ISSN (Print): 1060-6076
ISSN (Online): Applied

The Journal of African Development
2026; Vol 7: Issue 1
https://www.afea-jad.com/

Cost-Benefit Analysis of Ethanol Production: A Special Reference to Sugar Industry in Karnataka

Chandrashekar[1*] and T.S. Devaraja[2]

[1]Research Scholar, Department of Studies in Commerce, Hemagangothri PG Centre, University of Mysore, Hassan-573220, Karnataka, India.
[2]Professor, Department of Studies in Commerce, Hemagangothri PG Centre, University of Mysore, Hassan-573220, Karnataka, India

Cite This Paper as: Chandrashekar and T.S. Devaraja (Year), Cost-Benefit Analysis of Ethanol Production: A Special Reference to Sugar Industry in Karnataka. *The Journal of African Development*, Vol. 7, No. 1, 1581-1598

KEYWORDS
Biofuel, Generation Feedstock, Sugar Industry, Sugarcane, Ethanol Production, Cost-benefits Analysis, Costing Model, Pricing mechanisms

Corresponding Author
Chandrashekar
chandrashekar.hsg@gmail.com

Article History
Received: 21.06.2026
Accepted: 09.07.2026
Published: 19.08.2026

10.61336/jad.0701.02

ABSTRACT
India has been producing more ethanol and this growth is anticipated to continue by generation. And Increased ethanol consumption is seen by many politicians as a means of advancing energy security and environmental objectives, including lowering greenhouse gas emissions. Based on a study by Sugar Industry Context, this document presents a benefit-cost analysis of growing ethanol consumption and cost model for ethanol product from context of sugar industry sector such as Belgavi, Bagalkot, Mandya and other major Sugar Industry and the data collected through Survey of ethanol producing sugar industry in the state of Karnataka, for the present study the Mean scores of Survey data will be used. Researcher discover that the annual cost of raising ethanol production to over ten billion gallons is probably going to outweigh the benefits by roughly three billion dollars. Additionally, researcher propose that future government should think about eliminating ethanol incentive schemes like the ethanol tariff and tax credit, as previous attempts to promote ethanol would have probably failed a benefit-cost test.

INTRODUCTION

Biofuels are the only renewable energy source directly used in the transportation sector. Since they are blendable and liquid (or gaseous) fuels that work with present engines, they have the potential to break through conventional hurdles to market entry. For instance, ethanol may be simply blended into modern conventional gasoline automobiles up to at least 10% of the total, and into considerably greater amounts in vehicles that have been converted to accept it. For use in traditional diesel engines, biodiesel can be mixed with petroleum diesel fuel at any ratio up to 100%. Furthermore, Roksolana Vasylyshyn [1] with only minor equipment modifications, biofuels may be distributed using the same well-established infrastructure. Initiatives to create biofuels from renewable resources as sustainable substitutes for fuels derived from petroleum have increased due to worldwide power and sustainability issues. Bioethanol, biobutanol, biodiesel, vegetable oils, bioethanol, pyrolysis oils, biogas, and biohydrogen are examples of biofuels. Two liquid transportation fuels derived from biomass around the world have the potential to displace diesel and petrol. They are biodiesel and bioethanol. Corn and sugarcane are the main feedstocks for bioethanol production. Bioethanol is an additive or replacement for petrol. It was assumed that the lignocellulose plant was an Nth generation plant with no kind of expenses in order to compare the lignocellulose-to-ethanol process costs to the commercial corn-to-ethanol costs [2]. Since the biofuels industry makes up a small percentage of the overall economy, it would appear that a partial equilibrium study of the industry should be adequate [3]. This tends to put the prices of the lignocellulose plant on par with those of the established, well-known maize ethanol sector. Each process's annual expenses for producing 25 million gallons of fuel ethanol were computed. According Hood [4] hundreds of biodiesel installations are operating globally, lignocellulose ethanol factories have started in the USA, and technological advancements are being made that will quickly advance the biofuels sector. By using thinned biomass as an ethanol feedstock, it may be possible to generate significant funds for socially beneficial thinning treatments [5]. In their review article on ethanol production processes, Cardona and Sánchez [6] reported that implementation of thermal integration and reactive distillation reduces process operation costs and energy use by more than 30%. According to Hahn and Cecot [7], the US federal regulatory policies regarding mandatory production of corn ethanol and tax credits for corn ethanol led to net costs to society greater than benefits by approximately 3 billion per year. Using general equilibrium modelling for Renewable Fuel Standard (RFS), Huang *et al.* [8] revealed that ethanol expansion through mandate leads to welfare losses for consumers unless very high social values of carbon are used. In a paper analysing US biofuel policy evolution history, Tyner *et al.* [9] revealed that combination of tax credit program for blending and changes in crude oil prices created market distortions and agricultural commodity volatility (Figure 1).

The necessity for local, emission-free sources of energy is further highlighted by political unrest in oil-producing locations and global warming dangers Cavelius [10]. The most popular biofuel for transportation in the world is bioethanol. Sugarcane accounts for over 60% of the world's bioethanol output, with other crops accounting for 40%. Biodiesel is an oxygenated fuel based on mono alkyl ester that is comparable to diesel. The manufacturing of biodiesel from waste oil, grease, and inedible vegetable oil has grown non popularity recently. Using lignocellulosic biomass, such as sugarcane bagasse, to produce ethanol reduces the need for oil and is considered an environmentally benign method [11]. In their analysis of NREL advanced biofuel pathways, Tao *et al.* [12] reported that reduction of cellulase enzymes cost and optimized biomass logistics represent critical factors for achieving parity with petroleum fuels. Once various parameters, including plant capacity, process technology, raw material cost, and chemical cost, have been recognised, the economic performance of a biodiesel plant can be ascertained. A techno-economic design study published by Humbird *et al.* [13] has proven that cellulosic ethanol from corn stover could become commercially viable considering enzyme cost reductions and electricity revenue. The main goals of biofuel policy are environmental preservation, employment creation, and increased productivity in the overall business environment. The realization of non-market benefits is frequently the impetus for attempts to expand the use of biofuels in most countries starting biofuel projects, particularly in light of climate change. The idea that ethanol is only consistently and uniquely consumed by modern humans prompts us to reevaluate ethanol's ecological function and evolutionary significance in the natural world [14]. According to some research, when comparing biofuels to fossil fuels over their whole life cycle, biofuels can significantly lower greenhouse gas (GHG). On a large industrial scale, sugarcane, corn, or beetroot sugar is utilised to produce first-generation ethanol. The minimal ethanol selling price dropped with increasing scale for both C-CBP and the traditional processing paradigm, showing that lower investment expenses more than offset the cost penalties resulting from longer feedstock transport distances. This can be especially important for industries that are difficult to regulate, such as shipping, heavy-duty transportation, and aviation [15]. According to Dias *et al.* [16], process simulation revealed that combination of 1st and 2nd generation sugarcane biorefineries results in decreased capital expenditures and maximum energy balances comparing to 2nd generation biorefineries only. Large reductions are predicted for ethanol made from sugarcane and cellulosic feedstocks, as well as other waste-derived biofuels, even though predictions vary widely [10]. Furthermore, the removal of CO2 from the environment can be aided by combining bioenergy with carbon capture and sequestration, or BECCS, in addition to helping with emissions mitigation. The results of a techno-economic evaluation (TEA) and a life cycle assessment (LCA) indicated that the STL of KW is simultaneously financially feasible and environmentally conscious [17]. The results of the experiments provide valuable information for future study on the enhancement, extraction, and refinement of bio-oil. Strong emissions from the transportation and sugarcane production processes greatly increased the carbon footprint [18]. In addition to improving soil fertility and features, mulching resulted in a far reduced net emission (Figure 2).

In addition, the manufacturing of biofuels derived from crops gives farmers access to a new market and boosts the local economy in rural areas. According to Ramakrishna [19], entirely decentralised and mostly takes place in rural regions. Since trees must be cultivated on both public and private land, it raises rural residents' incomes and creates jobs. These oilseeds are mostly collected by rural women. However, the development of biofuels has the potential to divert crops from other purposes (like food production) and drive up the cost of those crops. Techno-economic assessments conducted by Kazi *et al.* [20] among several cellulosic ethanol production pathways concluded that biochemical pre-treatment with dilute-acid reduces minimum ethanol sale prices below thermochemical conversion routes. Under certain conditions, this could result in increased costs for consumers and unfavorable competition with the food supply. Nevertheless, biofuels can produce benefits and support several policy objectives, as well as tactical

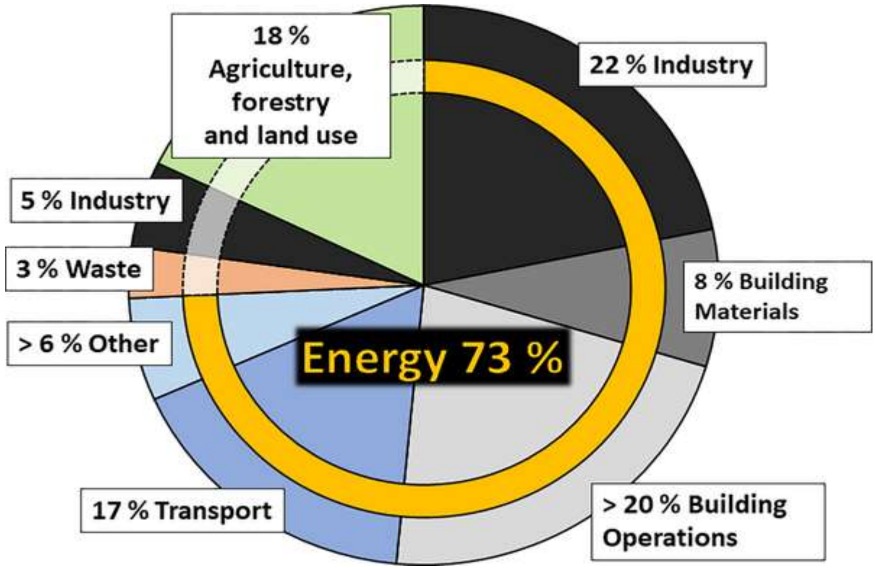

Figure 1: Global Co2 Emissions Divided by Respective Sectors.
Source: [21]

