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Techno-Economic Feasibility of Sugarcane-Based E-Fuel Production in India: A Sustainable Energy Alternative

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Abstract: India's growing dependence on fossil fuel imports presents significant economic and environmental challenges. This research investigates the techno-economic feasibility of sugarcane-based ethanol production as a sustainable alternative energy source. Using secondary data analysis, cost estimations, and case studies for Brazil and Maharashtra, the study evaluates production viability, environmental benefits, and potential policy impacts. Findings reveal that ethanol produced from sugarcane is both economically viable and environmentally sustainable, with the potential to significantly support India's E20 blending initiative. Challenges such as high water consumption and infrastructure gaps remain, but targeted policy interventions can mitigate these issues. The findings support sugarcane-based ethanol as a critical component of India's energy security and climate action strategies.

Keywords: *Sugarcane; Ethanol Production; E-fuel; Techno-Economic Feasibility; Renewable Energy; India.*

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I. INTRODUCTION

India, being one of the fastest-growing economies in the world, faces a critical challenge in meeting its ever-increasing energy demands while addressing concerns over environmental sustainability. The country's heavy dependence on fossil fuel imports - accounting for nearly 85% of its crude oil needs –not only places a significant burden on its economy but also exposes it to volatile global oil markets. In this context, the exploration of renewable and domestically sourced alternatives has become essential.

A promising opportunity exists in the production of bio-fuels, particularly ethanol derived from sugarcane. Sugarcane offers a high biomass yield and sugar content, making it a sustainable and efficient feedstock for ethanol production. When blended with petrol, ethanol can effectively reduce fossil fuel consumption, lower greenhouse gas emissions, and enhance India's energy security.

Recognizing this potential, the Government of India has introduced initiatives such as: the Ethanol Blended Petrol (EBP) Programme with ambitious targets like achieving a 20% ethanol blending ratio (E20) by 2025. However, the large-scale implementation of sugarcane-based ethanol production demands a careful assessment of both technological viability and economic practicality.

This research aims to study the technological feasibility and economic viability of sugarcane-based e-fuel production in India, analyzing whether it can emerge as a sustainable and scalable alternative to conventional fossil fuels. The study will explore the complete value chain from crop cultivation to ethanol conversion - evaluating the cost factors, environmental benefits, and infrastructural challenges involved. In doing so, it hopes to contribute valuable insights to policymakers, industry stakeholders, and researchers seeking to advance India's transition towards cleaner energy solutions.

II. BASIC CONCEPTS

- *What is Ethanol?*

Ethanol is a transparent, colorless form of alcohol commonly used as a fuel or blended with gasoline to enhance combustion efficiency. It is renewable, biodegradable, and can be produced through the fermentation of sugars present in crops such as sugarcane, corn, or wheat when blended with petrol; ethanol helps in contributing to the reduction of greenhouse gas emissions and the transition away from fossil fuel dependency.

- *Sugarcane-Based Ethanol Production:-*

Sugarcane is one of the most efficient crops for ethanol production due to its high sugar content and fast growth.

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- *Ethanol is produced through a series of steps, which typically include the following stages:*

✓ Juice extraction - wherein sugarcane is crushed to extract fermentable juice.
✓ Fermentation- The juice is mixed with yeast, which converts sugar into ethanol.
✓ Distillation- Ethanol is separated and purified through distillation.
✓ Blending- The ethanol is blended with petrol (gasoline) to create bio-fuel (e.g.,E10,E20)

➢ *This Process Results in a Clean-Burning fuel that emits less Carbon Compared to pure Petrol.*

- *Ethanol Blending in India (E20) Policy: -*

The Government of India has set a target to mix 20% ethanol with petrol by the year 2025. This policy encourages domestic ethanol production and supports farmers by increasing the demand for sugarcane and other feed-stocks.

- *Bio-fuel vs E-Fuel: -*

✓ **Bio-fuel** refers to fuel produced from biological sources (like sugarcane, corn, etc). Ethanol from sugarcane is a bio-fuel.
✓ **E-fuel or electro-fuel** is a synthetic fuel made using captured carbon dioxide and hydrogen from water, usually powered by renewable energy.

In this paper, the term E-fuel is used more broadly to include ethanol as a sustainable alternative to fossil fuels.

