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India's Accelerated Transition to E20 Ethanol-Blended Petrol: Implications, Challenges, and Opportunities in Achieving Sustainable Energy Goals

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Abstract
The socioeconomic, environmental, technological, and policy evolution have been included in the analysis of the impact of accelerating the rollout of India's E20 ethanol blended petrol policy by 5 years before it was originally intended. This study includes a comprehensive review of the various issues and opportunities of this policy transition and provides a complete examination of the economic impacts on stakeholders such as; agricultural production; rural employment; consumers accessing the new fuel; regulatory compliance; capital costs and other associated costs; impacts to the environment through reduced GHG emissions and pollution; implications for India's long-term climate goals; availability of E20 fuel; and the use of E20 in multiple vehicle platforms. The historical development of ethanol blending in India provides a basis for understanding the role that government incentives and regulations have played in reducing dependence on fossil fuels, improving the economic well being of rural citizens, and stimulating rural agricultural development. Additionally, the E20 program's rapid rollout has provided stakeholders, i.e., sugar cane producers, consumers, etc., with a distinct economic advantage but will require careful consideration of the potential costs before implementing E20 as an alternative fuel for motor vehicles. The connection between rural employment and rural growth will be strengthened by the adoption of E20; however, the implementation of E20 requires that manufacturers and consumers evaluate the total costs of E20 compared to petrol prior to making any decisions to adopt it. The transition from previous ethanol blends (i.e., E10) to E20 is expected to significantly reduce greenhouse gas emissions and air pollutants, and thereby, contribute to India's long-term climate change goals and support the ongoing development of renewable energy sources. While India has taken steps to mitigate potential environmental impacts, additional mitigation strategies will need to be implemented. There are several technology issues related to the use of ethanol that are affecting its implementation around the world, including the compatibility of vehicles with blended fuels, upgrades to the infrastructure to store blended fuel in tanks, and how to ensure the quality of the fuel produced and sold. Throughout the entire production and distribution chain, technological advancements will be needed to address all these issues. On the social side, it is necessary to generate increased public knowledge of the environmental and health benefits of using ethanol-blended fuels as well as drive behavioural changes among consumers that will ultimately lead them to choose to consume ethanol-blended fuels over gasoline or other fossil fuels. Globally, the example that India has set by its leadership, regarding its implementation of ethanol blended fuels, will have a substantial impact on energy security since it will reduce the nation's reliance upon imported fuels and will serve as a model for other countries to consider their own policies on ethanol blending.

Keywords: ethanol blending; India; sustainable energy; biofuel policy; greenhouse gas emissions; vehicle compatibility; energy security; rural economy; renewable energy transition.

1. Introduction

1.1. Background on ethanol blending in India

India has progressed towards ethanol blending as a tool to provide a roadmap for reducing our reliance on fossil fuels and addressing the environmental concerns associated with the energy consumption of the transportation sector. The biofuel policies in India promote the blending of ethanol into gasoline and have required increasing the quantity of gasoline that has been blended with ethanol beginning with lower-blend ethanol (e.g., E10) gasoline, with the vast majority of the ethanol produced being generated from sugarcane molasses, a by-product of the sugar industry [1], [2]. Despite high levels of ethanol produced from molasses, constrained supply has driven the industry toward the development of advanced second-generation ethanol production technologies, which convert agri-residues (i.e., bagasse and cane trash) into renewable energy sources and help to solve problems associated with a lack of ethanol supply and improve the economic feasibility of producing ethanol [1]. The evolution of ethanol Blending targets in India from 2003–2025 has been shown in the figure 1. The E20 Policy is an aggressive and rapid push toward blended gasolines that will contain 20% ethanol by volume (E20) blended with gasoline. The E20 Policy will remove any current E10 blended fuels that may be available and provide greater opportunities for fuel substitutions to be incorporated into the overall fuel supply infrastructure as well as provide greater use of renewable energy sources in the transportation fuel supply [3]. The E20 Policy was rolled out with the Government of India to achieve a fast track E20 implementation, and achieved this five years ahead of schedule. This shows the importance of establishing a solid foundation for any transition to renewable energy sources and demonstrates a commitment to establishing a "sustainable" energy platform in the transportation energy sector. In addition to this, the acceleration of the E20 Policy demonstrates the effectiveness of a policy change as a legitimate attempt to reduce dependence on crude oil imports, increase domestic production of ethanol, and aid in rural development for individuals with a direct relationship to the sugar crop (i.e., sugarcane producers and related businesses) [3], [4].

