sugar mill distilleries (operational)	242 mills; 788 Cr L capacity	Number; crore litres/year	Lok Sabha Committee Report 2024 [26]
CHM ethanol ex-mill price (ESY 2024–25)	Rs. 57.97 per litre	INR per litre	PIB PRID 2097305, MoPNG, 03 Jane 2025 [18]

Sources: NITI Aayog / MoPNG and official programme releases [1,13,18,26].

3.4. Environmental and emissions outcomes

The environmental justification for ethanol blending can be based on two distinct yet related mechanisms: The reduction of criteria pollutants during combustion and the reduction of lifecycle greenhouse gas emissions relative to other fossil fuels. With respect to the former, E20 blends create 50 % less carbon monoxide (CO) in two-wheelers than neat petrol, while there was a 30 % decrease in carbon monoxide observed in four-wheelers [14]. There were 20 % fewer hydrocarbon (HC) emissions produced in both two-wheelers and passenger vehicles when they operated using E20 [14]. These decreases were due to the role of ethanol as an oxygenate: It has an oxygen atom within its chemical makeup, which causes more complete combustion of the hydrocarbon components of the blend, decreasing the number of unburned hydrocarbon products formed during combustion and thus resulting in decreased levels of carbon monoxide and unburned hydrocarbon products that affect urban air quality. For India, where the number of two-wheelers is large and urban particulate matter remains a public health issue, this reduces per-vehicle pollution, yielding additional exposure benefits for a larger population.

Beginning with the lifecycle emissions of sugarcane-derived ethanol, which have been shown to be 65 % lower than those of petrol on a lifecycle emissions basis (and 50 % lower for maize) [15]; these estimates include agricultural inputs, processing energy, and transportation. Therefore, they provide a more comprehensive view of net climate benefits than just analyzing emissions from the combustion stage. The program-level emission avoidance totals approximately 20,000 tons CO_2 / crore liters of ethanol blended [27]. Based on the cumulative volume of ethanol produced, as indicated by ESY 2014–15 and through May 2026 [13], we can estimate an overall reduction in CO_2 of approximately 93.1 million metric tons, a significant contribution to India's nationally determined contributions under the Paris Agreement. Annual sustained operation at E20 will produce annual CO_2 reductions of 27 million metric tons / year [1]. **Table 4** and **Figures 3a**, **b** summarizes the environmental and emission benefits of ethanol blending in India.

Table 4. Environmental and emission benefits of ethanol blending in India.

Parameter	Blend level	Reduction / benefit	Source
CO reduction vs neat petrol (two-wheelers)	E20	50 %	Lok Sabha Q2074, 2024 [14]
CO reduction vs neat petrol (four-wheelers)	E20	30 %	Lok Sabha Q2074, 2024 [14]
HC reduction vs neat petrol (both categories)	E20	20 %	Lok Sabha Q2074, 2024 [14]
Lifecycle GHG reduction vs petrol (sugarcane ethanol)	E20	65 %	NITI Aayog study; PIB PRID 2155558 [15]
Lifecycle GHG reduction vs petrol (maize ethanol)	E20	50 %	NITI Aayog study; PIB PRID 2155558 [15]
CO2 averted per crore litre ethanol blended	All blends	~20,000 tons	NITI Aayog / PIB Factsheet October 2021 [27]
Cumulative net CO_2 reduction (ESY 2014–15 to May 2026)	All blends	~931 lakh metric tons	PIB PRID 2271798, MoPNG June 2026 [13]
Projected annual CO_2 reduction at full E20	E20	27 million tons / year	NITI Aayog Roadmap 2021 [1]

Sources: NITI Aayog / MoPNG and parliamentary / official emissions evidence [1,13–15,27].

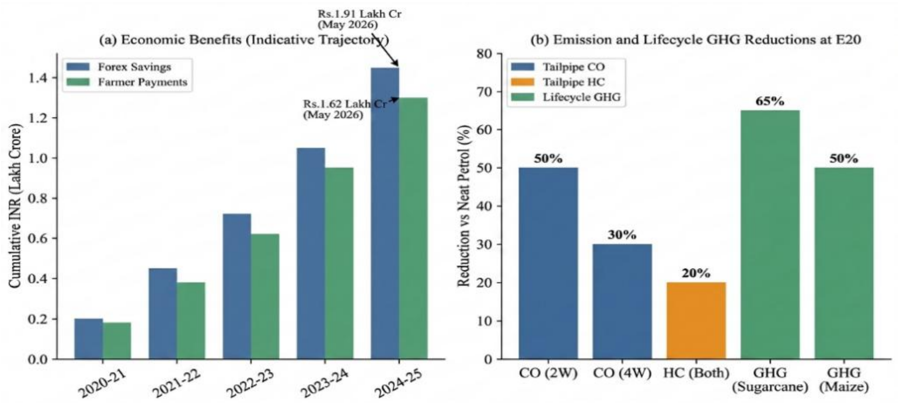

Figure 3. (a) Indicative cumulative trajectory of forex savings and farmer payments under India's EBP Programme (2020–2021 to 2024–2025), anchored to confirmed cumulative totals of Rs. 1.91 lakh crore and Rs. 1.62 lakh crore respectively as of May 2026. **(b)** Percentage reductions in tailpipe CO and HC at E20 versus neat petrol, and lifecycle GHG reductions for sugarcane-based and maize-based ethanol versus petrol.

Source: Authors' indicative reconstruction from confirmed cumulative endpoints [13] and reported emissions factors [14,15]; intermediate cumulative values are derived, not official annual observations.

