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## TECHNO-ECONOMIC ANALYSIS OF AN INTEGRATED SUGARCANE PROCESSING COMPLEX IN INDIA

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### SUMMARY

This study focuses on a systematic techno-economic feasibility analysis of an integrated sugarcane processing complex in India. The comprehensive process modelling was performed using SuperPro Designer. The economic viability of an integrated sugarcane processing complex was assessed with significant economic parameters and other financial indices. The process model was developed for a processing capacity of 9,000 TPD sugarcane. The model estimates 738 TPD of sugar crystals, 140 KLPD of ethanol from 492.38 TPD of B-heavy molasses, and 36.62 MW of captive power from residual sugarcane bagasse. The estimated CAPEX and OPEX of the process model were INR 13,942 and INR 11,803 million, respectively. The proposed model shows strong economic feasibility, with an ROI of 15.10%, an IRR of 13.37%, an NPV of 6,952 million INR and a payback period of 6.62 years. The sensitivity analysis highlights sugarcane cost as the most sensitive parameter in the minimum selling price of ethanol, which can affect process economics over the long run. The proposed integrated sugarcane processing complex offers an advantage in achieving zero liquid discharge. This is accomplished by treating vinasse through anaerobic digestion, which recovers energy while managing liquid waste. Through an integrated approach, such as sugar processing, ethanol production, and cogeneration, the facility contributes to the Sustainable Development Goals and to energy self-sufficiency. Thus, it serves as a circular biorefinery model that demonstrates resource efficiency and effective waste management.

**Key words:** sugarcane, techno-economic analysis, 1G ethanol, 1G biorefinery, circular biorefinery, zero liquid discharge, integrated biorefinery, ethanol distillery.

## INTRODUCTION

Sugarcane is considered the world's primary commercial crop. It has acquired industrial importance and influences regional and global economies. India ranks second in sugarcane production, followed by Brazil [1]. The sugarcane processing complexes have a robust industrial infrastructure for the overall research and development of the sugar industry [2]. Sugar and jaggery are among the predominant food items that contribute to nearly 10% of the nation's daily calorie intake. The major advantage of sugar and jaggery is that they contribute to daily necessities and are considered the most economical sources of energy [3]. The regions around the sugarcane-growing belts are home to the majority of India's sugar factories. The majority of the sugarcane-growing regions are found in rural areas. To enhance the socio-economic well-being of local farmers and beneficiaries, several sugar complex enterprises have implemented developmental projects [4]. India's leading sugarcane-producing states are Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, Gujarat, Bihar, Haryana and Punjab. Among these, Tamil Nadu leads in sugarcane yield, followed by Maharashtra and Karnataka [5].

Over the past few decades, the sugarcane processing complexes have experienced remarkable growth. The sugar and allied food industries play a significant role in contributing to the nation's GDP. These sugar industry complexes are also a source of rural employment generation in the country. The sugar industry complexes in India are broadly categorised as follows: those that focus solely on sugar production; those that produce sugar alongside ethanol as an additional revenue stream; and fully integrated mills that generate sugar, ethanol, biogas, and organic manure. These sugar complexes produce nearly 30-35 million tons of white sugar, 8-10 million tons of jaggery, 3.5-4 billion litres of fuel ethanol, and 4,700 MW of power [5].

The estimated waste generation from crushing 1,000 kg of sugarcane is 300 kg of bagasse, 40-45 kg of molasses, and 20-25 kg of press mud. Additionally, ethanol production also generates spent wash as an effluent after distillation [6]. These waste streams, if not correctly handled, can lead to water and land pollution. Most sugar mills in India utilise press mud and spent wash as organic fertilisers; however, excessive dosages may cause land pollution [7]. Waste management from sugar mills is a significant challenge at a commercial scale.

The sugarcane bagasse and spent wash have significant potential for utilisation within an integrated approach to energy demand substitution. The sugarcane bagasse can be effectively utilised as a boiler fuel after dehydration for electricity and steam production. The steam and electricity produced can be effectively recycled for various plant operations. The spent wash, a residue from the distillation of ethanol, contains considerable amounts of sucrose and other nutrients and can be utilised either as organic manure or as feed for anaerobic digestion to produce biogas and organic fertilisers [8]. Some conventional sugar mills also use sugarcane straw as fuel for their boilers to generate surplus electricity. The electricity generated by the sugarcane industry can significantly contribute to the mid- or short-term energy mix, similar to fuel ethanol.