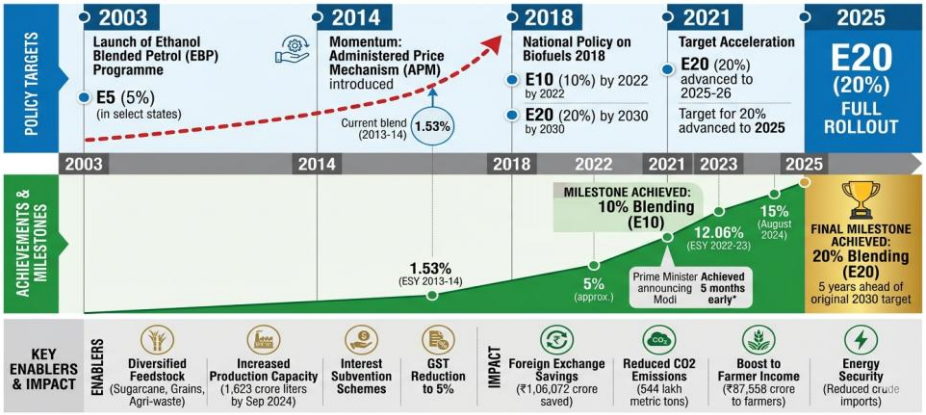

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Figure 1: Evolution of Ethanol Blending Targets in India (2003–2025)

The evolution of policies regarding ethanol blending in India throughout the last 20 years has involved various laws and mandates encouraging ethanol production and blending. The first ethanol-related policies were established through laws in 2003 and additional legislation in 2005. After this foundation was laid through these initial policies, additional guidelines were introduced that focused on: advanced biofuels, technology, and blending targets through 2030 [3]. Additional government incentives to promote ethanol blending include economic assistance, support for developing technology related to producing ethanol, and tax incentives that provide economic advantages to blending ethanol with gasoline. Furthermore, coordination of institutional efforts across sectors such as agriculture, energy and transportation have been key to expediting adoption rates and dealing with the complexities of the ethanol supply chain [1], [3].

Meeting the E20 target earlier than expected is a major milestone in India's path towards sustainability. Reducing the dependence on imported oil increases energy security, creates more opportunities for farmers to diversify their crops by increasing the demand for feedstock used to produce ethanol, and provides clarity to the world regarding India's commitment to reducing greenhouse gas emissions. Achieving the E20 target earlier than expected is also a symbol of India's leadership in biofuel deployment worldwide and demonstrates to other developing countries the ability to support energy needs, agricultural development, and long-term environmentally sustainable practices [3], [4]. The schematic of pathways to ethanol production is shown in figure 2.