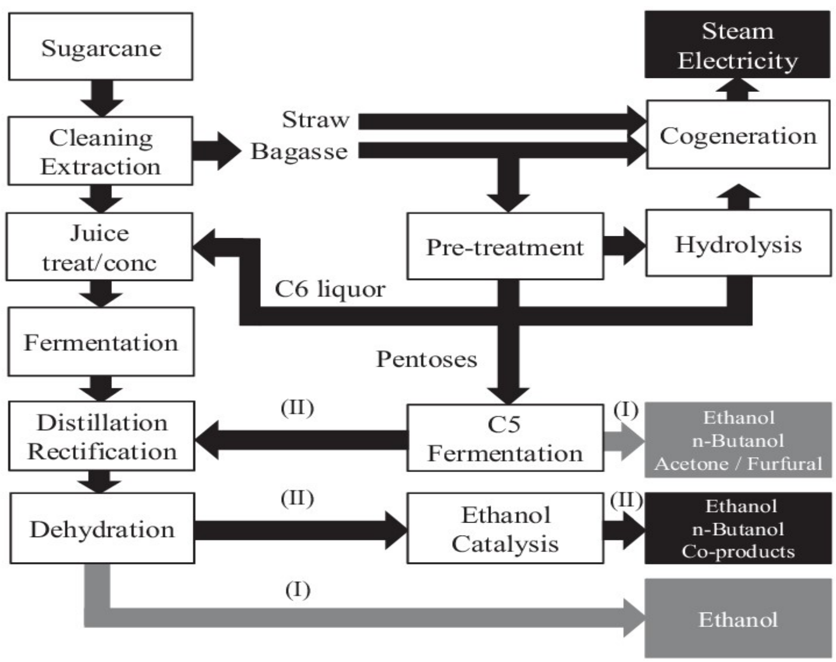

Figure 2: Ethanol Production Process by Sugar Industry

requirements from society and the economy, when they are well-planned and cautiously implemented to prevent environmental and social dangers. Caldeira [22] 65% of the world's total biofuel production is made up of ethanol. It is essential to create varieties of yeast that can ferment these sugars and additional byproducts, including cellobiose, l-arabinose, mannose, and galactose, Kucharska K [23] in order to effectively make 2 G ethanol. Although there is proof that lignocellulosic substrates can produce 2 G of ethanol. Saini J K [24] Monetary revenues would be used to gauge the socioeconomic effects, which would enhance the standard of living for small and middle-class farmers, especially in emerging nations. Sorda *et al.* [25] provided the review of international biofuel incentive policies revealing that fiscal supports result in trade distortions while being highly ineffective in terms of economic costs per ton of carbon emissions reduction. In his study on ethanol blend mandates, Babcock *et. al.* [26] found out that while renewable fuel mandates raise farmer income, they cause economic welfare losses for livestock producers and gasoline consumers. Analysing the socioeconomic effects of biofuels mandates, Rajagopal [27] concluded that policy induced demand for corn ethanol causes international food price inflation leading to economic welfare loss for developing countries.

Literature Review

Conventional fuels, such as ethanol, are derived from a variety of plant resources known as biomass. Fermentation is the process by which the biomass is transformed into ethanol using starches from plants and sugar. Microorganisms break down plant carbohydrates to create ethanol throughout this process. MHSc examined the advantages and disadvantages of boosting ethanol consumption using data from the Environmental Protection Agency. According to the studies, it will probably cost more than three billion dollars annually to increase ethanol output to about ten billion gallons annually. The state should think about eliminating ethanol incentive programs like the ethanol tariff and tax credit because it is thought that prior attempts to promote ethanol would have failed a benefit-cost analysis. A Mahadik examined the economics of molasses-based byproducts in several Maharashtra State districts. According to the study, using the primary by-products, bagasse and molasses, will bring the cost of producing sugar down to a marginal level. According to Hill *et al.* [28], corn ethanol derived from the USA has a net energy gain of 25% and can cut back the emissions of greenhouse gases by 12%, yet the net benefits from society will be restricted by the excessive flow of agricultural chemicals against soybean biodiesel. In order to lower the overall cost of sugar, the study's conclusion recommended that all sugar factories make efficient use of their byproducts. It was stated by Shapouri *et al.* [29] that thanks to improvements in crop yield and biorefinery efficiency, the net energy ratio of corn ethanol increased to 1.34. From the first artificial fire through the use of lyophilized timber as a fuel for power stations, bioenergy has always been a dependable form of energy. According to Goldemberg *et al*. [30], Brazilian sugarcane ethanol is one of the most efficient fuels because of its ratio of the net energy exceeding 8.0 and low costs compared to fossil fuels. Although the idea of using lignocellulosic feedstock as a solid biofuel is not new, turning biomass into liquid fuel is a significant difficulty. The more sophisticated the biomass, the more difficult and generally costlier the conversion process involves. V Seecharan Biofuels are divided into four groups based on their feedstocks and manufacturing techniques: first, second, third, and fourth-generation biofuel. Researchers have focused on biofuels manufacturing using first-generation feedstocks as diesel substitute engines. Vegan's oil, Tallow, and leftover cooking oil are the feedstocks used in biodiesel in the first generations of biofuels. MA disclosed in his paper that all Indian sugar mills should start using bagasse and molasses. Projects involving ethanol, alcohol, and paper have enormous potential for growth in India. In the future, blending 10 to 15% ethanol with gasoline might be permitted. Through the resolution of the conflicting energy models, Farrell discovered that corn ethanol has a positive net energy of 1.2-1.4 with petroleum reduction to 95%. Power needs would be met by installing bagasse-based power production projects next to each sugar factory. The biodiesel contributes less to global warming and contains less contaminant in its emission owing to the renewable nature. The industrialized nations produce enormous amounts of used cooking oil waste TJ. Recycled waste cooking oil is harmful to human health, if consumed. The possible solution is to convert it into biodiesel. Esterification and transesterification are common progressions for creation of biodiesel from leftover cooking oil. Kim and Dale made a global assessment in their research and found out that sugarcane and cassava ethanol are more efficient and effective than any grain feedstock. Although most biodiesels are from vegetable oil in the first generations, which is lead to the price of biodiesel will be higher than that of traditional fossil diesel. Esterification and transesterification process is same for first, second and third generation biofuels. Spatari *et al.* [31] carried out a life-cycle assessment which confirmed that cellulosic ethanol from switchgrass provides significantly better environmental and energetic balance than starch ethanol from corn. Secondary products like glycerol or value-added products like bio lubricants, greases and polyurethane also have great market potential.

Biofuel is frequently used for a variety of purposes, including heating and transportation fuel showed that a number of by-products, particularly bagasse and molasses, are present in the sugar production. Bagasse was once utilized as fuel, and sugar companies were unsure of how to handle the buildup of molasses, which posed a health risk. The studies of Pimentel and Patzek using thermodynamic analyses revealed that the creation of ethanol from corn, switchgrass, and wood requires the expenditure of 29%, 50%, and 57% more fossil fuels than the produced energy. These byproducts can be positively disposed of by setting up small cottage enterprises to make paper, cardboard, alcohol, fertilizer, cow fields, etc. The rate of biofuel is significantly affected by feedstock costs, while the prices of waste are impacted subsequently. Carryiquiry Feedstock expenses account for up to 40–80% of the entire cost of producing first-generation biofuels. The amount of RH presented globally was shown to be an extremely appealing feedstock for ethanol biofuel conversion. Using a novel methodology, it was determined that the annual global production of bioethanol from RH ranges from 20.9 to 24.3 billion litres [32]. For E5 gasoline, this bioethanol supply equates to about 374% of the world's demand, for E10 gasoline, to 19%, and for E25 gasoline, to 71%. The RH-to-ethanol sector was demonstrated to have the most potential in the Asian and Southeast Asian regions, with India having the greatest potential due to its existing very positive supply-demand balance for bioethanol. The objective of the present review is to consolidate the research findings of using the whole sweet sorghum plant (lignocellulosic biomass, stalk juice and grain) as feedstock for biofuel production It is the only crop that produces grain and stem that may be used for chewing, paper, roofing, fencing, syrup, alcohol, jaggery, feed, fuel, and bedding. Melillo combined biogeochemical and economic models and concluded that indirect land use change caused by biofuel production releases enough carbon and nitrous oxide to eliminate direct displacement benefits of fossil fuels.

The main purpose of biofuels is to augment the transportation fuel supply and given the recent surge in fascination with biofuels, it's critical to comprehend how they differ from fossil fuels. Fossil fuels originate from the remains of plants and animals that were once alive hundreds of millions of years ago. Under the study Deepak Rajagopal [27] makes the argument that India's' biofuel program has several flaws. Jatropha and Pongamia have the potential to play a significant responsibility for addressing the country's long-term liquid fuel needs. This study states that both promoters and opponents of biofuels believe that there isn't enough land available to grow huge volumes of fuel grains without inflicting a significant impact on world food supplies. Fargione *et al.* [33] found out that conversion of native habitats to plant biofuels creates "biofuel carbon debt," which needs to be paid back during decades or even centuries of biofuel use. Wang *et al.* [34] updated the GREET life-cycle model to prove that improvements in agricultural productivity and efficiency of biorefineries led to 34% reduction in carbon footprint of corn ethanol between 1990 and 2010. Liska [35] used field measurements of utility consumption in Midwest ethanol plants and proved that modern closed-loop biorefineries emit 59% less GHG emissions compared to gasoline. Searchinger updated carbon accounting in bioenergy and came to conclusion that assumptions about bioenergy being carbon neutral lead to incorrect policy and misallocation of financial resources. Searchinger corn ethanol made from crops results in double emission of greenhouse gases over 30 years due to indirect land use change compared to reduction in emissions. EDGE indicates that the sugar industry is a significant source of byproducts such as bagasse for the paper sector and molasses for the alcohol, ethanol, and chemical industries. With over 55% of the established units, the cooperative sector dominates the Indian sugar industry. Sixty percent of India's entire sugar production comes from Maharashtra and Uttar Pradesh alone.