The Indian government launched the National Biofuel Policy (NBP) in 2018 to reduce dependence on conventional energy sources and achieve the nation's sustainable development goals. Under NBP 2018, the flagship programme, i.e, Ethanol Blending Programme (EBP), was launched as a major framework of the policy [9]. The EBP has set the indicative target of 20% ethanol blending in conventional petrol by 2025. The various feedstock options proposed for ethanol production include sugarcane, B and C heavy molasses, and degraded food crops. By increasing domestic ethanol production, maintaining an effective supply chain, and setting a minimum feedstock price, the 20% blending target can be achieved. The sugar mills are the major producers of ethanol in India; primary feedstocks include sugarcane and B and C-heavy molasses [9]. The supply chain for sugarcane and raw materials, antiquated technology, infrastructural and financial limitations and environmental regulations are the main obstacles that sugar mills must overcome. The techno-economic analysis assesses the technical feasibility and economic viability in terms of long-term sustainable development goals. It helps identify optimal resource utilisation, energy self-sufficiency through steam and power generation, and the value addition of by-products such as molasses, press mud, and spent wash. The analysis is relevant in the context of India's NBP and EBP programmes, fluctuating sugar prices and surplus production. The integrated sugar

complexes can boost rural income and infrastructure in sugarcane-growing regions in the nation [9].

Various countries have developed their own biofuel policies, including the United States of America, Brazil, and the European Union. The USA has launched the programme under the name Renewable Fuel Standard (RFS) within the Environmental Protection Agency. The RFS mandates the use of a minimum quantity of renewable fuels, such as biofuels. The RFS 1 was mandated under the Energy Policy Act of 2005. Under RFS 2, the target for biofuels in the total energy mix was set at 9 billion gallons by 2023. The USA's primary focus is on cellulosic ethanol production from corn [10]. The oil crisis and price hike in 1973 led to the foundation of National Proalcool in Brazil to reduce oil dependency by promoting sugarcane-based ethanol production. The first biofuel policy was launched under the RenovaBio programme, with a significant focus on reducing carbon dioxide emissions by 2028 [11]. The European Union has also mandated the use of renewable energy, with a target of 20% in the total energy mix. Of the 20%, the transportation sector has dedicated 10% of its renewable energy use [11].

The present work aims to develop a process model based on an actual industrial setup, where process data for the sugarcane processing complex were primarily obtained from industry and literature. The basic framework is to investigate the integrated process for a sugarcane processing complex with a processing capacity of 9,000 TPD. Various region-specific techno-economic studies have been reported in the literature; most rely on a generalised process model. The proposed process model is based on the data from an actual operating sugar processing complex in India. The integrated zero liquid discharge framework treats spent wash for energy production, in line with stringent environmental regulations. The primary objective was to examine the economics of producing ethanol from B-heavy molasses for the Indian scenario. The analysis highlights the actual industrial practices in sugarcane processing complexes, providing decision-relevant insights for policymakers and sugarcane processing plant operators in the Indian sugar sector.

The paper is organised as follows: Section 1 highlights the general relevance of sugarcane processing complexes; Section 2 presents a review of previous studies on techno-economic analyses of sugarcane processing complexes. Section 3 describes the materials and methods, including a process overview of the sugarcane processing complex, model development and a system-level description of the proposed process model. Section 4 presents the results and discussion, covering the economic assessment, sensitivity analysis, energy efficiency evaluation, benchmarking through comparison with region-specific previous literature and scenario analysis. Section 5 presents the discussion of the proposed sugarcane processing complex model, along with its limitations, and Section 6 summarises the main conclusions of the study and outlines the potential directions for future research.

## REVIEW OF PREVIOUS STUDIES

Minimal region-specific literature has been reported regarding the techno-economic evaluation of an integrated sugarcane processing complex. Dias et al. (2010) investigated the techno-economic assessment of ethanol production from sugarcane in Brazil. The sugarcane processing capacity of 12,000 TPD, with 1,000 m<sup>3</sup>/day of ethanol production over 180 days, was evaluated. The software tools used for process simulation were Excel sheets for basic calculations and SuperPro Designer for detailed process modelling. The other parameters, such as the sugarcane price, were set to US\$16.58/ton of sugarcane, based on the 2010 price range. The equipment purchase cost ranged from US\$144 to US\$205 million, respectively. The ethanol production cost ranged from US\$0.26 to US\$40 for four different scenarios. Sugarcane trash can be effectively utilised for cogeneration, thereby significantly reducing ethanol production costs [12]. Mendes et al. (2017) conducted a techno-economic assessment of 1G ethanol production in Brazil using various sugarcane hybrids, including H146, H166, H140, H89, H58, and H321. The software tool used for the process modelling was Aspen Plus coupled with Virtual Sugarcane Biorefinery (VSB). From the results obtained, the H89 hybrid has excellent field productivity due to high fibre content, high sucrose and low lignin content. The results of the sensitivity analysis indicate that ethanol price is the most sensitive parameter, fluctuating between 12.5% and 23% with an average price change of  $\pm 25\%$  [13]. Silva Ortiz et al. (2019) investigated the integration of mass and thermal energy for a Brazilian 1G-2G ethanol-producing facility. The sugarcane bagasse was diverted from cogeneration to 2G ethanol production at a 50% ratio. The sugar mill's processing capacity was 4