3.5. Feedstock landscape and supply chain

The composition of India's ethanol feedstock base has undergone significant changes since the beginning of the EBP Program, when C-Heavy molasses was the primary feedstock. As of 28 February 2025, within ESY 2024–25, it is evident that the feedstock supply base has become significantly diverse, although there are still some embryonic developments to occur towards 2G feedstocks [6]. The majority of the sugarcane-derived ethanol feedstocks were B-Heavy Molasses at 148.81 crore liters, C-Heavy molasses at 15.94 crore liters, while the remainder came directly from sugarcane juice, syrup, or sugar at 2.63 crore liters. This resulted in a total of

167.38 crore liters coming through the sugarcane route, accounting for about 55 % of the partial-year volume reported by ESY 2024–25 [6]. Grain-based routes generated 138.40 crore liters of ethanol, accounting for about 45 %, with 119.45 crore liters derived from maize and 18.95 crore liters from damaged food grains [6]. A total of 305.78 crore liters is a partial-year result, as ESY 2024–25 recorded over 1000 crore liters [5,19].

Beginning with the transition from C-heavy to B-heavy molasses and then incorporating grain feeds into its feedstock mix was a very intentional government response to the structural limitations of relying too heavily on a single source. The availability of C-heavy molasses (and thus the ability to produce sugar) depends on monsoon rains, thereby creating vulnerability in the country's sugar-producing sector. With organizations like NAFED and NCCF purchasing maize at MSP, the program has now become linked to a broader geographic base of agriculture and has provided another revenue-enhancement option for maize producers. Diversifying the ethanol feedstock source reduces supply-side risk and mitigates variability within the sugar sector [6,28–30].

The most glaring omission in the feedstock picture is the lack of 2G ethanol. No 2G ethanol supply was recorded during the time frame represented by the OMC pipeline data [6]. The IOC Panipat facility, which processes about two lakh tons of rice straw each year to produce an estimated 100 kilo-liters of ethanol daily, with a production volume of roughly 3 crore liters per year [31–33], represents the current status of 2 G commercialization. While the Panipat facility shows that it is technically possible to make lignocellulose ethanol from agricultural waste such as paralic (paddy straw), whose field fires contribute heavily to seasonally high levels of particulate matter (PM10) and PM2.5 in north India, this does not currently contribute to blending volumes nationwide. The JI-VAN Yojana, which was extended through 2025–2026, is expected to help expedite growth in 2G capacity additions [34,35]; thus, how far India's feedstock base will be able to expand into other forms of lignocellulosic sources will depend on its results. In **Table 5**, we show feedstock-wise ethanol supply to OMCs.

Table 5. Feedstock-wise ethanol supply to OMCs, ESY 2024–2025 (snapshot as of 28 February 2025).

Feedstock category	Volume (Crore L)	Share (%)	Policy notes	Water / energy / GHG profile	Beneficiary and income evidence
C-Heavy Molasses	15.94	~5.2	Lowest-yield molasses route; terminal sugar extraction	Water-intensive cane route; bagasse can supply process heat; lifecycle results depend on allocation.	Cane growers, mills and distilleries benefit; no public split of farm-gate income or net gain.
B-Heavy Molasses	148.81	~48.7	Intermediate molasses; dominant sugarcane-route source	Water-intensive cane route; bagasse cogeneration can reduce fossil process energy.	Cane growers, mills and distilleries benefit; the administered ethanol price is not the grower price.
Sugarcane Juice / Syrup / Sugar	2.63	~0.9	Permitted in surplus cane seasons only	Highest direct cane demand; irrigation and cultivation energy are region-specific.	Cane growers and integrated processors benefit; recipient counts and net farm gains are unavailable.

Table 5. (*Continued*).

Feedstock category	Volume (Crore L)	Share (%)	Policy notes	Water / energy / GHG profile	Beneficiary and income evidence
Sugarcane Routes Combined	167.38	~54.8	Dominant category; monsoon-linked supply risk	Reported lifecycle GHG reduction is about 65 % vs petrol, but water and irrigation-energy burdens vary.	Aggregate payments cannot be allocated among growers, cooperative / integrated mills and distilleries [13].
Damaged Food Grains (DFG)	18.95	~6.2	FCI stocks unfit for consumption; no food chain impact	Avoids edible grain use; drying, transport and distillation still require energy; route-specific Indian GHG data are limited.	Grain suppliers and distilleries benefit; beneficiary numbers and income gains are not reported.
Maize	119.45	~39.1	NAFED / NCCF MSP procurement; rapid structural scale-up	Regional water and farm-energy use vary; distillation is energy intensive; reported lifecycle GHG reduction is about 50 % vs petrol [15].	Maize growers, aggregators and grain distilleries benefit; ethanol-attributable farm-gate income is not reported.
Grain Routes Combined	138.40	~45.3	Near parity with sugarcane; structural supply shift	Water, process-energy and GHG performance depend on the grain mix and production region [15].	Aggregate data do not separate farmers, aggregators, processors or regional gains.
2G / Lignocellulosic Sources	0.00	0.0	IOC Panipat plant not yet in OMC supply pipeline	Avoids dedicated crop cultivation and may reduce residue burning; pretreatment and conversion energy remain material [32,33].	Potential residue suppliers and 2G processors; no realised OMC-linked farmer income in the snapshot.
Snapshot Total	305.78	100.0	Partial ESY 2024–25 data; full year exceeds 1000 Cr L	The snapshot cannot yield one sustainability average because route-specific data and system boundaries differ.	The Rs. 1.62 lakh crore total cannot be disaggregated by feedstock, farmer category or region [13].

Note: Percentage shares calculated from snapshot totals.
Source: Authors' calculations from the OMC feedstock snapshot [6]; percentage shares are derived from the reported total.
Additional sustainability sources: [15,32,33]. Income effects are reported as evidence availability; the Rs. 1.62 lakh crore aggregate cannot be allocated by feedstock or farmer category [13].

Figure 4 shows the feedstock composition of ethanol supplied to OMCs.