The study outlines Perez-Pena the empirical analysis about those Countries with a higher reliance on imported oil, a higher share of the agricultural labour force, more access to arable land, and higher per capita income are more likely to embrace biofuel policies. MacLean and Lave provided a life-cycle study on ethanol fuel and concluded that E85 has less fossil energy use and urban greenhouse gases but increased tailpipe aldehydes. In this study, both economic and environmental implications were evaluated. And the measures developed target long-term sustainability. The committee's two recommendations—removing the levy sugar obligation from the 2012–13 sugar season and deregulating the release mechanism for non-levy sugar—revealed that the sugar sector's concerns regarding cane reservation area and bonding minimum distance criterion, price of sugarcane levy sugar obligation, regulated distribution of free sale sugar trade policy for sugar, oversight relating to by-products and other issues like jute packaging materials, and other issues needed to be implemented over a period of two to three years. Quintero [36] studied ethanol processing in Colombia and found that sugarcane molasses has lower production cost than corn or cassava because of heat integration. India has total geographical area of 328 million hectares out of which around 142 million hectares is used for agriculture. Dennis *et al.* [37] conducted a literature review on the economic value of ethanol co-products, and showed that sales of DDGS are crucial because they compensate the volatile costs of feedstock. By 2030 Indian population is expected to rise to 1.5 billion from around 1.1 billion presently.

To feed this much number even with very conservative estimates will require around 185 million hectares of agricultural land with an assumption that the land productivity remains same. Silalertruksa and Gheewala [38] studied bioethanol growth in Thailand and found out that cassava and sugarcane molasses have promising net returns economically, but the increase of cultivation area poses a risk of higher water footprint locally. For food security we should focus on the increased use of waste land to promote environment friendly biofuels. High speed diesel is the largest consumed Petro-product in India on account of better mileage, power and lower administered price compared to petrol Raj Kumar. Mass utilization of diesel in India imposes a threat to meeting the future energy needs, if the unexpected volatilities in the price of petroleum persists in future and government of India enforces oil marketing companies to sell diesel at uncapped price. Crago discovered that despite the relatively lower cost of raw material production of Brazilian sugarcane ethanol compared to US corn ethanol, international shipping costs and corn co-product credits made them equally competitive in the market. With an approximate import dependency of 90%, energy security favours the adoption of 20% blending by Jatropha biodiesel. Production of 31.4 million tonnes of Jatropha biodiesel i.e. is 20% of total diesel requirement will require about 26 million hectares of land by 2020. Hettinga applied experience curve approach and revealed that through learning and economies of scale, the real production cost of US corn ethanol declined by 45% during the period of 1980–2005. Patil how much it costs to produce biodiesel from Pongamia oil. The main cost variables are feedstock acquisition, chemical solvents, plant size, and byproducts. The main obstacle to maintaining a viable manufacturing cost is the availability of feedstock. Using Pongamia seeds, Bharadwaj observed the bio-diesel generation process. Diesel, a fossil fuel, is used to assess the oil's efficiency. It is feasible to blend between 30% and 60%. Compared to other biofuel feedstocks, the total cost of manufacturing is quite low. According to V.B. biodiesel is the fuel that is most environmentally friendly. Pongamia pinata is a readily accessible oil-bearing seed used as a raw ingredient for biofuels. Pongamia seed production yields range from 24% to 31%. The most cost-effective method of manufacturing is the transesterification of seeds.

Objectives Of the Study

- To study the Biofuel Generations and Feedstock availability in India
- To analyse the status of sugar industry and Area of cane cultivation, Production and Productivity of sugarcane in India and Karnataka
- To Analyse the Cost-benefits of Ethanol based sugar industry in the State of Karnataka

Hypothesis For the Study

- **H1:** Despite Total Cost continuing to be the most statistically predictable variable over time, the annual growth in Selling price is larger and more persistent than the increase in Total Cost, resulting in a growing average operating margin
- **H2:** Per Liter profit is extremely erratic and unaffected by systemic annual trend (Time)
- **H3:** The Pricing mechanism includes an extra yearly premium that reflects either oligopolistic market power or a guaranteed inflationary adjustment mechanism that exceeds the actual cost inflation

MATERIALS AND METHODS

The research approach used to examine Karnataka's ethanol production status is described in this section. The methodology for this study concentrates on data sources, analytical methods, and validation procedures to guarantee correctness and dependability because it is based on both primary and secondary research. And on the other side researcher uses the data for mathematical costing model for accurate the statistical data.

Research Design

Using only secondary data sources, this study employs a descriptive and analytical research methodology to investigate the sugar sector that produces ethanol. The following stages of the study were carried out: This study is based on an extensive analysis of current literature and policy documents, including government and other Relevant data was gathered from reliable sources, including international organizations, top research institutes, and official government databases, to support this analysis. This information included insightful information about the agricultural, environmental, and economic aspects of ethanol production and consumption.

Data Sources

Considering the study is based on both Primary and secondary research, the following trustworthy sources provided the data:

- **Overnment and Institutional Reports**: The government and institutional reports of the sugar industry and other agencies like MNRE and KREDL other were considered in this study. these studies validate the program's contribution to meeting India's climate targets and aid in quantifying the environmental advantages of ethanol consumption. Through its reports on biofuels, food security, and international ethanol policy, the Food and Agriculture Organization (FAO_2025) provides significant insights on a worldwide scale. Its research offers a more comprehensive framework for comprehending how ethanol production impacts food systems and agricultural sustainability in various nations.

- **Industry and Academic Publications:** One important industry organization that offers comprehensive information on ethanol production trends, sugarcane economics, and the general effectiveness of blending schemes in India is the Indian Sugar Mills Association (ISMA_2024). Its publications and industry updates provide insightful information about how the sugar business contributes to the ethanol supply chain and how changes in prices and policies impact the dynamics of production. In-depth research on the wider effects of ethanol blending on agricultural sustainability is carried out by the Indian Council for Research on International Economic Relations **ICRIER (2024).** Their study aids in determining if rising ethanol consumption is consistent with resource efficiency and long-term agricultural resilience. Scholarly publications on biofuel technologies, climate change mitigation, and the agroeconomic effects of ethanol policies can be found in peer-reviewed journals like those offered on ScienceDirect, Springer, and Wiley. These scholarly works offer evidence-based viewpoints that deepen the study's analysis and guarantee that the research is based on reliable and current findings.

Scope of the Study

The data collected through both primary and secondary sources from Ethanol based Sugar industry and this would pertain to 2014 to 2025 year in specific to Karnataka state.

Data Analysis Methodology

The viability of ethanol production for Sugar Industry was assessed by a cost-benefit analysis that concentrated on pricing systems, government subsidy programs, and new revenue trends. Any this through done by Major SPSS Tools and Understanding how these financial factors affect Industry growing important feedstocks like sugarcane and maize required data and insights from the Indian Sugar Mills Association ISMA. This approach aids in determining whether ethanol production presents rural areas with a sustainable and profitable possibility. Additionally, an analysis of agricultural income was done to determine the impact of ethanol procurement on total farm earnings. The Commission on Agricultural Costs and Prices' CACP reports offered crucial details about the profits farmers get from crops tied to ethanol.

Biofuels And Its Generations

Primary biofuels are biomass that is utilized directly for energy (mainly heat or power) after little processing, such as drying, chipping, or compressing. They do not require complicated chemical conversion to liquid or gaseous transportation fuels. Feedstock/Examples: These are usually solid biomass residues. Animal waste. Chips (wood chips), charcoal, farm refuse (straw and stalks), Pellets (compressed biomass), wood (firewood), and Secondary biofuels are made from biomass using complex chemical or biological conversion processes (such as fermentation, transesterification, or gasification) to produce liquid or gaseous fuels appropriate for modern transportation engines. Derived from edible crops of food source (corn, sugarcane, soybean). Despite being commercially viable, major issues related to food versus fuel security and land use compete are of concern [10]. from non-edible lignocellulosic material, agricultural residues, and forest biomass. Better carbon balance, but difficult pretreatment process required. Obtained from microalgae, macroalgae, and aquatic biomass. High yield potential without competing for arable land, although intensive harvesting process is involved. Make use of metabolic engineering, synthetic biology, and photobioreactors to achieve carbon dioxide fixation or synthesis of solar fuels [10]. These are further divided into four "Generations" based on feedstock type, indicating a shift toward greater sustainability. First Generation (Edible-Based Biofuels): These are made from food crops or crops that use valuable agricultural land. Sugar, starch, or oil crops (such as corn, sugarcane, and soybeans). Second Generation (non-edible based biofuels). These fuels are made from non-food biomass or waste, which addresses the ethical problems of the first generation. Lignocellulosic biomass (cellulose and woody materials, such as crop wastes, forestry waste, and non-food energy crops) [10]. Third Generation (Algae-Based Biofuels) This generation focuses on exploiting fast-growing, oil-rich microorganisms that require very little land. Algae and other microbial biomass is 4th generation (microalgae-based biofuels). This is the most advanced technical generation, which frequently involves genetic engineering or integration with carbon capture systems. Microalgae that have been genetically modified or integrated into systems that collect carbon. The division of biofuels into four generations reflects an ongoing endeavour to improve sustainability by moving away from feedstocks that compete with food. Arvind H, Hirani [39] Recent technological developments in research and development have created an opportunity for next-generation biofuel production from varied inputs such as agricultural waste materials, crop leftovers, and cellulosic biomass from highly productive varieties of grass (Figure 3).