million tons of sugarcane per year [14]. Vasconcelos et al. (2020) investigated the techno-economic analysis of 1G2G ethanol production coupled to a conventional sugar mill in Brazil. The sugarcane hybrid H89 was used as a feedstock. The processing capacity was estimated to be 12,000 TPD of sugarcane. To reduce equipment costs, a single fermentation was used for both 1G and 2G ethanol. Twelve scenarios were investigated by varying process parameters, including residence time and solid loading percentage [15]. Pachón et al. (2020) evaluated the process design, techno-economic analysis, and life-cycle assessment of a sugarcane biorefinery in South Africa. The processing capacity considered for the process model was 7,200 TPD of sugarcane. The sugarcane bagasse was diverted for 2G ethanol production and other biochemicals. Three scenarios were investigated: a sugar mill with lactic acid and ethanol production, a sugar mill with furfural and ethanol production and a sugar mill with only sugar and ethanol production. The sugar mill, which focused solely on fuel production, was the energy-efficient option for South Africa [16]. Munagala and Shastri (2023) conducted techno-economic and life-cycle assessments of a sugarcane processing complex under various configurations. The myriad range of products under different scenarios was sugar, ethanol, electricity, biogas, lactic acid, succinic acid and xylitol. The processing capacity of sugarcane was assumed to be 4,344 TPD with 330 days of operation [17]. Table 1 highlights the literature review of techno-economic analysis studies on sugarcane processing complexes.

Table 1. Literature review of techno-economic analysis studies on sugar processing complexes

| Sl. No. | Process description and configuration                                                                                                                                                                                                                          | Reference     |
|---------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| 1       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane<br>Processing capacity: 12,000 TPD<br>Operating days: 180                                                                                                                                                  | [12]          |
| 2       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane Hybrids in Brazil (H146, H166, H140, H89, H58 and H321)<br>Processing capacity: 12,000 TPD<br>Days of operation: 167                                                                                       | [13]          |
| 3       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane<br>Processing capacity: 12,121 TPD<br>Days of operation: 200                                                                                                                                               | [14]          |
| 4       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane hybrid H89 (Brazil)<br>Processing capacity: 12,000 TPD<br>Days of operation: 200                                                                                                                           | [15]          |
| 5       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane in South Africa<br>Processing capacity: 7,200 TPD                                                                                                                                                          | [16]          |
| 6       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane in India<br>Processing capacity: 4,344 TPD<br>Operating days: 150-330                                                                                                                                      | [17]          |
| 7       | Products: Sugar and Ethanol<br>Feedstock: Sugarcane in India<br>Processing capacity: 9,000 TPD (Industrial Scale)<br>Operating days: 250<br>Circular biorefinery approach with zero liquid discharge and MSP for ethanol as per the Indian government mandate. | Present study |

From the previous literature on sugarcane processing complexes that operate at processing capacities ranging from 4,344 TPD to 12,121 TPD, along with variations in operating days from 150 to 330 days depending on various geographical conditions. The country-specific studies from Brazil and South Africa highlight the role of sugarcane hybrids on process efficiency and product yields. The Indian case studies focus on variable plant scale and operational duration. The literature is mainly focused on conventional products such as sugar and ethanol, with limited attention to the circular biorefinery model.

The present study highlights the actual industrial-scale setup under Indian operating conditions, incorporating a circular biorefinery approach with zero liquid discharge and aligning with government

mandates. The present study advances the literature by integrating sustainability considerations into techno-economic assessment and highlights existing gaps in the circular biorefinery model.

## MATERIALS AND METHODS

### Process Overview

The sugar mill and the ethanol distillery are the two primary components of the sugarcane processing complex. Transporting sugarcane from the farm to the sugar mill is the first step in sugarcane processing, followed by sugarcane shredding and crushing in mills. Water is added to improve juice extraction. The sugarcane bagasse is separated and processed for the cogeneration section, where it is used to generate steam and power. The raw juice is heated after liming and sulfiting, then further processed in the evaporator to concentrate it. The syrup is then crystallised to form sugar crystals, and the leftover molasses is diluted with water and conveyed to the fermentation process, where yeast is added to convert sugars into ethanol and carbon dioxide. The fermented broth is then heated to separate ethanol from water and other residues. The distillation column residue, spent wash, is fed to anaerobic digestion to produce methane and carbon dioxide.