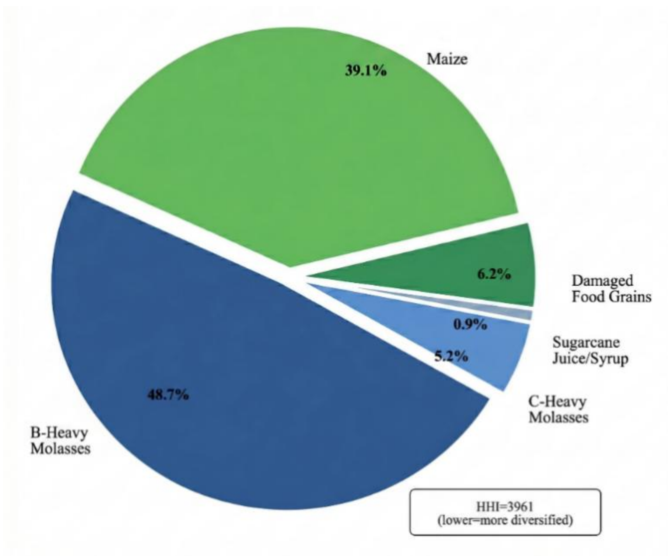

Figure 4. Feedstock composition of ethanol supplied to OMCs, ESY 2024–25 snapshot (28 February 2025; total 305.78 crore litres). HHI of feedstock

concentration = 3961, versus molasses-only baseline of 10000, confirming structural diversification.

Source: Authors' calculations from **Table 5** data [6]; HHI is derived from the reported feedstock shares.

3.6. Statistical analysis of programme outcomes

The Mann-Kendall (nonparametric) trend test was conducted on the percent blended nationally with ethanol from ESY 2013–14 through 2025–26. This results in the test statistic $S = 28.0$, standardized as $Z = 3.340$, and a p-value less than 0.001, confirming a statistically significant increasing trend in the percent of gasoline blended with ethanol [5,7]. Because the data are a time series where we can't assume they follow a normal distribution, this test is the most commonly used non-parametric method for determining if there exists an overall, monotonic trend over time in a set of numbers, which makes it well-suited for use on a policy-driven dataset like ours that has had numerous structural changes [8,11]. The Sen slope (a measure of the average annual rate of increase) calculates the median rate of change in the percent blended with ethanol at 2.37 percentage points per year; therefore, the increases were consistently across time and based upon a structurally stable policy path rather than some episodes of rapid growth [9,12]. The inference assumes independent observations and a monotonic tendency; with only eight reported annual observations, its p-value and slope should not be read as proof of an invariant long-run process.

The average compound rate at which ethanol was supplied to Oil Marketing Companies (OMCs) over the same time frame is at least 34.7 %, which is among the fastest recorded, serving as an example of the development of an energy feedstock in a developing country energy transition program [36,37]. A Spearman rank order correlation coefficient between the amount of ethanol supplied each year and the percentage of ethanol blended into gasoline yielded a value of 1.000 ($p < 0.001$). The high positive correlation indicates that the increase in ethanol supply is the primary factor driving higher blending percentages, rather than a decrease in petroleum demand [6,28]. This conclusion can be used to inform policy; i.e., any future blending requirements above E20 will ultimately depend on increasing ethanol supply and, therefore, by definition, are supply-limited rather than demand-limited. Therefore, this paper continues to support prioritizing second-generation ethanol production and diversifying feedstocks in its recommendations [38,39].

A Herfindahl-Hirschman Index (HHI) calculated from feedstock supply shares for ESY 2024–25 shows an overall value of 3961 relative to a hypothetical "base case" of 10,000 when using a pure molasses feedstock source. This equates to a 60 percent decrease in concentration levels, demonstrating that policy-driven efforts to incorporate grain-based routes into the Indian ethanol supply system have greatly increased the resilience of this critical supply chain component [6,40]. In addition, the HHI remains above 2500, a level commonly considered highly concentrated; therefore, while there are significant improvements over previous years, the ethanol supply remains vulnerable to future disruptions arising from agricultural supply chain events [41,42]. Due to the fact that all 2nd Generation (2G) Ethanol sources are absent from the OMC Pipeline, no additional improvement to the HHI can occur unless the government provides investment capital to support commercialization of 2G Ethanol technologies [38,43]

Collectively, these statistics provide descriptive evidence of sustained program scale-up and feedstock diversification, but they do not independently establish environmental causality. Additionally, they provide supporting evidence for H2 that structural constraints on the supply side (as evidenced by Spearman correlations and HHI) necessitate simultaneous actions to achieve the E22–E30 objectives through feedstock diversification, 2nd-generation (2G) commercialization, and compatible vehicle fleets [2,36,39].

4. Discussion

4.1. Policy architecture assessment and H1 evaluation

Beginning with energy security, there is no question about the success. With over 31 million metric tons of crude oil substituted as of May 2026 for ethanol, and nearly Rs. 1.9 lakh crores saved in foreign exchange through May 2026 alone (a total of nearly Rs. 2.7 Lakh Crore) from an original level of around 1.5 percent in ESY 2013–14 [5], to reach 14.60 percent by ESY 2023–24 [5,6], these results represent actual documented substitutions of crude oil imports. This record represents real, measured reductions in the country's exposure to imported crude oil. The direction of this trend is in and of itself a measure of the success of the government's policies. Thus, based upon energy security, H1 is supported.

On the environmental dimension, there is confirmation of a 50 percent reduction in carbon monoxide emissions and a 20 percent reduction in hydrocarbon emissions for two-wheelers using E20 compared to petrol [14] and the cumulative avoidance of approximately 931 lakh metric tons of CO_2 since ESY 2014–15 [13]; this provides confirmation that the program has delivered measurable co-benefits on the environmental dimension. Passive fuel efficiency standards operating alone would not have been able to produce equivalent fleet-level emission reductions over the same time frame without simultaneous blending mandates.