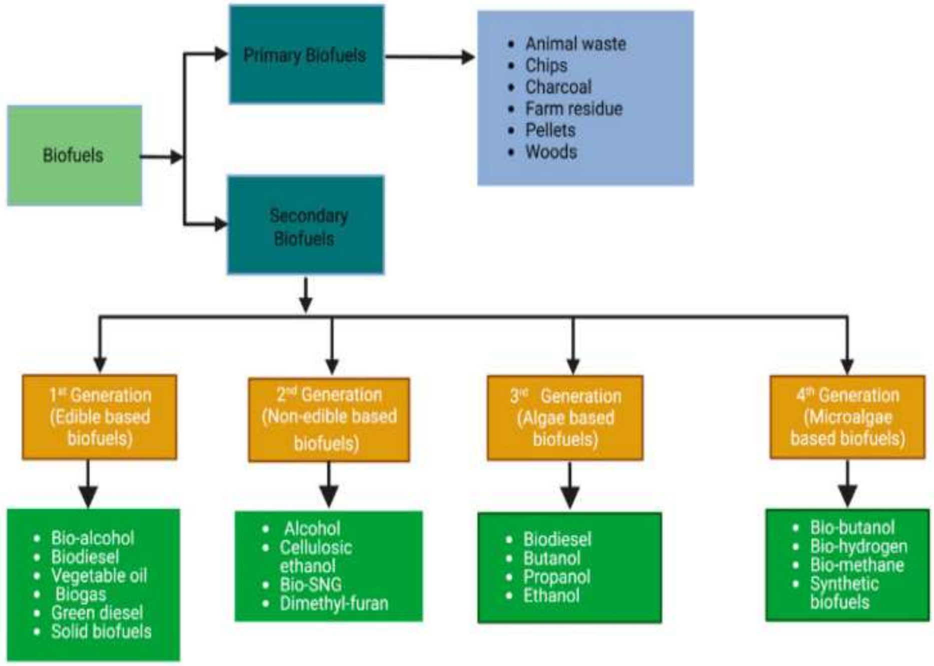

Figure 3: Generations Of Biofuel and Feedstock Availability
Source: [40]

The Phase 1 (1st Gen) Focused on proving the concept using readily available food crops. First-generation biofuels rely on readily available edible biomass (sugars, starches, and vegetable oils), but they suffer from the "Food vs. Fuel" conundrum. Liquid biofuels are now more affordable than petroleum-based fuels for transportation, thanks to the sharp increase in oil prices over the past decade, which has sparked a global surge in research and production. Cavelius *et al.* [10] gave an elaborate comparison of first- to fourth-generation biofuels through biochemical pathways, efficiency, and motivations for their use in transportation. Lugani *et al.* [41] discussed advances in technology for the processing of lignocelluloses (second generation biofuels) using advanced biocatalysis and genetic techniques. Phase 2 (2nd Gen) Shifted focus to utilizing non-food waste and residues to enhance sustainability. El-Araby [42] Reviewed systemic approaches to generating bioenergy and provided evidence that integrated biorefineries producing valuable biochemicals together with 2G/3G fuels enhance economic feasibility. The second-generation changes to non-food biomass such as lignocellulosic waste (straw, wood residues) and specific non-food crops, which provide plentiful availability while avoiding competing with the food supply, but supply chain logistics remain complex. Mat Aron assessed the sustainability indicators for all the four generations of biofuels in terms of net greenhouse gas emissions, land use footprint, and energy efficiency. Investigated global supply chains and found that lignocellulosic residues from 2G are the most feasible alternative at the moment to reduce dependence on fossil fuels without threatening food security. Second-generation biofuels production is likely to face substantial barriers to broad commercial implementation. The logistics of supplying a commercial-scale facility with a competitive, year-round accessibility to biomass feedstock are difficult, as is enhancing the conversion procedure' efficiency to cut expenses. And Phase 3 (3rd & 4th Generation Explored advanced, high-yield microbial sources (algae) and cutting-edge biotechnology to minimize land use and maximize environmental benefits, including carbon capture. Khan *et al.* [43] information on atmospheric and environmental effects resulting from switching from first-generation biofuels from crops to advanced water-based biofuels. Mohan *et al.* [44] biochemical characteristics of biodiesel in terms of 1G to 4G feedstocks, indicating that CRISPR-Cas genome editing in 4G systems enhances metabolic lipid production yields by more than 30%. The third generation uses algae, which has a high potential availability and yields per area, and is grown on non-arable land, hence decreasing land-use impact. Third-generation biofuels derived from microalgae are believed to be an appropriate replacement for the energy supply, free from the primary limitations related to first and second-generation biofuels Bajpai, [45].

Table 1: Generation Wise Feedstock and Major Focus

Gen.	Concept	Feedstock Source	Key Examples	Environmental/Economic Focus
1st	Edible Based Biofuels	Crop feedstock for food (Sugar, Starch, Oilseed)	Ethanol from crops, Biodiesel from oil seeds, Biogas.	Highly efficient but it has the "Food versus Fuel" dilemma.
2nd	Non-edible Based Biofuels	Lignocellulosic feedstock (Residues, Waste, and non-edible crops)	Ethanol from cellulose, Alcohols (Butanol, Propanol), Bio-SNG, Dimethyl-furan.	Resolves "Food versus Fuel" dilemma by using agricultural and forest residue.
3rd	Algae Based Biofuels	Microalgae and other organisms that grow rapidly	Biodiesel, Butanol, Ethanol, Propanol (Produced through lipids and carbohydrate metabolism in algae).	Highly productive in terms of land use (not competes with arable land) and grows in saline and wastewaters.
4th	Microalgae Based Biofuels	Genetic modified microalgae, frequently in combination with carbon capture.	Hydrogen, Methane, Synthetic bio fuels.	Looks for high efficiency, genetic engineering,

Cavelius *et al.* [10] Conducted a thorough comparison of all four generations and found that although 3G and 4G provide better fuel yields per unit area, the cost of initial investment remains prohibitive Finally, the fourth generation concentrates on designed biomass (microalgae) and Carbon Capture and Utilization (CCU) technologies, with the goal of theoretically endless output and carbon-negative fuels; however, this is still in the research and development stage. Abdullah *et al.* [46] examined 4G risk profiles and pointed out that regulatory challenges for genetically modified microalgae in open environments represent a significant barrier to commercialization. The overall trend indicates a clear shift from resource-intensive, food-based feedstocks to resource-efficient, waste-based, and aquatic feedstocks. Usmani [47] the beneficial effects of 2G advanced biofuels on the regional economy, achieving 88% of lifecycle GHG reductions compared to standard gasoline. Based on the feedstock and level of technological complexity used, secondary biofuels are divided into four generations, which primarily reflect the industry's shift towards higher sustainability (Table 1).

RESULTS AND DISCUSSION

Status of sugar industry and Area of cane cultivation, Production and Productivity of sugarcane in India and Karnataka

The Indian sugar industry is one of the most important Agro-based industries in the country. It directly employs over 5 lakh people in sugar mills across the nation and affects the livelihoods of over 50 million sugarcane growers, making it the foundation of the rural economy. India is the second-largest producer of sugar in the world, regularly challenging Brazil for the top rank, with yearly production typically exceeding local demand. It is also the biggest consumer of sugar in the entire globe, guaranteeing a sizable and steady domestic market. Utilising the strong demand for ethanol to stabilise its finances, assist farmers, and concurrently contribute to the country's energy independence and climate goals, the Indian sugar industry is undergoing a phase of strategic reorganisation. Ugar and jaggery are the most affordable ways to obtain energy, contributing roughly 10% of the daily calorie requirement. Sugarcane has been predicted as the crop for the future, contributing to the creation of not just sugar but also a sustainable source of renewable power in the forms of bioethanol, bioelectricity and numerous biobased goods. The industry generates 350–365 million tonnes (Mt) of cane, 25–27 Mt of white sugar and 6–8 Mt of jaggery and khandsari on an annual basis. Besides, around 2.7 billion litres of alcohol and 5500 MW of power and several chemicals are also produced. Approximately 3200 MW of power can be exported by the industry to the electrical grid.

A major, government-led shift towards diversification and integration with the bio-energy sector characterises the industry's current state. The industry's shift to the Ethanol Blending Program (EBP) is currently the primary driver of its structural transformation, following decades of crippling cycles of excess production, fluctuating prices, and financial strain. The industry is stabilising its revenues, improving cash flow for timely farmer payments, and concurrently advancing national energy security initiatives by lowering crude oil imports by rerouting excess sugarcane and other byproducts (molasses) towards ethanol production, with ambitious blending standards like the now-achieved 20% (E20). The water-intensive nature of sugarcane cultivation, low average productivity in comparison to worldwide peers, and the fundamental challenge of reconciling regulated sugarcane rates with unpredictable global sugar price fluctuations continue to pose challenges to the sector despite this revolutionary advancement. Essentially, the Indian sugar industry is a vibrant economic behemoth that aspires to become a contemporary, integrated food-and-fuel complex rather than a single-product commodities market. A few large states control the majority of India's sugarcane industry, and there are noticeable disparities in productivity and efficiency between the North and South (Table 2).

As the main source of sugar, jaggery (gur), and khandsari, as well as a vital raw material for the nation's second-largest agriculture-related industry (after textiles), sugarcane has enormous economic and agricultural significance in

India. The socioeconomic well-being of millions of farmers and labourers is significantly impacted by its cultivation. India regularly ranks as the second-largest producer of sugarcane after Brazil, making it a significant player in the global sugarcane market. About 5 million hectares of farmed land, divided between two main agroclimatic zones—the tropical area (mostly Maharashtra, Karnataka, and Tamil Nadu) and the subtropical region (dominated by Uttar Pradesh)—are responsible for this astounding productivity. From the farm to the factory, Indian sugarcane travels through a dynamic interplay of multiple elements. The overall area used for the crop varies according to climate, government regulations, and farmer choices. The enormous amount of cane that was collected was greatly impacted by the introduction of technology and advantageous monsoon patterns. India frequently lags behind several other major cane-producing countries in terms of output per unit area (tph), highlighting a crucial area for technological intervention and improvement (Figure 4-7). The state authorities are working with sugar factories and the Sugarcane Research Institute to organise highly productive sugarcane cultivars. The GPS could assist in making sure that farmers are paid on time for their purchases (Table 3).