### Model Development

The modelling and simulation of the integrated sugarcane processing complex were evaluated using SuperPro Designer (Intelligen, Inc., USA) version 12. The present study of the integrated sugarcane processing complex was divided into two main sections: sugar crystal production and an ethanol distillery. The sugar crystals production facility comprises five subsections: front-end operations, crushing, juice heating (for raw, sulphited, and explicit juice), evaporation, and crystallisation. The ethanol distillery section comprises five sub-sections: fermentation, distillation, purification, storage and anaerobic digestion. The cogeneration section utilises sugarcane bagasse as fuel to generate power and process steam. The stock mixture of sugarcane was created using SuperPro Designer. Table 2 represents the specific composition of the sugarcane.

Table 2. Stock mixture composition of sugarcane [17]

| S. No | Components                | %w/w |
|-------|---------------------------|------|
| 1     | Water                     | 65%  |
| 2     | Sucrose                   | 18%  |
| 3     | Sugarcane bagasse         | 15%  |
| 4     | Dirt and other impurities | 2%   |

### System Description

#### Front-End Operation

The sugarcane was transported from the farm to the sugar mill facility, a distance of 50 km, by truck. The transportation cost was assumed to be INR 2/MT-km, and the quantity per shipment was set to 100 MT of sugarcane. The sugarcane was initially shredded into small pieces and conveyed to the crushing section.

#### Crushing Section

The crushing section consists of two mills used to extract sugarcane juice. In the second mill, water was added to improve overall milling efficiency. The extracted sugarcane juice is conveyed to the heating section.

#### Heating Section

The heating section comprises three sub-sections: raw juice heating, precise juice heating, and sulphited juice heating. Using low-pressure steam, the raw sugarcane juice was heated from ambient temperature

to 67.5 °C. The heated raw juice is conveyed to the liming tank, where calcium oxide is added to reduce its pH. The liming process also clarifies the juice by settling down the dirt and impurities in the raw juice. The low-pressure steam further increases the temperature of limed juice to 78 °C. The final step in juice heating involves adding sulphur dioxide to prevent oxidation. The sulfited juice is heated with low-pressure steam up to 102 °C and then conveyed to the clarification section for the removal of impurities and dirt.

#### *Thickening and Evaporation Section*

Continuous thickening, which separates dirt and other impurities, and the sludge, known as press mud, can be used as an organic fertiliser. The clarified stream from the thickening section is conveyed to the blending tank for heating clean juice. The low-pressure steam is used to heat the clean juice to 110 °C. The heated clear juice is conveyed to the multi-effect evaporator for concentration using a forward-feed flow arrangement.

#### *Crystallisation Section*

The concentrated sugarcane juice is conveyed to the continuous crystallisation section, where it has a residence time of two hours and a pressure of 1 bar. The filtrate of the crystallisation section consists of concentrated sugarcane juice known as molasses, whereas the final product, i.e., sugar crystals, is separated from the bottom stream.

#### *Co-Generation Section*

The sugarcane bagasse was utilized as boiler fuel to produce superheated steam, with the help of RO water, which was expanded through an extraction steam turbine for electricity and process steam production [18]. The generated electricity and process steam were 100% recycled for plant operation.

#### *Fermentation, Distillation and Purification Section*

The initial step in molasses fermentation is dilution: the molasses is diluted with water in a 1:1 ratio, then conveyed to the fermentation section. The seed fermenter prepares the inoculum and acclimatises the yeast cell culture for the fermentation process. The sugars from molasses are converted, with the help of yeast, in the presence of air, to yield ethanol and carbon dioxide. The products of the reaction consist of a solution of molasses, ethanol, and water, separated in a distillation column. The distillation column cuts ethanol as overhead vapours, and the bottom stillage, also known as vinasse. The distillate from the first distillation is further enriched in the second column, resulting in anhydrous ethanol. The final distillate is then conveyed to the adsorption column for processing into fuel-grade ethanol.

#### *Anaerobic Digestion*

The bottom of the first distillation column, vinasse, is used as a feed for anaerobic digestion. Hydrolysis, acidogenesis, acetogenesis and methanogenesis are the different stages of anaerobic digestion. The bottom stream is composed of fermented organic manure, and the reaction produces raw biogas, a gaseous product consisting of carbon dioxide, hydrogen, and methane. The comprehensive process flow diagram for the integrated sugarcane processing complex is shown in figure 1.