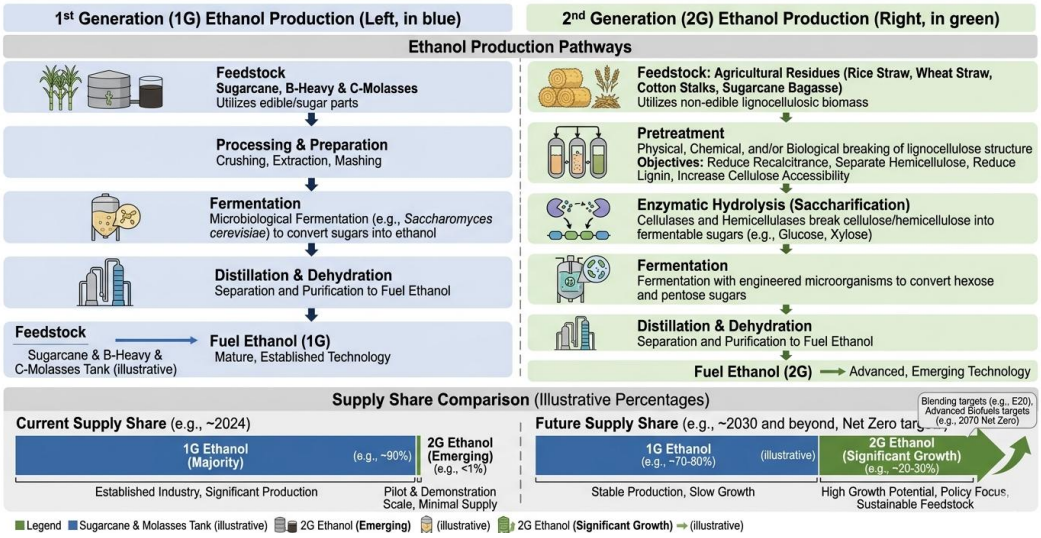

Figure 2: Schematic of Ethanol Production Pathways in India

In conclusion, India has made significant advances in ethanol blending by moving from initial small-scale blending of sugarcane molasses to current national policy that mandates the use of E20 fuel blends as part of an ongoing commitment to achieve sustainable transport energy goals, support rural economic development, and expand the overall use of renewable fuels [1], [2], [3].

2. Evolution of ethanol blending policies in India

The development of ethanol blending policy has been a purposeful and progressive journey for the Indian government. Ethanol blending policies have evolved significantly since 2003 when the government first initiated biofuels. Initially, India had relatively small-scale ethanol blending goals; however, more aggressive targets exist today, with the country's most recent goal being E20, which requires that 20% of gasoline must contain ethanol [3], [5]. In addition to increasing blending targets, the government has created a variety of incentives for ethanol producers, including: excise tax exemptions, guaranteed pricing, financial assistance, and regulatory frameworks that promote mandatory ethanol blending and establish standards for ethanol quality [3], [6].

The presence of government incentives has been one of the most important drivers in stimulating both the production of ethanol and its eventual consumption, as these supports have encouraged the sugar industry and, in particular, individuals who grow sugarcane by creating new markets for ethanol feedstocks as well as by supporting rural economic growth [4]. In addition to this, efforts to diversify the feedstock supply through second-generation ethanol production using lignocellulosic biomass such as sugarcane bagasse and agricultural waste have been aided through pilot projects that have created policy provisions aimed at stabilising the supply of ethanol production and decreasing dependence on molasses feedstocks, which are highly dependent on weather and the growing cycle of sugarcane crops [1], [2]. While these developments in the policy landscape have created new avenues for technological innovation and sophisticated infrastructure that will be necessary to successfully blend ethanol at an increasing percentage of the biofuels market share, the need for continued investment and development of all of these areas is essential to achieve the objective of achieving an average 25% ethanol blend in transportation fuels by 2025.

Accelerating the implementation of E20 policies is a major shift that has a very strong impact on many stakeholders. Many ethanol producers, and sugarcane farmers have been experiencing increases in demand and greater rural incomes and job opportunities as a result [4], [6]. The challenge for fuel manufacturers and distributors has been upgrading their infrastructure and keeping up with the demands of producing higher ethanol blends by updating their storage, distribution, and quality control systems [3]. The automotive industry is currently adapting to match new engine requirements for producing vehicles that are capable of using higher ethanol blends, and looking to make technology adjustments to allow for the use of these fuels. Consumers will benefit from the expected lower fuel prices tied to domestic production of ethanol, and thus will help to advance India's goal of energy independence [6].

At the same time, from an economic perspective, accelerating the implementation of ethanol blending policies has produced a decrease in US imports of fossil fuels, has improved trade balances, and has allowed for greater opportunity for diversification of agro-based industries. Additionally, it has created significant economic activity in rural areas due to increased demand for sugarcane and other feedstocks used for ethanol production, resulting in job creation and social and economic development [4]. However, some of the challenges remain, like having variability in feedstock supply, needing to have ongoing clear policies with enforceable targets and penalties, and having continued infrastructure and technological innovations necessary to support the long-term viability of the ethanol industry in India [1], [6].

The current status of ethanol blending regulations in India has reached a point where the system needs to develop into a complete program that unites government blending incentives with regulatory support and stakeholder participation to help the country reach its ambitious blending targets. The accelerated implementation of policies related to the blending of ethanol is changing both the energy and agricultural sectors in a

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way that provides substantial economic opportunities and poses technical and infrastructure challenges that will need to be addressed through ongoing refinements and innovations [1], [3], [6].