The economic-equity outcome remains more ambiguous. The Rs. 1.62 lakh crore paid to farmers and suppliers since ESY 2014–15 [13] is an aggregate transaction value covering smallholder sugarcane growers, cooperative mills, large integrated sugar mills, distilleries and other suppliers. It cannot, by itself, establish how much reached small farmers or whether benefits were distributed fairly. The published figure is not disaggregated by recipient category, farm size, region, crop, payment timing or farm-gate price; nor does it distinguish gross receipts from net gains after cultivation, transport and input costs. Consequently, a large aggregate payment can coexist with delayed payments, unequal bargaining power and concentration of value in processing segments. In the absence of recipient-level or representative farm-income data, the program's distributional effect cannot be independently verified. H1 is therefore supported for aggregate economic mobilization, but receives only partial and provisional support on equity. A stronger fairness claim requires regular disclosure of farm-gate payments and beneficiary distributions by farm size, region and supply-chain category. Distribution may also differ by region, farm size, feedstock route, mill organization and distillery ownership, but current aggregate reporting does not permit those comparisons.

Institutional coordination in this case was facilitated through the multi-ministerial architecture that included; the Ministry of Petroleum & Natural Gas (MOP&NG), the Ministry of Finance (MOF), the Bureau of Indian Standards (BIS), the Ministry of Road Transport & Highways (MoRTH), the Ministry of New and Renewable Energy (MNRE) and the Ministry of Consumer Affairs, Food and Public Distribution (MCA&FPD). This provides an illustrative example of long-term interagency cooperation among ministries related to India's energy sector. The National Bio-fuel Coordination Committee operates under MOP&NG as the main national forum for discussion on biofuels and serves as the principal vehicle for coordinating biofuel development over time. Additionally, it has enabled the government to respond swiftly to changes in the ethanol market by modifying the criteria for determining eligible feedstocks and making price adjustments administratively. Therefore, our assessment of H1 is positive, subject to the aforementioned caveats regarding equity [1,17,11,44].

4.2. Energy security: Depth and structural limits

The ethanol blending program will have achieved quantifiable energy security gains; however, these gains should be viewed as limited in the context of the structural challenges it faces. A fiscal benefit of the foreign exchange savings of U.S. $4 billion per year at full E20 is clearly important to the country's economy. An added element of reliability for India's chronically strained current account resulting from petroleum imports would be the annual savings of U.S. $4 billion. This equates to a cumulative total of 31 million metric tons of crude oil substitutes through the ethanol program alone, which is greater than any other demand-side conservation programs for energy have provided over the last decade [1,2,13].

Although the structural characteristics of India's oil import dependence have not changed, ethanol substitution under the current 1G-dominant supply structure is a marginal adjustment to a very high level of total imports. Therefore, due to the sugarcane feedstock route, which accounts for about 55 % of the ESY 2024–25 blending volumes [6], there exists a particular type of systemic vulnerability. Sugarcane is an irrigation-dependent crop that requires significant amounts of water, and its yield is closely related to the behavior of the southwest monsoons. When the monsoon performs poorly, it does two things: (i) reduces the amount of ethanol feedstock available; (ii) increases the cost of cane acquisition; and (iii) places upward pressure on sugar prices. Consequently, this programmatic model of ethanol adoption in India also inherits the risks associated with Indian agricultural production stemming from monsoon performance. In addition, a poor monsoon year will reduce blending volumes at the exact time when commodity price pressures increase fuel import costs.

The use of grain-based routes, which accounts for about 45 % of ESY 2024–25 volume and 119.45 crore liters of maize alone [6], provides partial diversification of these risks. Nevertheless, maize is an important agricultural feedstock, and, as such, large-scale diversion to biofuels has potential impacts on food systems that require ongoing monitoring [26,45]. Currently, there is no formal mechanism for coordination or information sharing between the forward markets commission (and/or state-level agricultural commodity marketing agencies) and the National Biofuel Coordination Committee regarding feedstock availability. Furthermore, the additional ethanol demand anticipated due to flex fuel vehicles, with a projected demand of over 312 crore liters of additional ethanol should the majority of new vehicles be flexing fuel vehicles [46], will likely increase pressure on feedstock supplies unless second generation ethanol can enter into the mainstream supply chain prior to the scaling up of flex fuel vehicle demand. The IOC Panipat 2G ethanol plant presently produces around 3 crore liters of ethanol annually from rice straw [32]. Therefore, at this output scale, the 2G component to meet the incremental demand of 312 crore liters would be negligible. Sustainability therefore depends jointly on regional water stress, food-feed-fuel competition, transport exposure and the speed at which the presently negligible 2G route becomes commercially material.

4.3. Environmental dimensions: Co-benefits and caveats

The environmental justification for the EBP is scientifically sound; however, before this program's environmental performance is fully endorsed in scientific discourse, multiple aspects of the existing official evidence will need to be critically evaluated [14,15,39,47,48].

Parliamentary documents cite reductions of 50 percent in CO and 20 percent in HC emissions for two-wheelers and passenger cars compared to neat petrol at E20, based on the road map of the National Institution for Transforming India (NITI) Aayog. These data are based upon technical estimates that were produced by measuring emissions through testing cycles using a controlled laboratory environment. Vehicles tested and the fuel blends used in such testing meet specific quality criteria. As such, the actual differences in real-world emissions of vehicles currently in operation will be vastly different than those reported. The Indian two-wheeled sector includes over 100 million carburetor-equipped vehicles, most of which have been in use beyond their original design life. Calibration of carburetors to deliver oxygenated fuels is suboptimal; moreover, field-level calibration of blended fuels at the point of sale may introduce additional variability that was not present during controlled testing. Therefore, the reported percentage emissions reductions provide directional guidance for future improvements, but do not represent average emissions characteristics of all vehicles within each class [14,15,49,50–52].