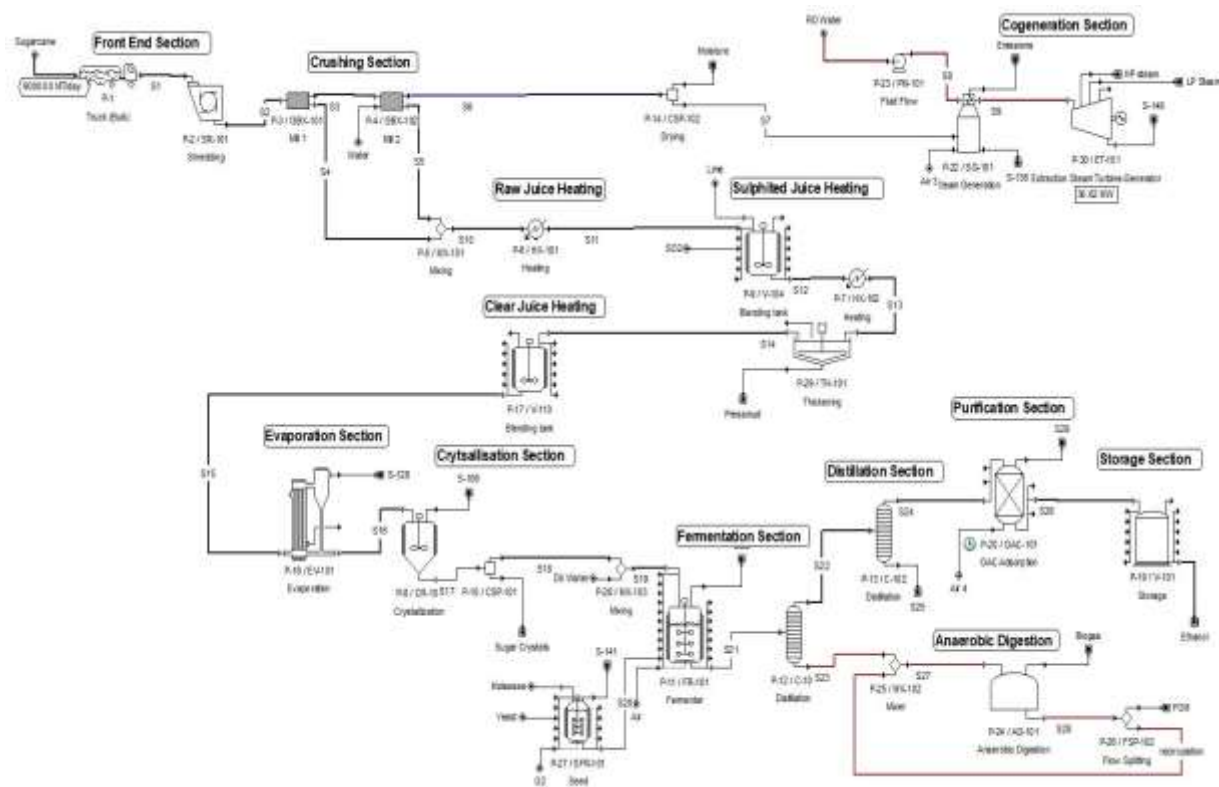


Figure 1. Detailed process flow diagram of the integrated sugarcane processing complex

## RESULTS AND DISCUSSION

### Economic Assessment

The equipment, such as shredders, mills, heat exchangers, distillation columns, and all other auxiliary equipment, and their associated costs, are considered by the SuperPro Designer integrated cost model. The software's additional feature is that direct costs are included in the techno-economic assessment. The direct costs include piping and insulation, instrumentation, electrical facilities, building construction, yard improvement and other auxiliary expenses. The software also accounts for indirect expenditures, such as those related to construction and engineering works, contractor fees and contingency. The total of all expenses, including direct, indirect, and additional costs, is accounted for as the project's capital cost.

For the proposed integrated sugarcane processing complex, a 30-year project lifespan, a 30-month construction period and a six-month start-up time were chosen for economic evaluation. The years of analysis and construction were set to 2025. The facility was scheduled to operate for 250 days per year [19] [20]. The income tax was set at 18%, and the inflation rate was set at 4%. It was estimated that the contractor's fees and contingency would be 5% and 10%, respectively, of the total direct and indirect expenditures. For the first three years, allocations of 30%, 40%, and 30% of direct fixed cost expenditure were considered. A 5% salvage value of direct fixed costs and a ten-year depreciation period were assumed. While working capital, direct fixed capital, and equipment acquisition expenses were used to assess the capital investment, comprehensive energy and mass balances were used to estimate operating costs.

