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A TECHNO ECONOMIC ASSESSMENT OF 3G ETHANOL PRODUCTION IN INDIA

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Abstract

Ethanol is a renewable and clean-burning fuel that can reduce greenhouse gas emissions and dependence on fossil fuels. India has set a target of 20% ethanol blending in petrol (E20) by 2025, which requires a significant increase in ethanol production capacity. Currently, most of the ethanol in India is produced from sugarcane molasses, a by-product of the sugar industry, which is limited by the availability of sugarcane and its competing uses. Therefore, there is a need to explore alternative feedstocks and technologies for ethanol production, such as 3G ethanol from algae. However, the commercial viability of 3G ethanol production needs to be ascertained for its long-term successful adoption. This study uses a case study approach to assess the techno techno-economic feasibility of 3G ethanol production in India. The algal biorefinery setup can become feasible with enhanced algae yield or better pricing of ethanol and byproducts. The NPV of the biorefinery becomes positive when the ethanol price is above Rs.90 per litre for 10-year lifespan. Further, the lifespan of algal biorefinery has a significant on its NPV (Net Present Value). Compared to 2G ethanol, 3G ethanol yield is higher due to its low lignin and high carbohydrate content. Though, 3G ethanol production faces multiple challenges in terms of viability, feasibility and technology, but these will be overcome with research and technical improvements, making it fuel for the future.

Keywords: 3G Ethanol, Algae, Biorefinery, Hydrothermal liquefaction

1. INTRODUCTION

Ethanol is an alcohol that can be used as a fuel for internal combustion engines, either alone or blended with petrol. Ethanol has several advantages over petrol, such as higher octane number, lower carbon monoxide emissions, lower particulate matter emissions, and lower net greenhouse gas (GHG) emissions (Kumar, 2021). Ethanol can also reduce the dependence on imported crude oil and enhance the country's energy security. After USA and China, India as the third highest demand of petroleum products (PPAC, 2023). India imports over 80% of crude oil to meet its energy demands, thereby calling for measures to strengthen the nation's energy security (IEA, 2020). To address these challenges, India adopted one such initiative, ethanol fuel blending, two decades ago. The program aided by National Biofuel Policies aimed to achieve 10% blending by 2022 and 20% by 2025. However, the program has had many ups and downs due to a mismatch in the demand-supply equation. Ethanol in India is primarily produced through the fermentation of sugarcane molasses, accounting for more than three-fourths of the nation's total ethanol production. The concentration of the sugar industry is predominant in a few states only, as shown in Fig.1.

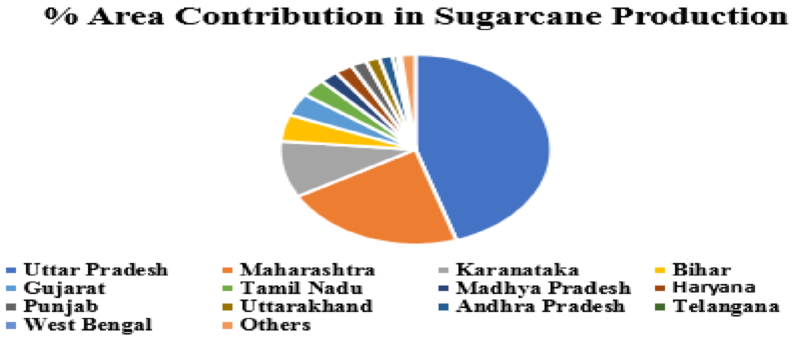

Figure 1: State-wise Contribution in Sugarcane Production in India

(Source: Department of Agriculture & Farmers Welfare, 2023)

The sugarcane supply or availability depends on multiple factors such as water availability, rainfall, and crop yield while molasses yield depends upon pricing, sugar demand, and sugar recovery rate (Malaiarasan et al., 2020). The threat to food security further elevates the uncertainty in sugar availability.