The NOx dimension remains insufficiently documented in official Indian reporting. International evidence indicates that NOx does not vary uniformly with ethanol concentration; outcomes depend on blend level, engine design and calibration, after-treatment conditions, driving cycle, and operating load. In Brazil, real-world portable-emissions testing of a flex-fuel vehicle found similar NOx emission factors for E27 and E85, but substantially higher values for E100, with strong sensitivity to vehicle power demand and traffic conditions [53]. In the United States, a review of E85 testing and certification data reported wide vehicle-to-vehicle variation: Average NOx reductions were observed for older Tier 1 flex-fuel vehicles, whereas the difference for Tier 2 vehicles was not statistically significant [54]. These findings caution against assuming either an automatic NOx benefit or an inevitable penalty from higher blends. The NITI Aayog roadmap [1] and subsequent parliamentary responses [14] do not provide fleet-specific NOx measurements for India. Before E22–E30 is scaled under BIS IS 19850: 2026 [13], independent testing should therefore cover legacy and current vehicles under laboratory and real-world conditions, with results reported by blend, vehicle technology and driving cycle.

The program's largest environmental claim at the system level is based on 65 % lifecycle GHG emissions savings for sugarcane ethanol compared with petrol, and 50 % for maize ethanol. Sugarcane and maize are both land-based crops, so their lifecycle GHG emissions savings will depend heavily on how land use is assumed in the lifecycle method. Specifically, if land that would have remained as natural vegetation (forest, wetlands, etc.) is converted into land used for the growing of additional sugarcane for ethanol, then this may offset some or all of the GHG emissions saved from producing the ethanol. There have been no systematic reports from government agencies regarding whether land currently being utilized to grow ethanol in India was previously cultivated or had remained uncultivated [15,39,42,55–57].

Field evidence also requires separating vehicle-use emissions from production-site impacts. Byrnihat's airshed has recorded particulate concentrations beyond its assessed carrying capacity and contains multiple industrial, traffic and dust sources; the available evidence does not justify attributing ambient pollution to ethanol production alone [58]. Distilleries should therefore be assessed against consent-specific stack and effluent limits through independent monitoring, while vehicles are assessed under Bharat Stage VI and real-world driving requirements. This preserves the documented lifecycle GHG and tailpipe CO / HC benefits while recognizing localized risks from boilers, fugitive dust, wastewater and transport.

The most widely recognized political environmental metric of the Government of India for the cumulative avoidance of nearly 931 lakh tons of CO2 emissions from ESY 2014–15 [13] is the program's most environmentally valuable metric. With a full blended E20 blend rate, an estimated 27 million tons of CO2 reductions per annum [1] is a real contribution to India's national emissions reduction plan. But the credibility of both numbers in peer-reviewed literature and international policy will depend on the public disclosure of a lifecycle methodology that can be independently verified by a third party. Commissioning an open, independent third-party lifecycle audit, with results presented in simple terms, will significantly enhance the program's international stature and its contribution to NDC accounting. Using rice straw as a feedstock [32] at the IOC Panipat 2nd Gen Plant has real local environmental value related to the issue of agricultural burning due to paralic (paddy straw) in Punjab and Haryana. However, at about 3 crore liters annually [32], it is a symbolic contribution to program-scale emission accounting.

4.4. Challenges to E22–E30 scaling: H2 assessment

Hypothesis two assumes that vehicle compatibility constraints, feedstock sustainability concerns, and farmer income equity (all of which are important) need to be resolved simultaneously for blending beyond E20 to be viable. The available evidence supports H2 on all three fronts and indicates that each type of constraint is structured to be interdependent with the other two; therefore, no single type of resolution can resolve the issue in a way that would allow the scale-up of blending [36,37,39].

The vehicle fleet compatibility constraint is the one with the most direct operational implications. From April 2023 onward, new vehicle standards require E20 compatibility. However, as of today (pre-2023), the majority of the fleet consists of older, non-compliant vehicles. As such, while transitioning to E25 and E30 blending ratios may be possible with flex-fuel vehicles, there is no requirement for manufacturers to build such vehicles. Therefore, in order to operate on multiple ethanol blends (e.g., E10–E85) without damaging engines or degrading fuel systems, FFVs require a unique architecture. There are currently plans to roll out 48 pilot stations to 500 by December 2026 and then to 5000 by December 2027 [46]. This is an aspirational goal for the infrastructure, and does not include a mandatory OEM production schedule for FFV’s or any official notice regarding fleet composition targets. During fleet turnover, clearly labeled parallel availability of a lower-ethanol petrol grade and E20 could protect legacy vehicles, although it would add retail storage and logistics costs. Any move toward E85 would require FFV calibration, ethanol-compatible tanks, hoses, injectors and seals, cold-start management, durability validation and dedicated storage and dispensing infrastructure [1,59,60].

The feedstock sustainability constraint is linked to the fleet demand projection. In addition, if fifty percent (50 %) of the new vehicles registered in the country are expected to be flexi-fuel vehicles (FFVs), then the additional ethanol required will exceed 312 crore liters. It is impossible for 1st generation (1G) technologies to meet this additional ethanol demand without either; expanding the cultivation and crushing of sugarcane significantly, thereby increasing the pressures on the availability of water and possibly affecting the price of food commodities, or by substantially increasing the utilization of grain based technologies, which as has been noted previously, would create an unpalatable scenario for food security concerns to be raised within parliamentary scrutiny. The extension of the JI-VAN Yojana in 2025–2026 [35] demonstrates a positive policy commitment to the commercialization of 2nd generation (2G) technologies. However, the funding amount allocated through viability gap funding and the long-term offtake contract structure established for commercial 2G producers have not been sufficiently articulated to allow an evaluation of whether commercial 2G producers can obtain financing on terms acceptable from a commercial standpoint.