The raw material costs, specifically the cost of sugarcane, were set at INR 3,200/MT [21]; the price of yeast was set at INR 80/kg, and calcium oxide, INR 7/kg were other noteworthy expenses. The labour costs were estimated to be INR 101.20/hour. The generated captive power was 100% recycled, and the electrical power utilised and consumed for plant operations was estimated at INR 2/kWh. Direct, indirect, and other costs are the three components of capital expenditures. Piping and insulation, instrumentation, electrical facilities, buildings, yard improvements, and other auxiliary facilities are all

included in the direct cost. At the same time, the other expenses include contractor fees and contingencies. The purchase cost of equipment (PCE) and direct fixed capital (DFC) are used to estimate the capital cost. A thorough capital cost technique used for the proposed integrated sugarcane processing complex is shown in table 3.

Table 3. Integrated sugar complex's comprehensive capital cost approach

| Sl. No.                           | Parameters                    | Assumption                            |
|-----------------------------------|-------------------------------|---------------------------------------|
| 1                                 | Unlisted Equipment Purchase   | $0.20 \times \text{PCE}$              |
| <b>Direct Costs (DC)</b>          |                               |                                       |
| 1                                 | Plumbing Cost                 | $0.35 \times \text{PCE}$              |
| 2                                 | Instrumentation Cost          | $0.40 \times \text{PCE}$              |
| 3                                 | Insulation Cost               | $0.03 \times \text{PCE}$              |
| 4                                 | Power System Cost             | $0.10 \times \text{PCE}$              |
| 5                                 | Buildings Cost                | $0.45 \times \text{PCE}$              |
| 6                                 | Site Development Cost         | $0.15 \times \text{PCE}$              |
| 7                                 | Supplementary Facilities Cost | $0.40 \times \text{PCE}$              |
| <b>Indirect costs (IC)</b>        |                               |                                       |
| 1                                 | Engineering Cost              | $0.25 \times \text{DC}$               |
| 2                                 | Construction Cost             | $0.35 \times \text{DC}$               |
| <b>Other costs</b>                |                               |                                       |
| 1                                 | Contractor Fees               | $0.05 \times (\text{DC} + \text{IC})$ |
| 2                                 | Safety Factor                 | $0.10 \times (\text{DC} + \text{IC})$ |
| <b>Direct Fixed Capital (DFC)</b> |                               | INR 12,219,532,000                    |

The direct fixed capital investment for the integrated sugarcane processing complex was estimated at INR 12,219 million. The various costs associated with capital expenditures include equipment purchase, working capital, start-up costs, and validation. The total capital investment for the sugar mill consisted of the equipment purchase cost of INR 2,042,500,000, direct fixed capital of INR 12,219,532,000, working capital of INR 1,112,013,537, and start-up and validation costs of INR 610,976,000, respectively. The operating costs involve materials, facility development, labour, laboratory and quality control, utilities, and transportation. The costs involve raw materials such as sugarcane, assumed to be INR 3,200/MT; calcium oxide, INR 7/kg; water and RO water, at INR 0.60/kg; and yeast at INR 80/kg, respectively. The proportion of operating costs for the integrated sugarcane processing complex is that materials account for nearly 72.81%, followed by facility-dependent costs at 19.50%, utilities costs at 5.59%, and transportation costs at 1.91%, respectively. The total annual operating cost was estimated to be INR 11,803,273,127. Figure 2 represents the proportion of annual operating costs.

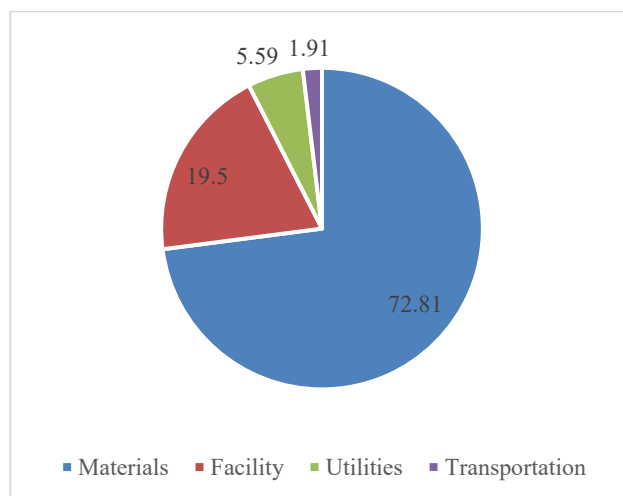


Figure 2. Proportion of annual operational cost for the integrated sugarcane processing complex