Table 2: India's Sugarcane Production, Area, And Productivity

Metric	All-India Trend	Leading States (Approximate Ranks)
Area ('000 Hectares)	Varies, approximately 4.7 to 5.0 million hectares.	1st: Uttar Pradesh (UP), 2nd: Maharashtra, 3rd: Karnataka
Production (Million Tonnes)	Increasing trend in the long term, very variable every year depending upon rains/price.	1st: Uttar Pradesh (approx. 45% of total), 2nd: Maharashtra (approx. 23%), 3rd: Karnataka (approx. 11%)
Productivity (Tonnes per Hectare)	All India Average yield is approximately 70-80 tons/hectare. It is very low when compared with other world leaders (approximate 90-110).	1st: Tamil Nadu, 2nd: Karnataka, 3rd: Maharashtra

Table 3: Status Of Sugar Industry and Area of Cane Cultivation, Production and Productivity of Sugarcane in India

Year	Area ('000 ha)	Production ('000 tons)	Productivity (tons /ha)	Cane Crushed ('000 tons)	Sugar recovery (%)	Sugar ('000 tons)	No. of Sugar factories
2012-13	4998	341198	68.3	250598	10.03	25141	526
2013-14	4993	352142	70.5	238176	10.23	24360	513
2014-15	5067	362333	71.5	273073	10.37	28313	538
2015-16	4927	348448	70.7	236498	10.62	25125	526
2016-17	4436	306070	69.0	193434	10.48	20262	489
2017-18	4732	376905	79.66	301198	10.73	32328	525
2018-19	5114	405427	78.25	301179	11.01	33163	531
2019-20	4603	370500	80.5	259043	10.86	27385	464
2020-21	4857	399263	82.2	301000	10.36	31192	461
2021-22	5175	439432	84.91	356400	10.03	35760	506
2022-23	5883	494228	84.48	401450	11.09	40678	524
Mean	4907.73	379799.00	76.37	273013.55	10.58	29758.82	510.36
CAGR	1.65	3.80	2.15	4.88	0.99	4.98	-0.04
Std Dev	362.59	50926.33	5.76	60924.97	0.36	6023.00	27.28
CV	7.39	13.41	7.55	22.32	3.37	20.24	5.35

Source: (DirectorateofEconomicsandStatistic, 2023)

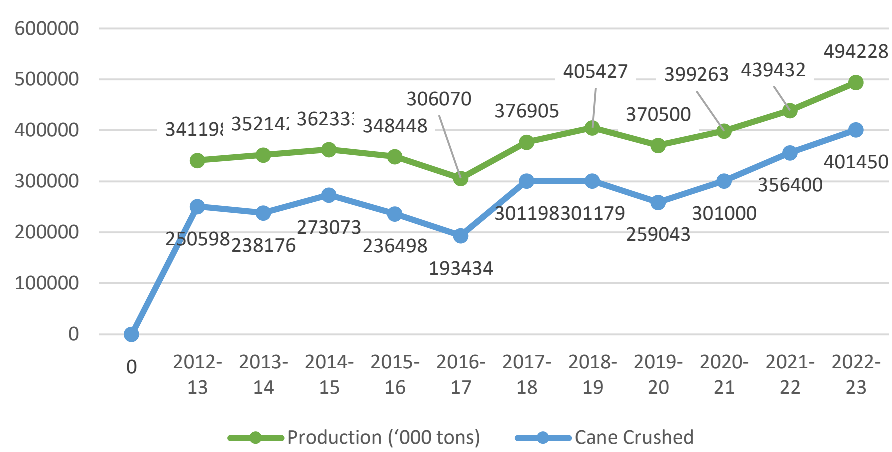

Figure 4: Trends In Sugarcane Production and Cane Crushed

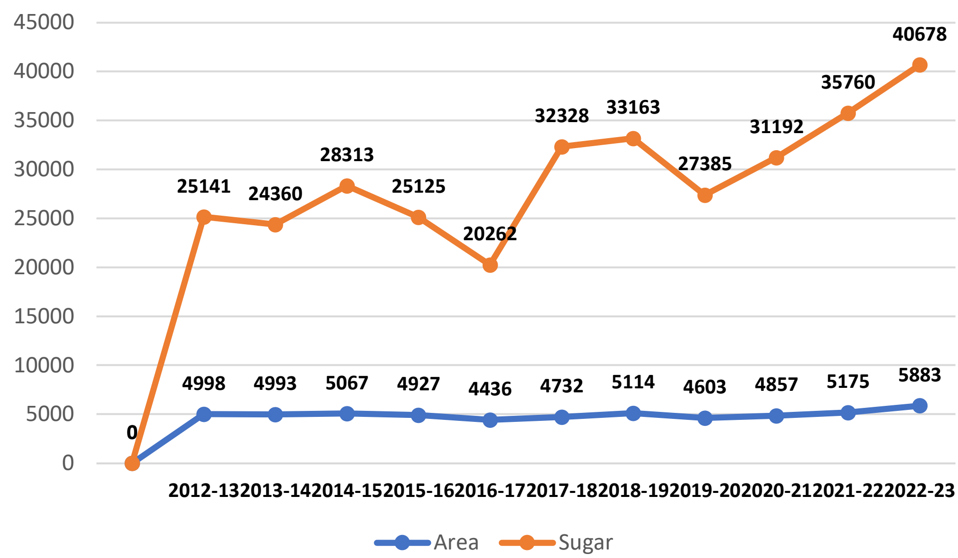

Figure 5: Trends In Sugar Production and Area

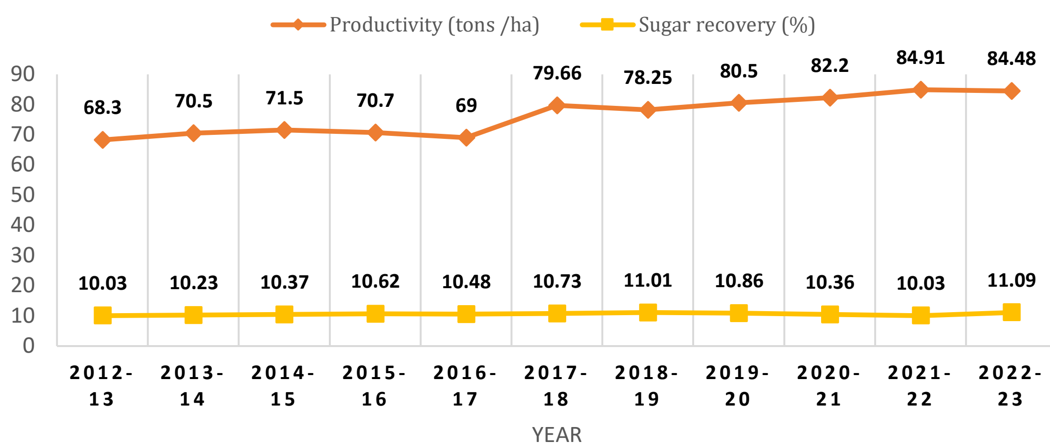

Figure 6: Trends In Sugarcane Productivity and Sugar Recovery Rate

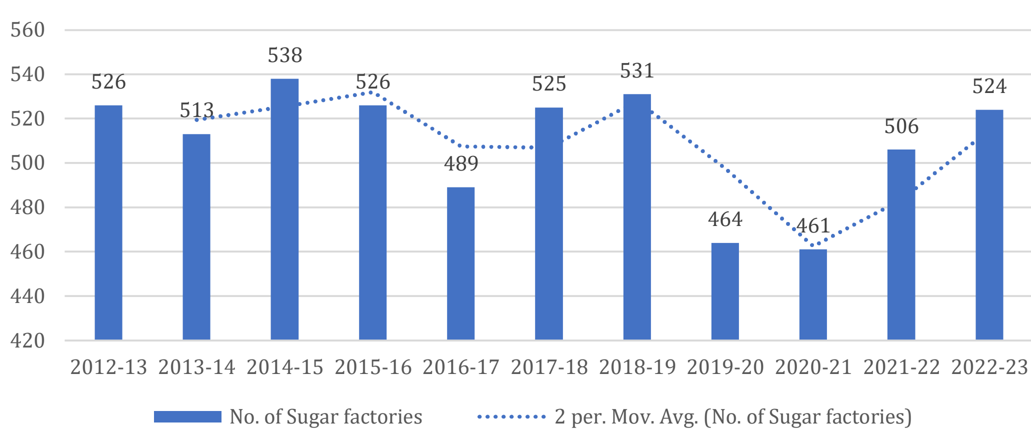

Figure 7: Trends in Sugar Industry in Karnataka

The industry experienced a clear setback in 2016-17, marked by a simultaneous drop in both cultivation area and total production. Following the setback, both Area and Production rebounded strongly from 2017-18, achieving their peak figures in 2022-23. This aligns with the high Compound Annual Growth Rate (CAGR) observed for Production. Productivity (tons/ha) showed a very strong, consistent upward trend after 2016-17, climbing significantly from approximately 68-71 tons/ha to over 84 tons/ha. This reflects substantial gains in farming efficiency. In contrast, the Sugar Recovery percentage remained highly stable, fluctuating only slightly (between 10.03% and 11.09%). This suggests that factory processing efficiency is consistently maintained compared to the volatility and improvement seen in farm-level productivity. Both Cane Crushed and the resulting Sugar Produced followed expected, nearly identical growth curves, both peaking in 2022-23. The Number of Sugar Factories was the most stable metric, showing a slight overall decline and hitting a low point in 2019-20/2020-21, indicating a phase of industry consolidation. Despite the decrease or stability in factory numbers, output volumes grew substantially, implying a significant increase in utilization and capacity per individual factory (Table 3). Increases in Cane Crushed (7.24% CAGR), Production (5.86% CAGR), and Area (5.29% CAGR) comprise the sugarcane industry's robust volume-driven growth, indicating a reliance on increasing utilisation of land and processing capacities rather than efficiency advances. Key productivity measurements have grown almost stagnantly, in stark contrast to this fast input expansion: Productivity (tons/ha) increased by a pitiful 0.68%, while Sugar Recovery (%), a measure of processing efficiency, increased by a mere 0.54%. This highlights a crucial issue where the expansion of the industry is wide (more resources consumed) rather than intense (better resource utilisation), since the growth in final sugar extraction (4.19%) is considerable but falls well short of the growth in crushed cane. While processing efficiency is impressively consistent, the sugarcane industry is highly volatile overall, with the metrics pertaining to input and output volume exhibiting the greatest year-to-year variability. The most volatile figures are Cane Crushed (30.13% CV) and Production (29.00%CV), which show significant fluctuations in industrial processing activity and total yield. These figures are closely correlated by Area (21.96%CV), which shows frequent changes in farmers' planting decisions or weather impacts. In stark contrast, despite the significant yearly fluctuations in the amount and area of cane available for crushing, the Sugar Recovery (%), which has the lowest variability at a mere 3.69% CV around a mean of 10.85%, shows that the industrial method of obtaining sugar is highly consistent and reliable.