III. LITERATURE REVIEW

The global shift towards sustainable energy has brought bio-fuels, particularly ethanol, into focus. Countries like **Brazil** have pioneered the large-scale use of sugarcane-based ethanol, establishing efficient production systems and nationwide ethanol-blending programs. The success of Brazil illustrates the potential of ethanol in minimizing fossil fuel dependence and mitigating carbon emissions.In India, various studies and government initiatives have explored the potential of bio-fuels. The **NITI Aayog, Ministry of Petroleum and Natural Gas (MoPNG)** and **Indian Sugar Mills Association (ISMA)** have published reports supporting the expansion of ethanol production from sugarcane. Policies like the **Ethanol Blending Programme (EBP)** aim to achieve **20%** ethanol blending by **2025**, reflecting strong national interest in reducing crude oil imports and promoting clean energy.

Academic research in India has focused on ethanol yield, production technology, and environmental benefits. However, there are still considerable shortcomings in the evaluation of technological and economic aspects.

- Comprehensive techno-economic evaluations of ethanol production specific to India are relatively limited.
- Regional disparities in agricultural output, resource utilization, and production costs.
- Lack of comprehensive studies comparing sugarcane ethanol with other renewable fuels.

This research attempts to address these gaps by evaluating the **techno-economic feasibility** of sugarcane-based ethanol in the Indian context, using secondary data and real-world case studies.

IV. METHODOLOGY

This research is based on a secondary data analysis approach, using verified sources such as reports from **NITI Aayog, MoPNG, ISMA** and global case studies like Brazil's ethanol model.

➢ *Data Collection:-*

- *The Following Parameters were Collected:*

✓ Crop Yield: Sugarcane production in tonnes per hectare
✓ Ethanol yield: Refers to the number of litres of ethanol obtained from each tonne of sugarcane processed.
✓ Production Costs: Cost of cultivation, harvesting, fermentation, distillation, and transportation (INR/tonne)
✓ Market Selling Price: Ethanol selling rates as per government notifications (INR/Litre)
✓ Environmental Factors: CO_2 emission factors for ethanol and petrol.

➢ *Economic Cost Analysis:-*

The economic viability is assessed by calculating the cost per Litre of Ethanol using:

➢ *Sample Example Calculation:*

$$\textbf{Cost per litre of ethanol} = \frac{\textit{Total Producation Cost}(INR/tonnes)}{\textit{Ethanol Yield}\ (litres/tonnes)}$$

➢ *Suppose*

- Approximately 70 litres of ethanol can be obtained from 1 tonne of processed sugarcane.
- Total production cost per tonne = 2,800 Then, ₹2800 ÷ 70 litres = ₹40 per litre

➢ *Cost per litre = ₹40*

This cost is then compared to the existing petrol prices (e.g., 100 Rs/litre) to evaluate competitiveness.

➢ *Feasibility and Break-Even Analysis:-*

- *The feasibility is checked by:-*

✓ Assess the price difference between ethanol and retail petrol.
✓ Assessing the time required to recover the initial investment in ethanol production facilities.
✓ Conducting a sensitivity analysis to understand the impact of variations in sugarcane yield and production costs.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25may1088

➢ *Environmental Impact Analysis:-*

- *Reduction in CO_2 emissions is estimated using the formula:*

CO_2 saving (Kg) = (Emission from Petrol − Emission from Ethanol)X Volume of Ethanol

➢ *Where,*

- Emission from Petrol = 2.31 Kg CO_2 per litre
- Emission from Ethanol = 1.50 Kg CO_2 per litre
- **Sample Calculation-** If **1000 litre** of ethanol replaces petrol- CO_2 Reduction (kg) = (2.31 - 1.50) × 1000
- **CO_2 Reduction =810 kg** Thus, large-scale ethanol blending significantly reduces environmental pollution.

➢ *Case Study Benchmarking:-*

Brazil's sugarcane ethanol success model is used as a comparative benchmark to validate the technical and economic assumptions in Indian conditions.

➢ *Summary;*

By combining economic analysis, environmental assessment, and benchmarking global practices, this methodology aims to systematically study the techno-economic feasibility of sugarcane-based ethanol production in India.

V. ANALYSIS AND DISCUSSION

➢ *Cost Analysis of ethanol Production:-*

According to secondary data The typical ethanol yield from sugarcane is approximately 70 litre per metric tonne of raw material.

- *Production cost: 2800 per tonne Thus,*

$$\text{Cost per litre} = \frac{2800}{70}$$

Cost per litre = 40 Rs/litre

Current petrol price: ₹ 100 per litre (approx)

➢ Observation:

Sugarcane-based ethanol is 60% cheaper than conventional petrol, making it an economically attractive option.

➢ *Feasibility Analysis:-*

- India's petrol consumption: **50 billion litre/year**
- To fulfill the E20 blending mandate, India would need to produce approximately **10 billion litres** of ethanol each year.