The sugarcane procurement cost was a significant factor influencing annual operating costs, accounting

for 83.78% of total material costs, followed by RO water costs. The RO water accounted for 8.21% of total material costs. The other expenses, such as yeast and molasses, accounted for 0.91% and 0.26% of total material costs. The utility expenses include chilled water, cooling water, high-pressure steam, and low-pressure steam. The cooling water accounted for nearly 78.1% of the total utility share, followed by chilled water at 21.8%, and high- and low-pressure steam recirculated from the combined heat and power section. The total share of fresh water requirement was 502.4 KLPD for plant operations and 4703.97 KLPD for the cogeneration section. The estimated total land requirement for the proposed sugarcane processing complex in India is approximately 45-50 hectares, equivalent to 100-125 acres [22]. The primary effluents from the proposed sugar mills include wastewater, boiler ash, press mud and fly ash. The wastewater from the distillation column, vinasse, was treated in an anaerobic digester to produce biogas and fermented organic manure, making the integrated sugarcane processing complex a circular biorefinery model. The estimated boiler ash is 78.97 TPD, and it can be supplied to brick manufacturers. The fly ash and press mud are saleable in the market. The estimated annual cost of waste treatment and disposal was INR 1,105,832, respectively.

The mainstream product from the integrated sugar industry complex, with a processing capacity of 9,000 TPD of sugarcane, was sugar crystals. In contrast, the revenue stream consisted of fuel ethanol, press mud, and captive power. The quantities of mainstream product, sugar crystals, and fuel ethanol were 738.57 metric tons per day and 140 kiloliters per day, respectively. The residual sugarcane bagasse produced 36.62 MW of captive power, which was recycled for plant operations. The net unit production cost of mainstream products, as estimated by the in-built cost model for sugar crystals, was INR 40/kg, whereas the fuel ethanol cost was set at INR 61/litre, as per market prices.

The total annual revenue was calculated by multiplying each product's selling price by its production volume. Net annual operating costs refer to the expenses incurred for materials, transportation, utilities, and other related costs. The estimated total annual revenues and net annual operating costs for the project were INR 12,955 million and INR 11,803 million, respectively. The gross margin, i.e., profitability evaluated by the in-built cost model, was 8.89%. The other project indices include return on investment (ROI), payback time and internal rate of return (IRR). The project's expected ROI was 15.10%, with a payback period of 6.62 years and an IRR of 13.37%. The expected net present value (NPV) of the project was estimated to be INR 6,952 million. The economic assessment of the project indicates a strong case for its long-term sustainability and financial feasibility.

### Sensitivity Analysis

The sensitivity analysis was conducted to evaluate the most sensitive parameters of the process model. The primary objective of the sensitivity analysis is to identify the risk factors that may impact the project over the time period. A probabilistic Monte Carlo sensitivity analysis was employed to assess uncertainty in the minimum selling price of ethanol. A triangular probabilistic distribution was defined, with lower and upper limits varying by  $\pm 30\%$  of the major key cost parameters, including sugarcane, molasses, yeast, and electricity costs.

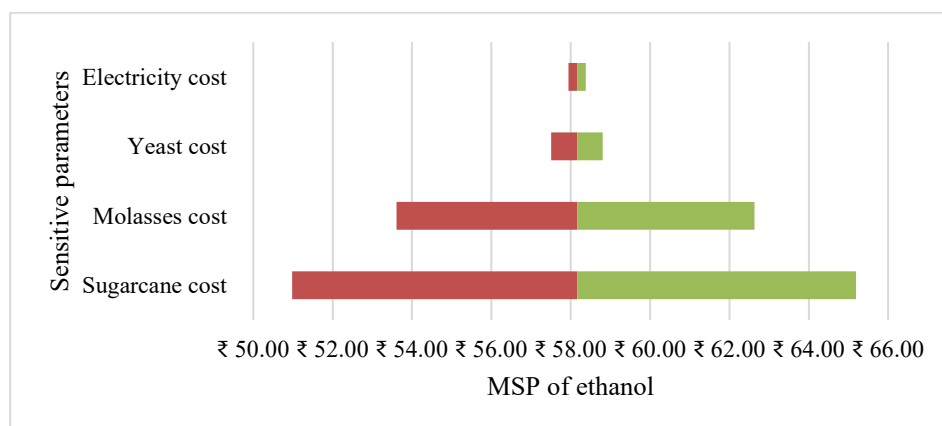


Figure 3. Tornado plot for sensitivity analysis of the integrated sugarcane processing complex

The minimum selling price of ethanol was set as an output performance indicator, with a base price of INR 61/L. The simulation was performed with 10,000 iterations, using input parameters randomly sampled from the distribution. From the results obtained, the sugarcane cost was the most sensitive parameter for the MSP of ethanol, followed by the molasses and yeast costs. Figure 3 represents the tornado plot of the sensitivity analysis of the proposed sugar mill.