To ensure sufficient supply of ethanol to cater to the market demands, the government is focussing on producing second-generation or 2G ethanol from non-edible feedstocks and agricultural residues such as crop straw and bagasse (Kumar, 2021). These feedstocks neither cause a threat to food security nor compete for water resources. But 2G ethanol production also faces many challenges such as economic viability and scalability, complex production processes and lack of commercial-scale demonstration (Sharma et al., 2020). Though there has been expansion in ethanol production capacity in both molasses and grain-based distilleries (Niti Aayog, 2021), ethanol production may remain insufficient to cater to fuel blends considering rising petrol demand. Hence, there is a need to explore avenues that facilitate stepping up of the ethanol production to meet the sectoral demands. One such solution is producing third generation (3G) ethanol from the algal feedstock.

Algae are a varied class of eukaryotic organisms that do not require natural resources like water or land. Algae have the potential to become next-generation biofuels because of their property to produce relatively higher amounts of biomass as feedstock (Guiry, 2012). Other characteristics that make algae popular for biofuel production are quick growth rate, lower lignin and higher lipid content coupled with superior photosynthetic efficiency and resistance to environmental stress (Dolganyuk et al., 2020; Datta et al., 2019). Also, algae help generate multiple bye products, contributing to pharma, fertilizer, water treatment, and biproducts oriented industries (Chisti,2007). However, at the same time, the success of algae as feedstock for ethanol production faces multiple challenges, such as lack of large-scale cultivation systems, improper dewatering and harvesting techniques, inefficient operating and production costs, and high capital costs. (Vassilev & Vassilev, 2016; Behera et al., 2015). These constraints make it to justify the commercial scalability of bio-ethanol production. Therefore, there is a need to assess the future viability and feasibility of 3G ethanol production in India. This study conducts techno-economic assessment of 3G ethanol production in India using a case study of an integrated algal biorefinery to analyse the challenges and success factors for its long-term adoption in India. The paper also compares the performance of 3G ethanol with 2G ethanol from agricultural residues, the latter being currently promoted by the government through viability gap funding.

2. LITERATURE REVIEW

A detailed literature review was conducted on the technical, commercial, and prospects of algal biofuels. The review revealed that extensive research has been carried out on the subject for over a decade. The knowledge base was initially focused on the technical aspects but gradually advanced to the evaluation of commercial scalability and life cycle analysis. Hence, the review has been arranged chronologically to track the development of algal biofuel research and to identify the gaps to be addressed by the current study regarding techno-economic analysis.

Khan et al. (2009) examined the prospects of biodiesel production from microalgae in India, considering the availability of land, water, and solar radiation resources, as well as the technical, economic, and environmental aspects of microalgae cultivation and biodiesel conversion. The authors estimated that India could produce 10.6 million tonnes of biodiesel per year from microalgae, which can meet about 25% of the current fuel demand in India. Through evaluation of associated production processes on different species of algae, the authors deduct the most suitable options for India.

Through techno-economic analysis, Singh and Gu (2010) studied the comparative production costs and revenues associated with algal biofuels vis-à-vis traditional fossil fuels. The authors derived the potential reasons hindering the economic viability of algal biofuels and proposed that algal biofuels should remain competitive and attractive in line with the respective market segments.

Anastasakis & Ross (2011) studied the hydrothermal liquefaction of brown macro-algae under different controlled and pre-defined conditions to study the variation in bio-oil yield. This study details the technical aspects about the properties of bio-oil and biochar and the impact of reaction parameters.

Debirmas (2011) discussed the advantages of algae over other feedstocks, such as faster growth rate, higher photosynthetic efficiency, higher carbon fixation rate, higher lipid content, lower lignin content, and higher tolerance to environmental stress. The author also reviewed the status and challenges of algae cultivation, harvesting, oil extraction, and biodiesel conversion technologies and conducted a life cycle assessment of algae-based biodiesel production.

Lanzafame et al. (2014) identified the research efforts required for the success of biorefineries. The study found that multiple factors influence the evolution of a bio-refinery. However, sustainability and chemical production integration remain the two most important success factors. Tan and Lee (2016) compared different process strategies for ethanol production and concluded that the fixed price of ethanol produced from red macroalgae is competitive with other feedstocks. Sudhakar et al. (2018) evaluated marine microalgae as a bioresource and found that multiple technological advancements are required for seaweeds' continued and maximised utilisation. Mohapatra et al. (2019) studied the technology, economics and challenges associated with bio-renewable feedstocks and discovered that although algal biomass can be a cost-effective production route for ethanol, immature technologies, complex logistics, and investor issues stand as barriers in progress. Kumar and Singh (2019) analysed the latest research on the microalgal biorefinery concept and concluded that the standalone production of biofuel is not economically and environmentally favourable.