The equity constraints are less apparent than other issues within the official discussions about the program’s long-term political feasibility. However, these constraints are also most impactful. The administered pricing system maintains distillery processing margins (the CHM ethanol price of Rs. 57.97 per liter in ESY 2024–25 [18]) serves as a minimum price that encourages investments in distillation equipment.

Early in 2025, India had an installed capacity for alcohol distillation of approximately 1713 crore liters per year [18]. In total, there were 242 sugar mills with distilleries, and they have a total capacity of 788 crore liters per year [26].

These mills have been primarily protected from market uncertainty regarding the off-take of their ethanol production. Sugarcane farm gate prices are currently controlled using the state-advised price mechanism and are therefore subject to state government jurisdiction and cannot be directed by the National Biofuel Coordination Committee.

Therefore, it is unknown what portion of the Rs. 1.62 lakh crore was paid directly to the growers, as opposed to retaining some amount at the mill level as profit or applying it toward outstanding cane arrears. The lack of available information on this issue alone represents another policy failure: The program will be unable to verify its key social equity claims until a transparent income-tracking method is developed and implemented, one that allows tracking of income at the grower level [13,22,30].

The confirmation of H2 has an immediate policy impact, as follows: A fleet mandate, without supporting fuel infrastructure investment (and thus operational viability), will be operationally ineffective; feedstock investment with no binding demand guarantee from a mandated FFV fleet will be commercially non-viable to private investors; and equity claims with no transparent income tracking are politically asserted yet empirically unverifiable. Therefore, all three constraints need to be simultaneously addressed by coordinated regulatory action rather than sequential interventions [36,37,39]

4.5. India's trajectory in global context

Brazil provides a useful comparator because its gradual flex-fuel-vehicle-led transition contrasts with India's compressed E10–E20 timetable.

India's ethanol-blended program (E22–E30) is framed in comparison to Brazil's Proalcool program (initiated in 1975), which achieved an average E27 blend standard for all vehicles sold in the country. To create this scenario, Brazil has employed a multi-pronged strategy, including compulsory flexible-fuel vehicle manufacturing since 2003; bringing sugarcane-based ethanol prices into price parity with gasoline through market competition; and vertical integration linking cane mills, distributors, and OEMs under a single regulatory umbrella and business model. A similar transition from mandated blending to a viable flexible fuel vehicle market in Brazil took 28 years of sustained political will, infrastructure investment, and incremental adjustments to its regulatory environment. India is attempting to make a comparable transition in one-tenth the time it took Brazil, moving from 1.5 % blending in ESY 2013 / 14 [5], to meeting a 20 % target in December 2025 [7] and announcing new post-E20 regulations in June 2026 [13]. **Table 6** gives the details.

The U.S. E15 waiver, established in 2022, provides an additional illustration of the lessons learned. A mature auto market with high per capita gasoline usage and strong OEM advocacy efforts were needed for an incremental increase of 5 % in the blended mandate ratio to be maintained through continued regulatory support: RFS point of obligation standards; warranties that protect consumers from the potential damage caused by using higher ethanol blends; investments made on behalf of retailers to develop infrastructure (e.g., pumps and tanks) capable of storing E15 /

E85 fuel; and a public education effort to reduce consumer concerns about travel distance limitations when using fuels containing added oxygenates [39,47].

The June 2026 Indian policy package, which includes the BIS IS 19850: 2026 Standard (for E22 through E30) and the extension of the exemption from excise duties to all of these blending ratios [13], is the appropriate first-step regulatory measure. The above-mentioned regulations establish both the product standards and tax incentives needed for the initial phase of the market formation process. However, in the absence of legally-binding obligations placed upon original equipment manufacturers (OEMs) by virtue of the Motor Vehicles Act or similar governmental statute for the manufacture of FFVs; public funding of a contractually assured 2G commercialization program which has clearly defined annual output requirements; and an auditable cultivators' income reporting system tied to payments made to those producers as documented in the program's database, the ambitions associated with E22–E30 fuels risk becoming overly complex regulatory systems devoid of practical implementation frameworks capable of supporting their sustainability.

Table 6. Vehicle compatibility and India-Brazil transition pathways.

Vehicle / stage	Compatible fuel	Key component or performance issue	Transition evidence
Pre-E10 gasoline vehicle	Petrol and low ethanol blends within manufacturer approval	Legacy elastomers, plastics, seals and calibration may not be validated for E20; misfuelling risk requires clear labels.	India's large legacy fleet makes an immediate single-grade transition more difficult [1].
E10-compatible vehicle	E10; higher blends only if approved	Higher oxygen content and lower heating value can affect calibration, fuel economy and material durability.	A lower-ethanol grade during turnover can protect non-E20 vehicles but increases retail complexity [1].
E20-compatible vehicle	E20	Indian testing found some elastomer/plastic deterioration and up to 6 % average fuel-economy loss, but no severe malfunction in tested vehicles [1].	New Indian models have been required to use E20-compatible materials from April 2023.
Flex-fuel vehicle	Multiple blends, potentially E20-E85/E100	Requires blend sensing, compatible fuel-system materials, recalibration, cold-start control and durability testing.	Brazil paired E27 with widespread FFVs and nationwide hydrous ethanol availability [59,60].
National strategy	India: Rapid E10-E20 progression; Brazil: Staged E27 / FFV system	Compatibility, warranties, labelling, storage and dispensing must develop with fuel availability.	Brazil tested E27.5/E30 before implementation; India should similarly validate legacy and current fleets before post-E20 scaling [1,59].

Sources: NITI Aayog/MoPNG vehicle-technology evidence [1]; Brazilian Ministry of Mines and Energy technical feasibility reports [59]; BNDES bioethanol review [60].