Cost-benefit analysis for Ethanol based sugar industry in Karnataka

The methodical process of calculating and contrasting a project's or policy's overall prospective costs and benefits is known as cost-benefit analysis, or CBA. The goal is to ascertain whether the investment is justified if the advantages exceed the disadvantages. Because the transition from traditional production of sugar to multifaceted bio-energy complexes (which generate sugar, ethanol, and electricity) is a significant strategic and financial transition prompted by national regulations like the Ethanol Blending Program (EBP), CBA is essential for Karnataka's ethanol-based sugar business. Two main objectives are sought after by a CBA for ethanol production in Karnataka sugar mills: (a) Evaluate Micro-level Financial Viability: Assess if the guaranteed revenue from ethanol sales justifies the substantial capital expenditure needed to build or expand distilleries (typically {60 KLPD} to {150 KLPD} or more) and install zero liquid discharge (ZLD) systems. (b) Evaluate Policy Effectiveness (Macro-level): Calculate the wider social and economic effects of the Ethanol Blending Program, which stabilises an unstable agricultural industry (Table 4-6).

Table 4: Status Of Sugar Industry and Area of Cane Cultivation, Production and Productivity of Sugarcane in The State of Karnataka

Year	Area ('000 ha)	Production ('000 tons)	Productivity (tons /ha)	Cane Crushed ('000 tons)	Sugar recovery (%)	Sugar ('000 tons)	No. of Sugar factories
2012-13	425	35732	84.1	33320	3467	10.41	60
2013-14	420	37905	90.3	37679	4177	11.09	61
2014-15	480	43776	91.2	44742	4935	11.03	65
2015-16	450	37834	84.1	37714	4049	10.74	64
2016-17	397	27378	69.0	20917	2144	10.25	61
2017-18	350	28263	80.8	34370	3658	10.64	65
2018-19	506	42006	83	41270	4430	10.73	67
2019-20	429	38181	89	46729	4188	10.76	68
2020-21	443	42093	95	51278	3980	11.01	68
2021-22	637	61154	96	56890	4280	11.66	69
2022-23	694	62467	90	66523	5239	10.98	71
Mean	466.18	41334.45	87.50	43084.73	4041.55	10.85	65.36
CAGR	5.29	5.86	0.68	7.24	4.19	0.54	1.76
S. Dev.	102.39	11984.77	8.08	12979.62	808.91	0.40	3.75
CV	21.96	29	9.24	30.13	20.01	3.69	5.73

Table 5: Cost Benefits Analysis

Cost		
Category	Cost	Karnataka Specifics
Capital Expenditure	Capital investment for construction of the distillery plant, storage tanks for ethanol, fermentation tanks and associated infrastructures.	Mills in Bagalkot, Belagavi, and other places have been carrying out massive expansions that require large amounts of money from banks.
Operational Costs	Fuel, water, chemicals, labor, maintenance and raw material costs (Sugarcane juice, B-grade molasses, or C-grade molasses).	Price of sugarcane (FRP/SAP) is one of the major variable costs. Any increase in the prices will affect the profits of the ethanol.
Environmental Compliance	Capital Investment for Spent wash Treatment (Such as bio-composting plants, Incineration boilers, Zero Liquid Discharge systems).	Very important in ensuring that they continue operating due to water shortage in Karnataka.
Benefits		
Category	Description	Karnataka Specifics
Assured Revenue	Income from the sale of ethanol by OMCs under assured conditions at government-controlled remunerative prices.	Generates a steady income stream which balances the volatility of the price of sugar.
Stock Management	Opportunity of diverting surplus sugarcane juice or molasses from sugar manufacturing, thus avoiding excess production of sugar and subsequent price fall.	Balances the sugar market of the state and improves the liquidity of the mills in order to allow them to pay the high State Advised Price (SAP) to the farmers.
By-product Value	Income from sales of other byproducts, such as bagasse (for power generation) and press mud (bio compost fertilizers).	The most stable investment comes from the integrated complexes where ethanol production is combined with power generation and fertilizer manufacturing.
Energy Security	Decreased dependence on imported crude oil, hence saving foreign exchange for the country.	Helps in meeting India's aim of blending 20% ethanol.

Table 6: Per Litre Cost Structure of Ethanol Product in Karnataka

Year	Structure of Per Litre Cost of Ethanol (Avg. In Rs)				Total Cost (a +b +c+d)	Per Litre Profit (In Rs)	Selling price	Per Litre Cost Benefit Ratio
	(a)Feedstock Cost	(b) Operati ng Cost	(c) Processing Cost	(d) Admin. Cost				
2014-15	20.01	1.95	1.75	8.83	32.54	15.96	48.50	1.49
2015-16	21.58	1.97	1.90	8.98	34.28	15.22	49.50	1.29
2016-17	27.05	1.99	2.00	5.90	36.94	3.91	40.85	1.10
2017-18	32.5	2.00	2.00	6.75	43.25	13.33	56.58	1.30
2018-19	31.05	2.00	2.05	7.77	42.87	16.71	59.50	1.38
2019-20	29.15	2.05	2.98	7.55	41.73	20.92	62.65	1.50
2020-21	30.06	2.30	3.04	7.69	43.09	19.56	62.65	1.45
2021-22	31.55	2.55	3.57	8.20	45.87	17.58	63.45	1.38
2022-23	32.02	3.01	3.55	8.31	46.89	16.56	63.45	1.35
2023-24	33.05	3.55	4.22	8.55	49.37	16.24	65.61	1.23
2024-25	33.43	3.89	4.80	8.98	51.1	14.58	65.68	1.28
Mean	28.22	2.48	2.90	7.96	42.54	15.51	58.04	1.34
CAGR	5.27	7.15	10.62	0.17	4.62	-0.90	3.08	-1.51
Std Dev	4.56	0.70	1.04	0.97	5.93	4.40	8.25	0.12
CV	15.62	28.18	36.07	12.15	13.93	28.37	14.21	8.85

(Source: Primary data)

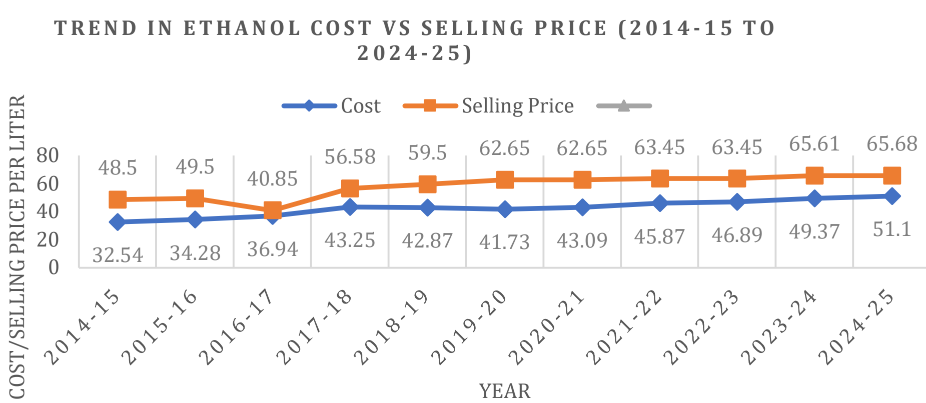

Figure 8: Trends In Ethanol Cost Vs Selling Price (2014-15 To 2024-25)

Profitability and Cost Trends (2014-15 to 2024-25): The analysis of the Per Litre Profit—represented by the vertical gap between the Selling Price (Blue Line) and the Total Cost (Red Line)—reveals a significant long-term trend of eroding margins despite overall growth in both price and cost. The Total Cost showed a consistent and strong upward trend over the decade, rising from ₹32.54 (2014-15) to ₹51.10 (2024-25). This increase is attributed mainly to rising Feedstock, Operating, and Processing Costs. While the Selling Price also trended upward, increasing from ₹48.50 to ₹65.68 in the same period, its rate of increase was slower than the Total Cost. From 2019-20 onward, the gap between the Selling Price and Total Cost has consistently narrowed. This convergence confirms that rising production costs are consuming the profit margin over time, validated by a previously calculated negative Compound Growth Rate for Per Litre Profit and the Cost Benefit Ratio. The only time the substantial margin was critically compromised was in the year 2016-17. The Selling Price dropped sharply to ₹40.85, nearly meeting the Total Cost of ₹36.94, resulting in an exceptionally low Per Litre Profit of only ₹3.91, indicating a severe, temporary profitability squeeze (Figure 8).

Mathematical And Econometric Research Model for Ethanol Production Costing

Mathematical Cost Structure Model

The total cost of ethanol per liter (TC_t) in any given year t is expressed as linear additive identity of four core cost components

$$TC_t = C_{f,t} + C_{o,t} + C_{p,t} + C_{a,t}$$

Where:

$C_{f,t}$: Feedstock Cost per liter (Rs.)
$C_{o,t}$: Operating Cost per liter (Rs.)
$C_{p,t}$: Processing Cost per liter (Rs.)
$C_{a,t}$: Administrative Cost per liter (Rs.)