Preat et al. (2020) studied and identified algal biorefinery scenarios along with mass and energy balance flow sheets. The study compared microalgae biomass with soy and concluded that microalgae-based technologies are still inefficient compared to current alternatives. However, the study provides quantitative analysis for evaluating microalgae projects but conclude that successful commercialisation of microalgae is still challenging.

Mu et al (2020) conducted life cycle assessment (LCA) and techno- economic analysis (TEA) of algal biofuel production and concluded that the economic and ecological parameters are critical in defining the production performance of algal biofuels. However, the study states that an appreciable quantum of uncertainty exists due to the non-development of commercially scalable microalgae applications.

Chong et al. (2020) conducted a techno-economic evaluation of third-generation bioethanol production utilizing the macroalgae waste in the Malaysian context. The study found that through heat exchange network synthesis and optimization of processes, energy utilization can be reduced to 32%. The study uses a case-based approach to identify the ideal production site, assuming 20 years of plant life. However, the study does not address the critical issue of deploying the bio-conversion process on an industrial scale through successful process control technology. The study also demands proof of concept for substituents in the production of 3G ethanol.

Almada et al. (2023) conducted a bibliometric analysis of biorefineries' Environmental and Techno-Economic Assessment (ETEA) for their optimisation and to attain sustainability targets. The study is helpful in determining the trade-off between the two pillars of sustainability (i.e. planet and profit).

Though, several studies have been conducted pertaining to technical and/or commercial evaluation of algal biofuel production, the elements of uncertainty and assumptions remain on the higher side. There are still multiple bottlenecks in view of the non-consolidation of 3G ethanol production process Further, no such study in the Indian context has been conducted so far. Further the available studies do not compare the performance of 3G ethanol vis-à-vis 2G ethanol which is currently incorporated in the National Policy of Biofuels, 2018. This study considers real-time data for accurate evaluation and addresses these research gaps for a holistic evaluation of 3G ethanol adoption in India, particularly.

3. METHODOLOGY

A detailed and thorough literature review was conducted to identify the potential algal strains, cultivation systems, harvesting and dewatering methods, conversion processes, and co-products for 3G ethanol production in India. Subsequently, a conceptual design of an integrated algal biorefinery was developed based on the literature review. The biorefinery consists of four main stages: cultivation, harvesting and dewatering, conversion, and co-product recovery. Mass and energy balance were performed for each stage of the biorefinery using Aspen Plus software. The input parameters were taken from the literature or assumed based on engineering judgment/actual values obtained from running plants. The output parameters were the mass and energy flows of each stream in the biorefinery. A techno-economic analysis was performed for the biorefinery using Aspen Process Economic Analyzer software (as it works on Baseline Analysis for Cost Optimization). The capital and operating costs were estimated based on the mass and energy balance results and the equipment sizing and costing data from the literature or vendor quotes. The guiding economic indicators were calculated based on the assumptions of a 10-year plant life span (Pasha et al., 2021), a standard 10% discount rate, a 30% income tax rate, a 100% equity financing (as no viability gap funding is available for 3G ethanol production), and current ethanol price of INR 62 per litre.

Further, sensitivity analysis was performed to evaluate the impact of critical parameters on the economic indicators. The key parameters identified were algal biomass productivity, the algal oil content, the ethanol yield, the co-product prices, and the ethanol price.

Lastly, a comparison was made between 3G ethanol and 2G ethanol from agricultural residues in terms of technical performance, economic performance and other related parameters.

4. CONCEPTUAL DESIGN OF THE INTEGRATED ALGAL BIOREFINERY

There are four stages involved in designing an algal biorefinery, which are discussed below for techno-economic assessment.

4.1 Cultivation

Algae can be grown either in open ponds or enclosed photo bioreactors. Open ponds are easiest and most primitive systems for mass cultivation of microalgae. Multiple options of wastewater resources exist for developing algal species. Though the method is cost effective, but it has multiple drawbacks. Due to evaporation loss of water, contamination, and inefficient uptake of carbon dioxide, the biomass yield is on the lower side (Chishti, 2007). Maintaining ideal conditions to improve algal output comes at an appreciable cost (Molina Grima et al., 2003).