The new version of the national biofuels policy needs to make all three obligatory, not just goals. Similarly, the EBP Program's expected annual emission savings (CO_2) of 27 million tons by the time it reaches full E20 [1,50], as well as its development toward higher blends, should be formally connected to India's nationally determined contributions to account for emissions reductions in the context of the Paris Agreement. This will provide an internationally audited link between the nation's commitment to reducing greenhouse gas emissions through increased domestic blending and national greenhouse gas emissions reduction commitments.

4.6. Challenges in transition and in rapid transition

***Challenges in transition*:** Even where E20 has been technically validated, transition management remains distinct from fuel chemistry. India's on-road fleet contains vehicles certified for different blend limits; consumers need clear fuel-grade and compatibility information; OEMs and service networks need consistent parts and warranty guidance; and retailers need quality control, accurate labeling, and, if a lower-ethanol protection grade is retained, additional storage and logistics. Higher blends add cold-start, material compatibility, calibration, fuel economy, and durability requirements, while feedstock and second-generation infrastructure must scale without intensifying water, food, or feed-fuel pressures. These are significant coordination costs, but they do not by themselves demonstrate that E20 is intrinsically unsafe [1,59,61,62].

Challenges in rapid transition: India's progression from E10 to E20 has occurred on a compressed timetable compared with Brazil's decades-long development of an E27 and flex-fuel ecosystem. A faster schedule concentrates vehicle turnover, retail conversion, consumer communication, and supply-chain adjustment into a shorter period, increasing the risk that fuel availability, fleet compatibility, and service preparedness develop at different rates. It can also shift adjustment costs toward owners of legacy vehicles and fuel retailers before sufficiently disaggregated complaint, warranty and durability data are publicly available. For this reason, movement beyond E20 should be gated by blend-specific fleet testing, transparent field and warranty evidence, clear labeling, an assessment of dual-grade retail feasibility, and demonstrated readiness of infrastructure and feedstock [1,59,61,63].

Government, research and industry evidence: The Government has strongly rejected generalized claims that E20 necessarily causes drastic mileage loss, engine damage or invalid insurance, citing the staged public roadmap, consultations with the Society of Indian Automobile Manufacturers (SIAM), and the absence of a widespread pattern of E20-attributable failures [14]. ARAI, SIAM, and vehicle manufacturers have likewise reported laboratory, durability, and field evidence supporting E20 use in validated vehicles, while SIAM has also acknowledged the practical challenge posed by the legacy E10 fleet [61,63]. Experimental work led by IIT Delhi across E0–E50 blends show that emission responses are not uniform and that some unregulated pollutants increase at blends above E20, reinforcing the need for blend- and vehicle-specific calibration rather than either blanket reassurance or blanket rejection [62]. Taken together, this evidence supports a measured defense of the E20 program while preserving the case for independent testing and public disclosure before E22–E30 or E85 is scaled.

5. Conclusion and policy recommendations

5.1 Conclusion

The first research objective examined how India's ethanol blending program evolved from a pilot and fragmented initiative into a full-blown national program. The consistent nature of the evidence over previous parts clearly shows there was a coherent (if somewhat hurried) policy pathway. The national policy on Biofuels 2018 and its 2022 revision, which advanced the E20 target date to 2025–26 [5], implemented the long-term vision outlined in the NITI Aayog roadmap [1]. The fact that 20 percent ethanol blending was achieved in December 2025 [7,51]; the release in June 2026 of the BIS IS 19850: 2026 standard; and the simultaneous suspension of excise tax for all blends up to E30, including E22 [13] clearly demonstrate that the program has gone past its original goal and is now in a stage of building new post-E20 architecture.

The second research objective was to estimate the economic (energy security), environmental, and agricultural impacts generated by the program. The results in each dimension are significant. Foreign exchange savings from ESY 2014–15 to May 2026 exceeded Rs. 1.91 lakh crore; crude oil substitution was approximately 31 million metric tons; total cumulative CO_2 reductions were approximately 931 lakh metric tons; and payments to farmers and ethanol suppliers were Rs. 1.62 lakh crore [13] based on a single authoritative Government press release. These numbers, which collectively constitute a comprehensive report of program performance, demonstrate that the EBP Program has produced tangible, quantifiable benefits in energy security, environmental impacts, and income to farmers related to agriculture, as defined by its architects.

The third research objective was to identify the structural barriers that will restrict the scaling of the program in terms of financial viability, from the E20 level up to the E22–E30 levels, now financially and technologically viable with the policy bundle for June 2026. There were three structural constraints identified. Firstly, while there is a technical capability to support vehicle fleets through an advisory framework, this is still not binding at all because, currently, there is no mandatory flexible fuel vehicle production requirement, so there can be no guarantee of increased consumption through the use of higher blend fuels (only) by way of infrastructure development [46]. Secondly, feedstock concentration risk has remained high; as of February 2025, 2G ethanol had supplied zero crore liters to the OMC supply pipeline [6], and therefore the program has been entirely reliant on first-generation routes that must contend with agricultural variability. Finally, the empirical basis for farmer equity claims under the program has yet to be demonstrated as there is no disaggregated farm gate income data available.

5.2. Hypothesis verdicts

The data support the first hypothesis that the EBP program has enhanced energy security and environmental performance relative to what could have been achieved with passive fuel-efficiency technologies alone. There is also strong support for energy security at two analytical scales: Namely, the 31 million metric tons of crude oil substituted and Rs. 1.91 lakh crore of foreign currency saved [13] from imported petroleum products. Similarly, there is strong support for environmental performance at three or more analytical levels, as evidenced by laboratory-determined emission reductions (carbon monoxide) of 50 percent for two-wheelers and 30 percent for four-wheelers compared to gasoline, and a 20 percent hydrocarbon reduction across all vehicle types when running on E20. Additionally, an estimated total of 931 lakh MT of CO_2 was avoided over the duration of the program [13].