3. Economic Perspectives

The growing use of E20 ethanol-blended petrol in India has an impact on several areas of the economy and has changed how the fuel market operates, how farmers make their living in agriculture, how much consumers pay for their fuel and how much potential there is for rural economic development. At the same time, increased blending of ethanol with petroleum products creates a more diverse domestic fuel supply, which reduces dependence on imported crude oil, and leads to changes to price patterns by creating more of an endogenous fuel supply to the market. In addition, since blending ethanol with gasoline will help stabilise the price of gasoline by partially offsetting volatility due to fluctuations in global oil prices, the extent of that stabilisation is dependent on production capacity and feedstock availability for making ethanol [6]. The refining and distribution system needs improvements to manage the growing ethanol production which results from market changes because these upgrades will create short-term and medium-term effects on petrol and ethanol pricing together with supply chain operations. Ethanol demand increases, which helps the agricultural sector and sugarcane farmers to achieve economic growth. The expanding ethanol market provides sugarcane farmers with dependable income streams which exceed their traditional sugar market revenues [4]. The need for sustainable feedstock production has created an economic incentive for producers to use secondary crops, while responsible resource management is required to control environmental effects from increased water usage during crop intensification [7]. In Brazil, governmental policies combine ethanol incentives with agricultural policies to boost farmer incomes and promote rural development.

Consumers may also benefit from lower fuel prices because the growth in ethanol production in the domestic market reduces the level of dependence on more costly fossil fuel imports [6]. Similarly, businesses involved in biofuel production and blending will see increasing economic opportunities within an expanding marketplace and create additional value chain options; however, these businesses will incur initial cost outlays associated with investments in infrastructure improvements and adjusting to fuel compatibility standards, which are both considered short-term expenditures. In terms of total economy-wide impacts, benefits are achieved through improvements to the trade balance and enhanced energy security, resulting in offsetting expenditures associated with petroleum imports[37-68].

Overall, India's E20 ethanol blending policy promotes rural employment and economic growth by expanding the economy by generating non-agricultural employment, processing of feedstock, ethanol production, logistics and other related services. Together, these activities provide rural communities and their populations additional job opportunities and increased entrepreneurship. This is consistent with the needs of the nation for developing an inclusive economy and innovative agriculture [7], [8]. The biofuels industry provides an opportunity for rural India to be economically, socially and environmentally sustainable by creating a culture of socio-economic resilience.

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In terms of the economy, environmental sustainability is a critical part of the overall economy, because blending ethanol is an effective way to reduce emissions, which will enable compliance with climate and air quality targets and generate indirect economic value through reduced health care and environmental costs [7]. Nevertheless, sustainable production of feedstock and efficient use of resources are critical to ensuring that economic benefits are realised without jeopardising long-term ecological balance.

Fundamentally, the economic effects of India's E20 ethanol blending policy can be viewed as transformational effects on fuel and pricing stability, increasing income of farmers, in particular sugarcane farmers, and improving cost efficiency for businesses and consumers. The economic benefits of the E20 ethanol blending policy are dependent upon the development of sound policy frameworks that support sustainable practices and integrate environmental stewardship and economic development objectives [4], [6], [7], [8].

4. Environmental and Sustainability Considerations

The implementation of E20 ethanol-blended fuel in India will greatly help in reducing greenhouse gas (GHG) emissions and air pollutants compared to other fuels currently being used. Bioethanol when derived from cellulosic biomass like agricultural and wood waste has tremendous life-cycle GHG reductions compared to conventional gasoline. In fact, research shows that fuel produced from integrated biorefineries can produce up to 87% less GHG emissions (per unit of energy) than gasoline. Also, with lower blends like E10 you usually see a reduction of about 10-20% and higher blends like E85 can lead to reduction of around 65%-70% [9], [10].

Ethanol blends such as E10 are proven to be effective at reducing harmful exhaust emissions (e.g., nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbon (HC)) while delivering the same or better engine performance than gasoline. Therefore, E20 is anticipated to provide even greater reductions of these harmful pollutants; however, achieving this will require proper engine calibration and fuel quality standards. Overall higher ethanol blends typically produce less CO2 or GHG than straight gasoline, leading to cleaner air [11], [12].

The use of E20 blended gasoline fits into India's plan to protect its climate through its renewable energy goals. Using more renewable bioethanol as a fuel will result in the use of fewer fossil fuels, and will also help India meet its targets according to the Paris Agreement. Ethanol made from cellulose (plant material) that comes from agricultural waste is a viable way of making fuel that has zero carbon emissions, which further supports India's long-term goal to be sustainable [9], [13].