➢ *Given India's sugarcane cultivation potential-*

- With proper incentives, India can meet 50-70% of its blending target through sugarcane ethanol.
- Additional ethanol can come from other sources like corn, damaged grains, etc.

➢ *Sample calculation:*

- Sugarcane yield per hectare: 80 tonnes
- Ethanol yield per tonne: 70 litres

➢ *Thus,*

- Ethanol yield per hectare = 80 tonnes × 70 litres/tonne
- Ethanol yield per hectare = 5,600 litres of ethanol

➢ *Comparative Case Study: Brazil vs India.*

Table 1 Brazil vs India Ethanol Comparison

Parameter	Brazil	India
Typical sugarcane yield (t/h)	≈ 85 t/ha	≈ 80 t/ha
Ethanol Yield (litre/tonnes)	≈ 85 l/t	≈ 70 l/t
Average ethanol cost (Rs/litre)	₹ 35-40	₹ 45-50
CO_2 reduction per 1000 litres ethanol (kg)	≈ 1,500	≈1,200
Ethanol Blending target	≈ 27%	20 % by (2025)
CO_2 Emission Reduction	45% Reduction	Projected 35-40% Reduction

Source: Compiled from secondary data (2024)

➢ *Observation: Brazil's success is due to:*

- Continuous investment in ethanol distilleries.
- Flex-fuel vehicles (Run on any ethanol-petrol blend)
- Government policy support {like fuel of the future law, national program for sustainable aviation fuel (ProBioQAV), etc.}
- **Suggestion**: India can adopt similar strategies.

➢ *Environmental Impact Analysis:*

Switching to ethanol can save large quantities of CO_2 emissions.

➢ *CO_2 saving Calculation:*

For **1,000 litres ethanol** replacing petrol- By replacing conventional fuels with ethanol, India can save approximately **810 kilograms** of CO_2 per **1,000 litres**, based on a difference of **2.31 kg CO_2/litre** (for petrol) and **1.50 kg CO_2/litre** (for ethanol). This translates to a total potential saving of **8.1 million tonnes** of CO_2 for the country's **10 billion litre** ethanol targets.

"An annual reduction of 8.1 million tonnes of **CO_2— equivalent to 8.1 × 10^6** metric tonnes or **8.1 × 10^9**

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kilograms—constitutes a significant step toward meeting the climate goals outlined in the **Paris Agreement**."

➢ *Risk and Challenges Analysis:-*

Table 2 Challenges, Impact, Suggestions

Challenge	Impact	Suggestion
Water usage	High water consumption for sugarcane	Promote drip irrigation and water-efficient varieties
Land usage	Risk of shifting land from food crops	Encourage use of surplus land only
Infrastructure	Lack of distilleries and blending units	Government incentives from ethanol plant –setup
Farmer Risk	Crop failure Risk	Introduce minimum support prices (MSP) for ethanol cane

Source: Compiled from secondary data (2024)

➢ *Policy Recommendations:-*

- **Subsidies and incentives**: To promote ethanol plant development and support the widespread adoption of flex-fuel vehicle technology.
- **Water Management**: Encouraging the adoption of micro-irrigation methods in sugarcane cultivation to improve water efficiency.
- **Integrated Ethanol Programs**: Parallel development of ethanol from sources (grains, molasses) to support sustainability.

VI. CONCLUSION

The study comprehensively examined the economic and technical prospects of sugarcane-derived ethanol as a viable renewable fuel for India. The findings highlight that sugarcane-derived ethanol offers a cost-effective and environmentally sustainable substitute for fossil fuels, aligning well with India's ambitious energy transition goals under the **E20 policy**.

Comparative analysis with Brazil's well-established ethanol program demonstrates that India possesses significant potential to replicate similar technology adoption. Infrastructure development and agricultural management must be promptly implemented.

Moreover, the environmental benefits, particularly the substantial reduction in CO_2 emissions, position ethanol as a critical contributor to India's climate action targets.

However, challenges related to water resource management, land use optimization, and rural infrastructure must be addressed through holistic policies, research innovation, and public-private partnerships.

In conclusion, sugarcane-based ethanol production is not merely a supplementary energy source, but a transformational opportunity for India to achieve energy self-reliance, empower rural economy, and lead global efforts towards sustainable development. Future research must explore the integration of second-generation Bio-fuel technology, precision agriculture for sugarcane farming, and the development of a flexible, decentralized ethanol production system to maximize both economic and environmental benefits.

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