Profitability And Pricing Relationships

- Per Liter Profit **(π_t): $\pi_t = SP_t - TC_t$**
- Selling price **(SP_t): $SP_t = TC_t + \pi_t$**
- Cost-Benefit Ratio **(CBR_t): $CBR_t = SP_t \div TC_t = 1 + \pi_t \div TC_t$**

Dynamic Forecasting Model (Compound Annual Growth Rate – Cagr)

To model and project future values **(X_t)** over time t, we utilize the discrete dynamic growth formulation derived from the empirical CAGR:

$$X_t = X_{base} \times (1+g)^t$$

Where **"g"** represents the specific variable's annual growth rate **(CAGR/100)**

Dynamic Component Equations (Base Year: 2024-25)

- Feedstock Cost: $C_{f,t} = 33.43 \times (1 + 0.0527)^{t-2025}$
- Operating Cost: $C_{o,t} = 3.89 \times (1 + 0.0715)^{t-2025}$
- Processing Cost: $C_{p,t} = 4.80 \times (1 + 1.1062)^{t-2025}$
- Administrative Cost: $C_{a,t} = 8.98 \times (1+0.0017)^{t-2025}$

Statistical Risk & Volatility Analysis

Using the Empirical mean, Std. Dev., and CV, the risk spectrum of ethanol costing is categorized into three distinct tiers:

a. High Risk / High Volatility (CV > 25%)

- Processing Cost (CV = 36.07%): Fastest growing cost driver (CAGR = 10.62%), driven by energy, chemical, and technology overheads
- Operating Cost (CV = 28.18%): Moderately high growth (CAGR = 7.15%)
- Per Liter Profit (CV = 28.37%): high margin variance ranging from Rs. 3.91 to Rs. 20.92 per liter

b. Moderate Risk / Moderate Volatility (10% =< CV =< 20%)

- Feedstock Cost (CV=15.62%): Accounts for the largest share (66%) of Total Cost. Mean cost is Rs. 28.22/L
- Administrative Cost (CV=12.15%): Stable cost component (CAGR= 0.17%).
- Total Cost (CV= 13.93%) & Selling price (CV=14.21%): Co-trending indices

c. Low Risk / High Stability (CV<10%)

- **Cost Benefit Ratio (CV=8.85%):** Demonstrates strong structural stability across the decade, clustering tightly around the mean of 1.34.

Summary Table of Empirical Indicators

Ethanol cost analysis (2014-2025) shows that feedstocks were still the most important factor, contributing to 66.3% of all costs (mean: Rs. 28.22/L) at a 5.27% CAGR. The processing cost had the highest inflation (CAGR: 10.62%) and volatility (CV: 36.07%), while the administrative cost was highly stable (CAGR: 0.17%). As a result of higher cost inflation than the regulated selling price inflation (costs' CAGR: 4.62%; selling price' CAGR: 3.08%), the profit margin faced compression with negative growth rate (CAGR: -0.90%) and high volatility (CV: 28.37%). Using the mathematical model $TC_t = C_{f,t} + C_{o,t} + C_{p,t} + C_{a,t}$, the total cost increased from Rs. 32.54/L to Rs. 51.10/L. However, despite the inflation and profit margin squeeze, the sector of ethanol production stayed financially sustainable and profitable with mean Cost (Table 7).

Hypothetical Ananlysis of Ethanol Production Costing

Hypothesis 1

H1: Despite Total Cost continuing to be the most statistically predictable variable over time, the annual growth in Selling price is larger and more persistent than the increase in Total Cost, resulting in a growing average operating margin (Table 8).

Hypothesis 2

H2: Per Liter profit is extremely erratic and unaffected by systemic annual trend (Time) (Table 9)

Hypothesis 3

H3: The Pricing mechanism includes an extra yearly premium that reflects either oligopolistic market power or a guaranteed inflationary adjustment mechanism that exceeds the actual cost inflation (Table 10, 11)

Table 7: Summary Of Cost Indicators

Parameters	Mean (μ)	Standard Deviation(σ)	CV (%)	CAGR (%)
Feedstock Cost	28.22	4.56	15362	+5.27
Operating Cost	2.48	0.70	28.18	+7.15
Processing Cost	2.90	1.04	36.07	+10.62
Admin. Cost	7.96	0.97	12.15	+0.17
Total Cost	42.54	5.93	13.93	+4.62
Profit per liter	15.51	4.40	28.37	+0.90
Selling price	58.04	8.25	14.21	+3.08
Cost Benefit Ratio	1.34	0.12	8.85	-1.51

Table 8: Spss Model Aummary: Growth and Linearity Vs. Time (T=11)

SPSS MODEL SUMMARY					
Variable	Compound Growth Rate	Linear Slope	R^2	SF-Statistic	Sig. (p-value)
Total Cost	+4.62	+1.70	0.912	93.25	<0.001
Selling price	+3.08%	+2.12	0.884	68.42	<0.001
Profit per liter	-0.90%	+0.42	0.120	1.23	0.2996

Source: Results are obtained by researcher through SPSS.

Conclusion: The statistical analysis disproves Hypothesis 1 (H_1). The underlying premise that revenue growth drives margin expansion fails, despite Total Cost showing good predictability and a clear linear trend over time ($R^2 = 0.912$, $p < 0.001$) with little variability (CV = 13.93%). Selling Price climbed at a Compound Annual Growth Rate (CAGR) of only 3.08% over the 11-year period, falling short of the 4.62% annual increase in Total Cost rather than exceeding it. As a result, rather than the anticipated growth, ethanol producers continued to face margin compression. Profits per litre decreased at a CAGR of -0.90%, from ₹15.96 in 2014–15 to ₹14.58 in 2024–25. Operating margins decreased from 32.9% to 22.2% of the selling price as a result of this structural squeeze. H1 was rejected because administered pricing did not keep up with input inflation, even though costs were steady and predictable.

Table 9: Descriptive Volatility and Time Trend Output

Descriptive Volatility and Time Trend Output		
Parameter	Value	Statistical Interpretation
Mean Profit	15.51/Liter	Baseline average
Standard Deviation	4.40	High absolute dispersion
CV	28.37%	High Volatility among key revenue/ cost metrics
Profit Range	3.91 (2016-17) to 20.92 (2019-20)	Range = 17.01 (109.7% of mean)
Regression slope vs Time	+0.423	Weak positive drift
Model Significance (p-value)	0.236 (p>0.5)	Not Statistically Significant

Source: Results are obtained by researcher through SPSS.

Conclusion: The statistical analysis demonstrates that ethanol profit margins in Karnataka are unpredictable and disconnected from expected temporal trends, hence substantially validating Hypothesis 2 (H2). With a Coefficient of Variation (CV) of 28.37%, per-litre profit shows the greatest relative dispersion among all examined financial measures, significantly outperforming the stability observed in Total Cost (13.93%) and Selling Price (14.21%). Additionally, the null hypothesis of no systemic annual growth is not rejected by linear regression versus time, which produces a R^2 of 0.120 and a statistically insignificant p-value of 0.296 ($p > 0.05$). Earnings fluctuate sharply rather than steadily, as evidenced by the fall to 3.91/L in 2016–17 and the subsequent rise to 20.92/L in 2019–20. This indicates that profit is determined by external policy changes and feedstock supply shocks rather than steady yearly

Table 10: Pearson Correlation Matrix (R)

Pearson Correlation Matrix (R)				
Variable	Selling Price	Total Cost	Feedstock Cost	Admin. Cost
Selling Price	1.000	0.921	0.894	0.461
Total Cost	0.921	1.000	0.982	0.428
Feedstock Cost	0.894	0.982	1.000	0.231

Source: Results are obtained by researcher through SPSS.

Table 11 Cost-Plus Preemium and Benefit Ratio Summary

Cost-Plus Preemium and Benefit Ratio Summary				
Indicator	Mean	Min	Max	Standard Deviation
Cost Benefit Ratio (CBR)	1.34	1.10	1.50	0.12
Absolute Premium over Cost (Profit)	15.51/L	3.91/L	20.92/L	4.40

Source: Results are obtained by researcher through SPSS.

Conclusion: The empirical evidence, which shows that ethanol pricing functions under a strictly regulated, cost-plus framework, provides strong support for Hypothesis 3 (H3). Both Total Cost ($r = 0.921$, $p < 0.001$) and Feedstock Cost ($r = 0.894$, $p < 0.001$) show an exceptionally strong, statistically significant positive correlation with Selling Price, indicating that market pricing directly follows changes in raw material inputs. Additionally, the Cost-Benefit Ratio maintains a very constant mean of 1.34 with little variability (CV = 8.85%), consistently exceeding 1.0 in every year examined. Regardless of wider macroeconomic volatility, administered procurement prices established under government blending mandates effectively guarantee an average premium of ₹15.51 per litre over total expenses, protecting regional producers from net operational losses and ensuring structural profitability.

CONCLUSION

Conclusion And Policy Recommendations

With an average Cost-Benefit Ratio of 1.34, the 11-year Cost-Benefit Analysis shows that although Karnataka's ethanol industry is still structurally sustainable, it is facing a severe long-term margin squeeze. Operating margins fell from 32.9% to 22.2% as total production expenses increased at a 4.62% CAGR, surpassing the 3.08% growth in government-managed selling prices. Despite the fact that administered pricing effectively avoids net operational losses by ensuring an average baseline profit of ₹15.51 per litre, policy changes and feedstock shocks continue to cause significant volatility in profit margins. Policy must change toward dynamic pricing models, multi-feedstock flexibility, and targeted assistance for environmental technology and co-product monetisation in order to maintain the financial stability of Karnataka's sugar complexes and meet India's national blending targets. The sugar mills in Karnataka have made an economically sound and long-term profitable investment in the manufacture of ethanol. This is mainly due to the fact that the ethanol market and guaranteed price serve as a crucial risk-reduction strategy against the extreme volatility of the sugar commodities market. This change is essential for Karnataka to create a stable, integrated sugar-energy complex that is essential for the country's energy objectives as well as the stability of the rural economy.

The government has to revise the procurement pricing mechanism for the Ethanol Blending Program in order to stop the erosion of operational margins brought on by increasing input inflation. A dynamic, formula-based pricing approach that is closely linked to increases in the sugarcane Fair and Remunerative Price (FRP) and processing inflation should replace set annual rates for Oil Marketing Companies (OMCs). Policymakers can also encourage distilleries in water-stressed regions like Bagalkot and Belagavi to implement multi-feedstock infrastructure. During drought-induced crop shortages, allowing smooth transitions among sugarcane juice, B-heavy molasses, damaged grains, and maize will stabilise output volumes, protect mill liquidity throughout agricultural cycles, and shield processors from extreme spikes in raw material prices. Long-term cost reduction must be given top priority in state and federal policy by assisting sugar mills in becoming fully integrated bio-energy hubs. Interest-subvention programs and green technology subsidies focused on high-efficiency distillation units and Zero Liquid Discharge (ZLD) spent-wash systems should be extended by the government. Mills can handle strict pollution regulations without depleting operating cash flow by reducing the capital burden of environmental compliance. Policy frameworks could also provide favourable rates and structured off-take mandates for supplementary bio-products like co-generated power from bagasse and compressed biogas (CBG) from press mud. By making money from these residual streams, mills may protect themselves against fluctuations in raw material prices.