But growing ethanol will cause some environmental problems, such as increased water use, land use changes, and runoff of fertilizers, which can cause lakes and rivers to become polluted from the fertilizer runoff (eutrophication). To help reduce these impacts, it is necessary to continue to develop new technologies to produce renewable fuels from more sustainable materials such as agricultural waste and crop residuals versus energy crops and innovative crop production methods. Ethanol produced using different types of renewable energy has a different environmental impact depending on how much input energy was required to process the raw materials. The analysis of these inputs makes understanding how much renewable energy can be produced from bioreactors and how to increase the productivity of bioreactors very important to the overall production of ethanol [10], [14].

To sum up, the faster shift to the E20 ethanol blend in India has substantial environmental benefits compared to E10 and pure petrols, primarily due to substantial decreases in the GHG emissions and air pollutants. This not only favors the climate and renewable energy interests of the nation but also sustainable transport. Nevertheless, these benefits can be maximised and the environmental risk minimised only through the policies which promote the sustainable feedstock management, development of technologies, and strict quality and emission criteria.

5. Technological and Infrastructure Challenges

There are some notable technological and infrastructure issues associated with the execution of the E20 ethanol blending policy in India: the compatibility of the vehicles, the fuel distribution networks, the innovations in production, and the quality control.

The study on vehicle compatibility shows that the majority of the vehicles that have been manufactured since the last 50 years, especially those that meet the Tier 1 and Tier 2 emission regulations, are highly compatible with ethanol blends up to at least E15. Research has pointed on the

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fact that Tier 2-level cars have the right materials and engine control to operate safely with E20 blends, but long and comprehensive real-world data are still somewhat scarce on this upper blend level [15]. The flexibility of modern vehicles to ethanol and blends can also be supported by the historical experience of such countries like the United States and Brazil as the fuel system components have increasingly been made of materials resistant to ethanol corrosion and degradation, including specialised poly-mer and metals. Nonetheless, there are more chances of the fuel system wear, material degradation and functioning of the old vehicles or those that do not have the ethanol-compatible parts and components and, consequently, will have to be evaluated specifically and potentially retrofitted to guarantee safety and sustainability in the Indian vehicle fleet [15].

Another critical issue is the upgrade of the fuel distribution and storage infrastructure because the chemical properties of ethanol are quite different with pure petrol, especially its hygroscopic character that contributes to the absorption of moisture and the probability of fuel phase separation and wear. The currently available pipelines, storage tanks, and dispensing equipments in India mostly need to be altered or changed to accommodate ethanol or the equipment should be made of ethanol compatible materials to avoid corrosion and to ensure fuel quality [3].Another aspect of decentralised blending will be placing it closer to retail locations, thereby increasing the efficient operation of the supply chain and reducing the logistical difficulties of getting high-ethanol blends to the most distant locations [3]. The establishment of standardised requirements for the storage; handling; and pipeline transport of ethanol fuels is critical to the proper functioning of the overall system and the quality of fuel throughout the supply chain [16].

India is also pursuing technology for bioethanol production from sources other than sugarcane molasses and is beginning to consider alternative sources, such as agricultural residues and second-generation lignocellulosic biomass, to supply the increasing demand for ethanol—expected to exceed 10 billion litres by 2025—renewably [17]. Examples of technology development include integrated biorefineries, which combine biochemical and thermochemical processes to utilize the biomass resource in an efficient manner, reduce greenhouse gases, and improve economic viability for the long run [17]. Moreover, pretreatment optimisation attempts to reduce the production of inhibitors that hinder enzyme hydrolysis and fermentation to increase ethanol production and reduction of costs of ethanol production [16]. To aid in the decentralisation of processing, provide flexibility within the supply chain and support rural job growth, the use of modular and scalable processing technologies is being examined [17].

Quality control and standardisation are critical for the successful implementation of E20 blending. The purity of the ethanol used, as well as the moisture content and the minimisation of by-products or deterioration resulting from storage influence both the performance of the ethanol fuel as well as its comparability to engine requirements [16]. To maintain consistent quality of fuel across both the various methods of production and throughout the distribution channels, we will need to implement rigorous testing protocols, certification systems and real-time monitoring capabilities to ensure compliance with a common set of international standards [6], [16]. Furthermore, regulatory frameworks should contain clear guidelines describing how storage, handling and on-site blending processes must be conducted in order to ensure that the quality of ethanol is not compromised and to help maintain the confidence of consumers in the product.