Photobioreactors made from transparent materials with a large surface area to volume ratio have been deployed in algae cultivation to overcome the challenges associated with pond cultivation. The biomass yield in the latter process can be as high as 13 times as compared to pond system but the reactors are more costly, and issues persist in scaling them up. Although biomass concentration increases, the growth and yield may remain limited depending on light intensity and temperature.

For the purpose of assessment, the following parameters have been adopted in our study:

S.No.	Parameter	Value
1.	Cultivation Area	100 acres (assumed)
2.	Pond Depth	0.3 m
3.	Pond Area	1 hectare each
4.	Algal strain	Nannochloropsis sp.,
5.	Algal biomass productivity	20 $g/m^2/day$
6.	algal oil content	30% (dry weight).

Table 1: Cultivation Parameters for Algal Biorefinery

(Source : Zhu et al., 2018) & BrownBridge et al., 2014)

Nannochloropsis sp. Algal strain has been selected owing to its advantages of possessing high lipid content and sable response to temperature and salinity of water (Ma et. al, 2016).

4.2 Harvesting and Dewatering

Post-cultivation of microalgae, harvesting needs to be carried out to process the microalgae further. Gravity settlement is the most commonly used harvesting method, wherein the oil is removed from the biomass for biofuel production. Dewatering involves decreasing algal biomass water content (Pandey et al., 2019).

Flocculation combined with dissolved air flotation (DAF) has been accepted as the best harvesting technique for microalgae and hence adopted in this study (Rao et. al, 2023).

Due to high energy consumption and associated costs, the dewatering process is a challenge in 3G ethanol production. We have adopted forward osmosis in our study. Despite issues like reverse solute diffusion, membrane fouling, and polarization, forward osmosis has remarkable advantages of lower energy consumption and excellent cell recovery (Yazdanabad et al, 2021).

The harvesting and dewatering parameters adopted for the study are as follows:

S.No.	Parameter	Value
1.	DAF Capacity	1000 m^3/hour
2.	Recovery Efficiency	90%
3.	Belt Filter Press Capacity	10 tonnes/hour
4.	Dewatering Efficiency	80%
5.	Initial water content in algal biomass	99.5%
6.	Final water content in algal biomass	80%

Table 2: Harvesting and Dewatering Parameters for Algal Biorefinery

(Source: Tanveer et al., 2021 and Lin et al., 2015)

4.3 Conversion

In the conversion process, obtained algal biomass is converted into ethanol or another biofuel. The conversion process depends upon environmental conditions and is suitable for biomass with moisture content exceeding 50% (Islam et al., 2023).

The conversion process selected for this study is hydrothermal liquefaction (HTL). This method utilises high pressure and temperature to convert biomass into four parts: bio-oil, biochar, aqueous phase, and gas phase. The aqueous phase, which is comprised of sugars, organic acids, and alcohols, can be fermented into ethanol. Gaseous phase consisting of methane, CO2, CO and hydrogen may be utilised for power and heat generation. We have selected simultaneous saccharification and fermentation (SSF) for fermentation. This method utilises microorganisms and enzymes for converting sugar into ethanol.

The parameters adopted in the study are as follows:

S.No.	Parameter	Value
1.	Hydro-Thermal Liquefaction Unit Capacity	10 tonnes/hour at 300 °C and 20 MPa
2.	Bio-oil yield	11.81%
3.	Bio-char yield	68-80%
4.	Aqueous Phase Yield	0.30
5.	Gaseous Phase Yield	0.09.-0.45
6.	Bio-oil energy content	16.0 MJ/kg
7.	Bio-char energy content	7512.96 cal/g
8.	Simultaneous Saccharification and Fermentation (SSF) Unit Capacity	10 tonnes/hour at 37 °C and Atmospheric Pressure
9.	Ethanol Yield	21.4%
10.	Ethanol Energy Content	27 MJ/kg

Table 3: Conversion Parameters for Algal Biorefinery

(Source: Dey et al., 2015, IEA, 2019 and Ran et al., 2020)

4.4 Co-product Recovery

The conversion stage yields some co-products such as heat, power, and biochar. Biochar finds its use as feedstock for carbon production or as a soil amender. Excess power generated may be sold to the electric grids, while the excess heat can be utilised in a chiller for heating or cooling purpose.