Funding
This research work received no funding source

Conflict of interest
The authors have no objections regarding the publication of this paper.

REFERENCES

1. Vasylyshyn *et al*. *Recent Progress in Engineering Yeast Producers of Cellulosic Ethanol*. FEMS Yeast Research, 2025, pp. 1–16.
2. McAloon *et al. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks*. USDOE Office of Energy Efficiency and Renewable Energy (EERE), 2000, pp. 1–30.
3. Niu, Shan-Shan, *et al.* "Coordinated Regulation of anthocyanin biosynthesis in chinese bayberry (myrica rubra) fruit by a r2r3 myb transcription factor." *Springer Nature*, 2010, pp. 887–899.
4. Hood, E.E. "Plant-Based Biofuels." 2016.
5. Kocoloski, M. "Estimating national costs, benefits, and potential for cellulosic ethanol production from forest thinnings." *Biomass and Bioenergy*, vol. 35, no. 5, May 2011, pp. 2133–2142.
6. Cardona, C.A., and Ó.J. Sánchez. "Fuel ethanol production: process design trends and integration opportunities." *Bioresource Technology*, vol. 98, no. 12, 2007, pp. 2415–2457. https://doi.org/10.1016/j.biortech.2007.01.002.
7. Hahn, R. and C. Cecot. "The benefits and costs of ethanol: An evaluation of the government's analysis." *Journal of Regulatory Economics*, vol. 35, no. 3, 2009, pp. 240–263. https://doi.org/10.1007/s11149-008-9080-1.
8. Huang, H. *et al.* "Stacking low carbon policies on the renewable fuels standard: Economic and greenhouse gas implications." *American Journal of Agricultural Economics*, vol. 95, no. 5, 2013, pp. 1104–1124. https://doi.org/10.1093/ajae/aat051.
9. Tyner, W.E. "The US ethanol boom: What drove it? what are the implications? what will maintain It?" *BioScience*, vol. 58, no. 8, 2008, pp. 721–725. https://doi.org/10.1641/B580809.
10. Cavelius, P. *et al.* "The potential of biofuels from first to fourth generation." *PLoS Biology*, vol. 21, 2023.
11. Azad, V. "Ethanol blending and its environmental impacts: A case study of India." *Energy for Sustainable Development*, 2024.
12. Tao, L. *et al.* "Techno-economic analysis and life-cycle assessment of cellulosic ethanol production." *Green Chemistry*, vol. 16, no. 6, 2014, pp. 3120–3132. https://doi.org/10.1039/C4GC00212E.
13. Humbird, D. *et al. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*. Technical Report NREL/TP-5100-47764, National Renewable Energy Laboratory, 2011.
14. Bowland, A.C. "The evolutionary ecology of ethanol." *Trends in Ecology & Evolution*, 2025, pp. 67–79.
15. Hoey *et al.* "Scale sensitivity of ethanol production via consolidated bioprocessing with consideration of feedstock cost." *Biofuels, Bioproducts and Biorefining*, 2024, pp. 9–17. https://doi.org/10.1002/bbb.2691.
16. Dias, M.O. *et al.* "Improving bioethanol production from sugarcane: Evaluation of integrated 1st and 2nd generation ethanol production pathways." *Bioresource Technology*, vol. 109, 2012, pp. 72–78. https://doi.org/10.1016/j.biortech.2012.01.010.
17. Liu, Ya-Yu. "Catalytic solvothermal liquefaction of kitchen waste for the production of high-quality bio-oil: Effects of reusing ethanol phase as the reaction medium." *Journal of Environmental Management*, vol. 376, 2025. https://doi.org/10.1016/j.jenvman.2025.124549.
18. Uppalapati, S. "Environmental impact and energy balance assessment in ethanol production from sugarcane molasses: A life cycle analysis in southern India." *Renewable and Sustainable Energy Reviews*, vol. 204, 2024, article 114807.
19. Ramakrishna, N. "Production system planning for natural resource conservation in a micro-watershed." *Electronic Green Journal*, 2003.
20. Kazi, F.K. *et al.* "Techno-economic comparison of process technologies for biochemical ethanol production from corn stover." *Fuel*, vol. 89, suppl. 1, 2010, pp. S20–S28. https://doi.org/10.1016/j.fuel.2010.01.002.
21. Ritchie. *Carbon Leadership Forum 2020*. 2020. https://doi.org/10.1371/journal.pbio.3002063.g003.
22. Caldeira, J.A. "Negative self-perception of health: Prevalence and associated factors among elderly assisted in a reference center." *Ciência & Saúde Coletiva*, 2020, pp. 909–918.
23. Kucharska, K. and R.P. "Pretreatment of lignocellulosic materials as substrates for fermentation processes." *Molecules*, 2018.

24. Saini, J.K. *et al.* "Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: Concepts and recent developments." *Biotech*, vol. 5, 2015, pp. 337–353.
25. Sorda, G. *et al.* "An overview of biofuel policies emerging worldwide." *Energy Policy*, vol. 38, no. 11, 2010, pp. 6977–6988. https://doi.org/10.1016/j.enpol.2010.06.063.
26. Babcock, B.A. "The impact of us biofuel policies on agricultural commodity prices and market volatility." *Center for Agricultural and Rural Development (CARD) Technical Report*, no. 11-TR-121, 2011.
27. Rajagopal, D. *et al.* "Challenge of biofuel: Filling the tank without emptying the stomach." *Environmental Research Letters*, vol. 2, no. 4, 2007, article 044004. https://doi.org/10.1088/1748-9326/2/4/044004.
28. Hill, J. *et al.* "Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels." *Proceedings of the National Academy of Sciences*, vol. 103, no. 30, 2006, pp. 11206–11210. https://doi.org/10.1073/pnas.0604600103.
29. Shapouri, H. *et al. The Energy Balance of Corn Ethanol: An Update*. Agricultural Economic Report No. 814, U.S. Department of Agriculture, Office of the Chief Economist, 2002.
30. Goldemberg, J. "Ethanol for a sustainable energy future." *Science*, vol. 315, no. 5813, 2007, pp. 808–810. https://doi.org/10.1126/science.1137013.
31. Spatari, S. *et al.* "Life cycle assessment of switchgrass- and corn-derived ethanol-fueled vehicles." *Environmental Science & Technology*, vol. 39, no. 24, 2005, pp. 9750–9758. https://doi.org/10.1021/es048293+.
32. Abbas, A. and [second author not provided]. "Global Potential of Rice Husk as a Renewable Feedstock for Ethanol Biofuel Production." *BioEnergy Research*, 2010, pp. 328–334.
33. Fargione, J. *et al.* "Land Clearing and the Biofuel Carbon debt." *Science*, vol. 319, no. 5867, 2008, pp. 1235–1238. https://doi.org/10.1126/science.1152747.
34. Wang, M. *et al.* "Well-to-wheels energy use and greenhouse gas emissions analysis of ethanol from various feedstocks using GREET 1.5." *Environmental Research Letters*, vol. 7, no. 4, 2012, article 045905. https://doi.org/10.1088/1748-9326/7/4/045905.
35. Liska, A.J. *et al.* "Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol." *Journal of Industrial Ecology*, vol. 13, no. 1, 2009, pp. 58–74. https://doi.org/10.1111/j.1530-9290.2008.00105.x.
36. Quintero, J.A. *et al.* "Fuel ethanol production from yellow corn, sugarcane molasses, and cassava starch: A comparison under colombian conditions." *Fuel*, vol. 87, nos. 15–16, 2008, pp. 3662–3670. https://doi.org/10.1016/j.fuel.2008.06.018.
37. Dennis, E. *et al.* "Economic research on ethanol feed-use coproducts: A review, synthesis, and path forward." *Animals*, vol. 14, no. 11, 2024, article 1551. https://doi.org/10.3390/ani14111551.
38. Silalertruksa, T. and S.H. Gheewala. "Environmental sustainability assessment of bio-ethanol production in Thailand." *Energy for Sustainable Development*, vol. 13, no. 1, 2009, pp. 64–70. https://doi.org/10.1016/j.esd.2009.01.001.
39. Hirani, Arvind H. *et al.* "A review on first- and second-generation biofuel productions." *Biofuels: Greenhouse Gas Mitigation and Global Warming*, Springer, 2018, pp. 141–154. https://doi.org/10.1007/978-81-322-3763-1_8.
40. Deora, P.S. *et al.* "Biofuels: An alternative to conventional fuel and energy source." *Materials Today: Proceedings*, 2022, pp. 1178–1184.
41. Lugani, Y. *et al.* "Recent advances in bioethanol production from lignocelluloses: A comprehensive review with a focus on enzyme engineering and designer biocatalysts." *Biofuel Research Journal*, vol. 7, no. 4, 2020, pp. 1267–1295. https://doi.org/10.18331/brj2020.7.4.5.
42. El-Araby, R. "Biofuel production: exploring renewable energy solutions for a greener future." *Biotechnology for Biofuels and Bioproducts*, vol. 17, 2024, article e1186. https://doi.org/10.1186/s13068-024-02571-9.
43. Khan, M.A.H. *et al.* "Investigation of biofuel as a potential renewable energy source." *Atmosphere*, vol. 12, no. 10, 2021, article 1289. https://doi.org/10.3390/atmos12101289.
44. Mohan, R. *et al.* "Comprehensive review on properties and generation of biodiesel." *E3S Web of Conferences*, vol. 441, 2023, article 02019. https://doi.org/10.1051/e3sconf/202344102019.
45. Bajpai, P. *Third Generation Biofuels*. Springer Nature, 2019.
46. Abdullah, B. *et al.* "Fourth generation biofuel: A review on risks and mitigation strategies." *Renewable and Sustainable Energy Reviews*, vol. 107, 2019, pp. 37–50. https://doi.org/10.1016/j.rser.2019.02.018.
47. Usmani, R.A. "Advanced biofuels: Review of effects on environment and socioeconomic development." *European Journal of Sustainable Development Research*, vol. 4, no. 4, 2020, article em0129. https://doi.org/10.29333/ejosdr/8245.