Overall, technological and infrastructural issues can be addressed through policy support, stakeholder engagement and through research and development investments. Incentives that support the improvement of infrastructure, compliance of vehicles and production innovations are necessary as well as public education about the benefits of E20 fuel and the compatibility of such a fuel with engines [3], [6]. Moreover, systematic real-world testing of cars specially adapted or designed to operate with E20 is needed to develop strong evidence to guarantee that it is operational with numerous reliability and safety [15]. These infrastructural and technological advancements are the key to achieving the environmental, energy security and economic benefits that the ambitious E20 ethanol-blending program by India envisages.

6. Social and Public Health Impacts

Ethanol-blended fuels have become an important measure in India to solve the urgent public health issues of air pollution, especially in enhancing air quality in the ambiance and reducing respiratory and cardiovascular diseases. In India, air pollution continues to be a major cause of morbidity and mortality, whose causes are linked to particulate matter (PM 2.5), nitrogen oxide (NOx), and other contaminants associated with chronic respiratory diseases like asthma, chronic obstructive pulmonary disease (COPD), acute lower respiratory infections, and cardiovascular complications [18], [19], [2 Ethanol mixing, particularly with higher blending targets like E20, leads to a reduction in the vehicle emissions of carbon monoxide, hydrocarbons and PM emissions over pure petrol, which provides an avenue to reduce concentrations of pollutants in the ambient air and consequently enhances the overall health outcomes in the population [11], [12].

The overall benefits of cleaner fuel consumption on respiratory illnesses and cardiovascular health, cognitive development, and maternal and foetal well-being serve the populations that are most vulnerable to the effect of indoor and outdoor air pollution the elderly, children, and women, who are disproportionately impacted by such pollution [21], [22]. The high levels of household air pollution caused by burning biomass in India (which in turn has created respiratory health issues), provide a strong case for replacing ethanol blended fuels with fossil fuels.

The public's awareness and acceptance are also paramount to their adoption on a massive scale, which will ultimately result in health benefits. Studies have shown that consumers' awareness of the health & environmental benefits of bioethanol varies by geography and also is impacted by consumer education and personal experiences with environmental pollution, as well as government outreach programs designed to educate consumers about the benefits and usage of bioethanol. Improved sensitisation campaigns are associated with acceptance and behavioural change to cleaner fuels, which is evident in urban centres, where the visibility and health effects of pollution are more significant [18], [24]. The policymakers and stakeholders stress on the significance of clear communication concerning the quality of fuel, its environmental positive effects, and threats to health to develop trust in the fuel and make consumers switch to ethanol blends [6].

Along with the ethanol blending initiative, there are behavioural shifts in fuel consumption patterns with findings indicating that consumers are increasingly turning to ethanol-blended petrol due to its perceived price benefits, cleaner combustion and conformity to national energy security objectives [19]. This adoption is supported by the regulation requirements and adjustments to the infrastructure which enable an easy access to E20 fuel at the retail points. Also, the switch to ethanol mixtures makes it possible to lessen the reliance on older fossil fuels and encourages fuel-saving driving habits by driving consumers to find more interest in energy use and environmentally-friendly practices [20], [22].

In a broader societal sense, the adoption of ethanol-blended fuel policies creates positive externalities, including better health in the communities, lower healthcare expenditure, and higher living standards, especially in high-density urban and peri-urban cities faced by extreme instances of air pollution [18], [25]. Rural populations and marginalized communities continue to face obstacles regarding awareness and access to low-quality fuel and will require educational/infrastructure initiatives to ensure that all populations receive equal access to health benefits from these fuels [8], [21].

In summary, introducing ethanol-blended fuels in India has great potential to improve the country's air quality and health outcomes by reducing the amount of harmful pollutants emitted into the atmosphere, thereby contributing positively to respiratory and cardiovascular disease incidences associated with these types of emissions. However, the benefits associated with an ethanol blending program will only be fully realized in the long run if there is ongoing public awareness and acceptance of clean burning fuels, as well as behavioural changes occurring among individuals who use or burn fuels. Continued policy support through community involvement and education will help ensure maximum

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benefit from the ethanol blending program, which in turn will support the goals of sustainable development and climate change in India [6], [18], [19], [20], [22].