The second hypothesis that vehicle fleet compatibility (with E30), feedstock sustainability (as opposed to unsustainable), and farmer income equity are interconnected (interdependence) rather than separate (independence) was supported. There is considerable evidence that attempting to resolve each constraint individually creates new obstacles (bottlenecks) to achieving E30. Without a guaranteed fuel supply, 500 flex-fuel vehicle retail outlets will be unable to meet demand by December 2026 [46], and since there has been no addition of second-generation biomass to the OMC pipeline, this would direct grain supply lines into areas that could increase food security risks [6]. If a second-generation feedstock diversity strategy is implemented without having verified equitable price transmission at the farm-gate level, then it will remain speculative whether or not the program's equity rationales have merit.

5.3. Policy recommendations

The first recommendation would be a binding mandate to require flex-fuel vehicles for all new four-wheeled and two-wheeled vehicles by April 2027. This will be done through the Ministry of Road Transport and Highways through a Gazette Notification. The advisory nature of the current regulations does not provide OEMs with the same level of investment confidence to modify their manufacturing lines as needed, nor does it give consumers assurance that there are options in each of the E20 to E30 blends now available at the retailer [13,46]. Without a binding requirement, the voluntary approach will not ensure adequate penetration into the existing fleet to create sustainable demand at higher blend levels.

The second recommendation would provide dedicated viability gap funding of at least Rs. 5000 crore to enable second-generation ethanol facilities across India as part of the forthcoming Union Budget cycle. Additionally, there should be obligatory long-term off-take commitments from Oil Marketing Companies (OMCs) for their entire ethanol requirement. With an annual production capacity of approximately three crore liters, to be produced using about two lakh tons of rice straw [32], the IOC Panipat 2G facility is technically viable; however, this business requires the financial structure to establish the same model on a large scale. Obligatory long-term off-take commitments must therefore be operational by ESY 2027–28 to eliminate the commercial risks associated with the lack of guaranteed off-take agreements, which have been the barrier to attracting private investments.

Thirdly, a formal limit on sugar cane use will be implemented as a cap (i.e., 55 percent) to be applied to all future ethanol purchases made by ESY starting in ESY 27 / 28. All other ethanol purchased would need to be produced from grains or 2nd-generation technologies. Currently, the feedstock mix has sugarcane making up around 55 % of total ESY supplies and grains around 45 %, and this is a good ratio that policy can now establish and begin to move towards lignocellulose-based ethanol [26,28,40,41].

The fourth recommendation involves the establishment of a compulsory, disaggregated system of mandatory income reporting by farmers as part of the

National Bio-Fuel Coordination Committee, requiring all oil marketing companies and distilleries to provide details on how much of the administered ethanol price is retained by the cultivator (the "farm-gate" price) and how much is retained by the distillery. The administered price of C-Heavy Molasses Ethanol of Rs. 57.97 / Ltr. for ESY 2024–25 [18] is a procurement price paid to distillers; it is NOT a farm-gate price paid to growers. Therefore, to make its claims about enhancing agricultural incomes credible both within academia and in policy discussions, the program requires an evidentiary base provided by this new reporting requirement.

The fifth recommendation is for the Automotive Research Association of India (ARAI), along with an alliance of Indian Institute of Technology laboratories, to develop a real-world emissions database that has been verified by national standards to include the E20–E30 range, and focus specifically on nitric oxides as a function of concentration in this blend range. The CO_2 savings estimated to result from the deployment of E20 fuels of 27 million tons per year [1], and the total carbon footprint reductions relative to petroleum-based fuels of 65 percent for sugarcane based ethanol and 50 percent for corn based ethanol [15] provide a compelling basis to justify the adoption of E20 and subsequent blends; however, these estimates are contingent upon obtaining real-world NOx emission data prior to defending the post-E20 fuel blending plan on strictly scientific terms.

The sixth recommendation is that BIS IS 19850: 2026 be operationalized (and audited) at the retail level through a joint BIS and Ministry of Petroleum and Natural Gas Compliance Audit Program across all Oil Marketing Company retail outlets before the start of ESY 2026 / 27. Although the standard was published in May 2026 [13], it has set the technical specification for the E22 through E30 Blends. To ensure consumer confidence in the new fuel grades, there must be Rigorous Accuracy in Dispensing and Labeling from the Start. The current target is for all mainland OMC outlets to dispense E20 by Early 2026 [7]. Therefore, the Distribution Infrastructure will exist on which E22–E30 retail can be built; however, auditing mechanisms must precede commercialization.

The seventh recommendation: Aligning the next generation of the national policy on biofuels with India's Nationally Determined Contribution (NDC) and Long Term Low Carbon Development Strategy (LT-LEDS), which will embed the EBP program's cumulative and projected GHG emissions reductions into the international accountability structure provided by the Paris Agreement. By doing so, it will be possible for the EBP Program to access international co-financing for second-generation ethanol infrastructure development via multilateral climate funds; reduce the fiscal burden on the Union Budget of India; and position India's ethanol program as part of an international comparative analysis that enhances both domestic legitimacy and diplomatic standing at the international level [11,43,52].

Author contributions: Conceptualization, AK and SN; methodology, RS (Rijwan Shaikh), MP, AG; software, YW; validation, SR; formal analysis, RKS, MC, SN, SP, AS; investigation, RS (Rajkumar Sarode), MC, SN, SP, AS, SRK; resources, SR; data curation, YW; writing—original draft preparation, YW; writing—review and editing, SR; visualization, AK; supervision, SR; project administration, SRK funding

acquisition, none. All authors have read and agreed to the published version of the manuscript.

Funding: None.

Ethical approval: Not applicable.

Informed consent statement: Not applicable.

Acknowledgments: We would like to thank the Editors and Reviewers for their valuable insights to improve the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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