S.No.	Parameter	Value
1.	Combined Heat and Power (CHP) unit electrical efficiency	35%
2.	CHP thermal efficiency	50%
3.	Chiller coefficient of performance (COP)	0.70

Table 4. Co-product Recovery Parameters for Algal Biorefinery

(Source: Pilavachi et. al, 2000 and Afzali & Mahalec, 2017)

4.5 Mass and Energy Balance

The mass and energy balance results for each stage of the biorefinery are shown in Table 1. The biorefinery has an input of 1000 t/day of algal biomass (dry basis) and 9000 t/day of wastewater. The biorefinery produces 42 t/day of ethanol, 24 t/day of bio-oil, 134 t/day of biochar, 20 t/day of aqueous phase, and around 20 t/day of gas phase. The biorefinery also produces 8.4 MW of excess power and 16.8 MW of excess heat.

Stage	Input	Output
Cultivation	1000 t/day algal biomass (dry basis) 9000 t/day wastewater	10000 t/day algal biomass (wet basis)
Harvesting and Dewatering	10000 t/day algal biomass (wet basis)	200 t/day algal biomass (dewatered) 9800 t/day water
Conversion	200 t/day algal biomass (dewatered)	42 t/day ethanol 24 t/day bio-oil 134 t/day biochar aqueous and gas phase
Co-product Recovery	24 t/day bio-oil and 134 t/day biochar with gas phase	8.4 MW excess power 16.8 MW excess heat

Table 5: Mass and Energy Balance Results for the Integrated Algal Biorefinery

5. TECHNO ECONOMIC ANALYSIS

The techno economic analysis results for the biorefinery are shown in Table 2. The capital cost of biorefinery has been kept at INR 500 crores, which includes 20% margin of safety owing to advanced technical costs (Toro et al., 2021). The cost includes the direct costs of equipment, installation, piping, instrumentation, electrical, civil, and structural works and the indirect costs of engineering, contingency, contractor fees, land, and working capital. The biorefinery has an operating cost of INR 150 crore per year (Vieira et al., 2020; Kumar et al., 2021), which includes the variable costs of raw materials, utilities, chemicals, enzymes, catalysts, waste disposal, and maintenance, and the fixed costs of labour, insurance, taxes, and administration. With current market trends, the biorefinery has an estimated revenue of INR 200 crore per year, which includes the sales of ethanol, bio-oil, and excess power. The biorefinery has a net present value (NPV) of Rs. -192 crore, an internal rate of return (IRR) of 0%, and hence a payback period of 10 years.

Parameter	Value	Unit
Capital Cost	500	Crore
Operating Cost	150	Crore/year
Revenue	200	Crore/year
NPV	-192	Crore
IRR	0	%
Payback Period	10	Years

Table 6: Techno Economic Analysis Results for the Integrated Algal Biorefinery

5.1 Sensitivity Analysis

The sensitivity analysis is carried out to understand the impact of input parameters o output values. The key parameters identified in the current study are discount rate, plant life span, ethanol yield, pricing, and co-products. It is shown that NPV of algal biorefinery is most sensitive to the ethanol price. The NPV of the biorefinery becomes positive when the ethanol price is above Rs.90 per litre for 10 year life-span. Alternatively, the NPV can also improve with the increase in ethanol yield or co-product prices.

The two most interesting parameters in the analysis are discount rate and life span of bio-refinery. We have plotted the results in different scenarios as illustrated below:

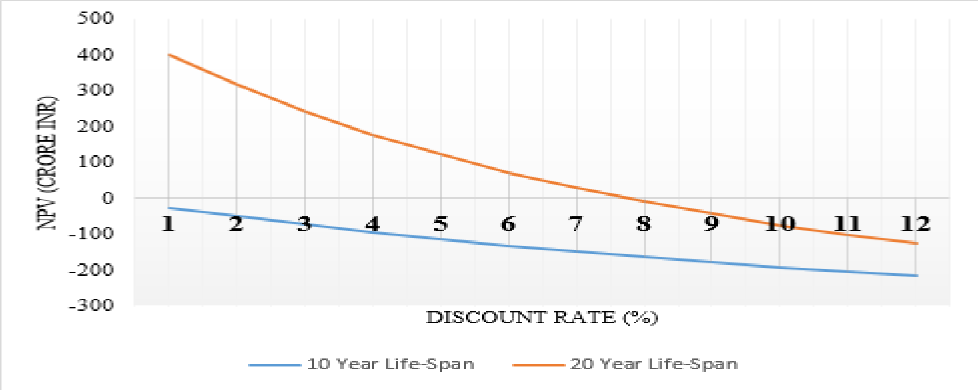

Figure 2: Impact of discount rate on NPV with varied Life-span of Algal Biorefinery

For 10 year life span of algal biorefinery, NPV remains negative irrespective of decrement in the discount rate. However, for 20 year life span of refinery, the NPV becomes positive when the discount rate touches 7%.

The biorefinery achieves breakeven after a span of 10 years and becomes profitable thereafter, if the lifespan of the biorefinery exceeds 10 years. If the capital cost or operating cost becomes higher than the above derived costs, the economic indicators shall deteriorate from the current values. However, with the aid of Government funding or increased revenues, the economic performance can be proportionately improved. As the current priorities focus on attaining net zero emission, including the social cost of carbon in the economic evaluation, can improve the feasibility and viability of biorefinery.

5.2 Comparison with 2G Ethanol

The comparison shows that 3G ethanol has higher technical performance than 2G ethanol in terms of biomass productivity, oil content, and ethanol yield. However, 3G ethanol has lower economic performance than 2G ethanol in terms of capital cost, operating cost, revenue, NPV, IRR, and payback period (CSTEP, 2021 & Kumar, 2021). 3G ethanol has a similar environmental performance to 2G ethanol in terms of GHG emissions reduction and fossil fuel displacement. However, 3G ethanol has higher environmental benefits than 2G ethanol in terms of wastewater treatment and carbon sequestration. 3G ethanol is believed to have higher social performance than 2G ethanol in rural development, employment generation, and food security. The comparison results between 3G and 2G ethanol for other parameters are shown in Table 3.

Parameter	2G Ethanol	3G Ethanol
Feedstock	Non edible stocks	Microalgae
Employment Generation	1200 jobs/100klpd	Uknown
Carbohydrate content	Low to Medium	High
Lignin	Present	Absent
Ethanol Yield	Low	High
Common Technological Barriers	Enzyme production, Fermentation, Separation and purification	Enzyme production, Fermentation of Microbial strains, Product separation and purification,
Uncommon Technological Barriers	Feedstock availability, Pretreatment	Hydrogen-rich feed gas, Chemical composition for Nutrient Solution, Integration with existing infrastructure

Table 7: Comparison Results between 3G Ethanol and 2G Ethanol from Agricultural Residues

6. CONCLUSION

This study assesses the techno economic feasibility of 3G ethanol production in India, using a case study approach of an integrated algal biorefinery. The study shows that though the technical feasibility of 3G ethanol production is challenging and technically competitive, but the same can be overcome through technology and R&D improvements. Regarding economic performance, ethanol pricing plays the most crucial role, followed by plant life span, discount rate, ethanol yield, and co-product pricing. Improvement in algae yield can also significantly improve the economic performance of the algal biorefinery. Funding, subsidies and support from the government can aid in filling the viability gap and in the abatement of associated economic risks. Since 2G and 3G ethanol, both have their own advantages and disadvantages; thus, it would be in order to simultaneously use multiple generations of ethanol to address the overall ethanol demand and contribute to the environment. As 3G feedstocks have lesser lignin and higher carbohydrate content, they hold immense potential to become an advantageous feedstock for ethanol production.

Though the study conducts a comprehensive techno-economic assessment of algal biorefinery, it also has some limitations. The case study is based on the usage of a single type of algal strain (Nannochloropsis sp.). The study does not take into account the social cost of carbon and carbon credits in the calculation which can play a vital role in enhancing the financial productivity of such initiatives. There is further scope of conducting future research on similar lines considering an integrated biorefinery concept.

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