7. Global and Geopolitical Context

India's role in the biofuels sector represents both the ambitious policy commitments made to promote biofuels while facing operational challenges. India, being one of the largest emerging economies in the world, and heavily dependent on agriculture, is well placed to take advantage of bioethanol production using the biomass resources available in large quantities, including sugarcane molasses and agricultural waste. Nevertheless, even with the policy requirement of incorporation of ethanol in petrol, the ethanol industry is now experiencing disequilibrium in the supply of ethanol in India. The average production of ethanol is always below the consumption needs resulting in greater imports of ethanol and the necessity of greater capacity of production and feedstock diversification [2], [6]. The fact that the country is concerned with the second-generation production of bioethanol using lignocellulosic biomass, including sugarcane bagasse and agricultural waste, points to a visionary approach to improving sustainability and minimizing the reliance on the conventional molasses pathways [1].

The ethanol blending requirement in India is in line with the trends in the world concerning biofuels, and it is based on lessons learned by countries that have developed ethanol programs. The example of long-established use of sugarcane-based ethanol in Brazil and the corn ethanol industry in the United States is an example of how availability of feedstock, technological advancement, and sound policy frameworks are necessary to meet large-scale blending goals in the bioethanol sector. These experiences underscore the following issues of importance to India: the need to diversify feedstock to deal with fluctuations in crop cycles, investment in new bioconversion technologies and co-ordinated regulations that promote both producers and consumers [1], [2]. Additionally, pilot-scale research in India has revealed the economic feasibility of lignocellulosic residue conversion, which is an encouraging indicator of the possible replications of the Brazilian and American achievements in bioethanol production to the Indian setting [1]. Notably, the changing policy in India represents a dynamic amalgamation of roadmap-making advances towards 20 percent ethanol blends that need constant development depending on international best practices and local realities.

The ethanol blending program in India has important geopolitical and energy security effects. Through the expansion of local production of ethanol, India hopes to lessen its excessive reliance on foreign crude oil and petroleum products and enhance its energy independency and protection against global oil prices and geopolitical risks [6], [26]. This strategic goal will help India to pursue its larger climate objectives, such as supporting the use of renewable energy in the transport sector and supporting sustainable development objectives. The transition to ethanol blending also helps to curb carbon emission and to align the energy mix of India with the global decarbonisation initiative, and at the same time rural economic development is achieved through the increased agri-based biofuel industries [3], [6]. However, policy and regulatory frameworks should tackle supply chain limitations, technology and feedstock sustainability to realise the desired benefits as highlighted by the experiences of other countries that produce ethanol [2].Conclusively, India has a chance at the crossroads of the global biofuel environment as it is tapping into its agricultural advantages and challenges inherent to the process of increasing ethanol blending. The global experiences can offer great information as to how to secure feedstock, in order to encourage innovation and maintain market growth. They are essential in improving energy security in India by lessening importation reliance and playing a significant role in climate and economic objectives by using bioethanol blending strategies [1], [2], [6], [26].

8. Future Outlook and Recommendations

The future perspective of ethanol fuel in India depends upon the feasible ability to increase production at a sustainable rate accompanied with technological innovation, enhancement of policy, and experimentation of blending beyond the E20 with the inclusion of complementary renewable fuels.The ethanol production needs to be pushed to sustainable levels; this needs to focus on the diversification of feedstocks besides using the sugarcane molasses to include rice husks, straw, and municipal solid waste which are in large quantities. This type of diversification of feedstock lowers the dependence on food crops and removes the competition on land, in line with the biomass availability and international potential of cellulosic ethanol production of residues in India [2], [27], [28]. The use of lignocellulosic biomass via enzymatic hydrolysis development and low cost bioconversion technologies are of essence to surmount the current deficiencies in production and achieve the high blending goals set by India [2], [29]. Moreover, the promotion of agricultural and municipal waste creates the advantage of a circular economy, improving environmental sustainability and minimizing the emission of greenhouse gases in accordance with life cycle assessment of ethanol obtained using these sources [28].

The biofuel sector growth in India is based on strong research and development. The focus areas are enhancing the enzymatic efficiency of lignocellulosic biomass, scaling integrated biorefineries and investigating new bioenergy carriers, bio-methanol made using CO 2 and renewable hydrogen [29], [30]. Such technologies will be piloted in scale and commercialised, which will give important information on how processes and costs can be optimised to sustain ethanol availability. Moreover, there are possibilities to diversify the supply using new feedstocks, including non-food biomass, glutinous rice, and cassava varieties [31].

The continued pressure on policy support is necessary to sustain the initiative towards greater ethanol blending. The national biofuel policies in India should be amended with clear phased blending requirements going beyond the existing ones (such as E20) in order to be able to signal the market and create investor confidence [2]. Based on the experience of Brazil with its extensive ethanol program, which is defined by integrated incentive measures, environmental protection and integration of infrastructural developments, a balanced system promoting sustainable growth of feedstock, environmental conservation and social justice is necessary [32], [33]. Assuring the certification mechanisms to include green house gas accounting, land use planning and fair labour practices will enhance credibility to the sustainability of the sector.

Ethanol beyond the E20 point is also promising as there is more potential to reduce fossil fuel reliance and emissions in future, depending on the compatibility of the vehicles and the availability of infrastructure [2]. They can be adopted by parallel investments in fuel distribution networks and consumer awareness campaigns. In addition, the combination of ethanol with other renewable fuels, including green methanol and biohydrogen, which are produced in biorefinery complexes, can enable synergies, diversifying the renewable fuel portfolio of India and exploiting land-neutral production routes as a result of new CO 2 utilisation technology [30].

In conjunction with environmental protection to prevent deforestation, soil erosion and social injustices as it has been practiced in Brazil in handling sugarcane planting and labour practices, India can make sure that bioethanol development is socially and ecologically sustainable [33]. Circular waste valorization and new approaches to land-use will further reduce these adverse effects.

To sum up, the sustainable and scalable development of the ethanol industry in India needs to be a multifaceted approach that involves the diversification of feedstock, increased research in advanced biofuel technologies, definite and consistent policy requirements, and readiness to increased ethanol blending along with new renewable fuels. This will support energy security, lower carbon footprints, and boost rural economies as well as sustain environmental and social sustainability

9. Conclusion

The adoption of biofuels in India is a dynamic process with a proactive orientation to the solution of the energy security, environmental sustainability, and rural economic development. The dependence of sugarcane molasses as the main feedstock of producing ethanol has been used as a starting point in India; with the realisation of the limitations of this monoculture source, India is taking calculated steps in diversifying

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feedstocks through lignocellulosic agricultural residues and other non-food biomass. This diversification is essential to scale production in a sustainable manner and achieve high levels of ethanol blending, e.g. E20, without stressing food security and land use [1], [2].

India has been at the forefront of biofuel adoption and policy initiatives have been the foundation of this achievement with regulatory frameworks and blending requirements gradually encouraging industry adoption. However, the issues such as periodic crop production, the inconsistency of policies, and the absence of second-generation biofuel commercialization also highlight that effective and consistent policies are necessary to be dynamic and coherent to promote innovation and confidence in the market [3], [6]. The advent of technology, like enzymatic hydrolysis enhancements and pilot-scale manufacturing of lignocellulosic bioethanol, announces promising avenues of cost reduction and higher output which is needed by the biofuel hopes of India [34], [35]. The future research and development will be important in the exploitation of next generation biofuels and the general sustainability of production processes.

Environmentally, lifecycle analyses conclude that the sustainably produced bioethanol, especially that produced using second-generation feedstocks, can significantly lower greenhouse gas emissions relative to fossil fuels, and thus help India meet its climate commitments and renewable energy goals. This green trajectory can alleviate negative social and ecological effects of first-generation biofuels, which places India in a good position to be part of the global shift to low-carbon transport fuels [1], [2], [36].

The growing maturity of India in the use of biofuels is an indication of its rising prominence in the use of renewable energy as compared to other developing economies. India leads by example in implementing biofuel projects that are sustainable in terms of economic, environmental and social aspects through alleviating supply-side constraints, improving technological innovation, and improving supportive policies. Over the long term, bioethanol when combined with other renewable fuels and possible going beyond the E20 mark, opens opportunities to further decarbonise, lessen reliance on fossil fuels, and strengthen energy security [3], [6].

After all, the biofuel strategy of India is a comprehensive vision of energy transformation; the vision that balances the economic growth with environmental responsibility and social justice. The fact that it has continued to make commitments and dynamic policy structures offers a valuable case to study global bioenergy future as it highlights the potential potential of biofuels in terms of ensuring a sustainable and secure energy system across the globe.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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