### Energy Efficiency

The energy efficiency of a system is its ability to convert input energy into sound output energy with minimised losses. In the sugarcane processing complex, energy efficiency measures the effectiveness of converting sugarcane into valuable products, such as food, fuels, and electricity. Energy efficiency is an important aspect for project sustainability and for economic considerations. It maximises utility by reducing the process's excess environmental burden. A detailed energy-efficiency evaluation was conducted for the proposed process model. Energy efficiency is defined as the ratio of the system's total energy output to its total energy input. The energy efficiency of products and resources in terms of lower heating value (LHV), as shown in equation (1), and described by Silva Ortiz et al. (2019) [14]. Table 4 presents a detailed theoretical energy-efficiency analysis of the proposed sugarcane processing complex in India.

$$\text{Energy Efficiency}(\eta) = \frac{\sum(m \times \text{LHV})_{\text{products}} + W_{\text{net}}}{\sum(m \times \text{LHV})_{\text{resources}}} \quad (1)$$

Where,

$\eta$  = Energy Efficiency

$m$  = mass flow rate

LHV = Lower heating value (MJ/kg)

$(m \times \text{LHV})_{\text{products}}$  = Total energy content of the products (MJ)

$(m \times \text{LHV})_{\text{resources}}$  = Total energy input from the resources (MJ)

$W_{\text{net}}$  = Net work output (MJ)

The electricity (MW) from cogeneration was converted to daily energy (MJ/day) by multiplying by 86,400, the total number of seconds in a day. The estimated theoretical energy efficiency for various sections of the sugarcane processing complex is as follows: sugar crystals at 41.2%, the ethanol distillery at 96.7%, and the cogeneration section at 25.56%, respectively. There are potential improvements in energy efficiency in the sugar production and cogeneration sections, as a significant amount of input energy is being wasted due to improper usage of thermal energy. The overall system efficiency is 20.58%; the primary reason is that a significant part of the total input energy is recovered as sound energy in products. Non-energetic byproducts, inefficient equipment, and other losses result in residual energy being wasted.

The steam-to-cane ratio is the amount of total steam consumed in an integrated sugar processing complex for various unit operations per unit mass of sugarcane crushed in the mill. The estimated steam-to-cane ratio for the proposed model was 0.33 kg steam per kg of cane crushed, i.e., 33.29%. The proposed cogeneration system operates on a high-pressure steam cycle, using residual sugarcane bagasse as fuel. The estimated fuel input is 2,286 TPD of bagasse, with available heat of 1,647 kcal/kg. The total thermal energy input to the boiler is 182.5 MW. Considering boiler losses, the effective useful heat is 173.4 MW. The boiler operates at 120 bar and 540 °C, with a steam turbine producing 36.62 MW of electricity along with 2,399 TPD of high-pressure (10 bar, 236 °C) steam and 470 TPD of low-pressure (5 bar, 180 °C) steam. The electrical efficiency of the proposed system is about 20%.

Table 4: Theoretical energy efficiency analysis by process section: sugar, ethanol and cogeneration

| Sl. No.                                                                 | Input/Output      | LHV (MJ/ton) or (seconds) | Mass flow (TPD) or (MW) | Energy (MJ)        |
|-------------------------------------------------------------------------|-------------------|---------------------------|-------------------------|--------------------|
| <b>Sugar crystals</b>                                                   |                   |                           |                         |                    |
| 1                                                                       | Sugarcane         | 17,000                    | 9,000                   | 153,000,000        |
| Total input energy (MJ)                                                 |                   |                           |                         | 153,000,000        |
| 1                                                                       | Sugarcane bagasse | 19,000                    | 2,286.38                | 43,441,220         |
| 2                                                                       | Sugar crystals    | 16,000                    | 738.57                  | 11,817,120         |
| 3                                                                       | Press mud         | 10,000                    | 188.18                  | 1,881,800          |
| 4                                                                       | Molasses          | 14,000                    | 492                     | 6,888,000          |
| Total output energy (MJ)                                                |                   |                           |                         | 64,028,140         |
| Theoretical Energy efficiency = (Output/Input) = 64,028,140/153,000,000 |                   |                           |                         | <b>41.84%</b>      |
| <b>Ethanol distillery</b>                                               |                   |                           |                         |                    |
| 1                                                                       | Molasses          | 14,000                    | 492                     | 6,888,000          |
| Total input energy (MJ)                                                 |                   |                           |                         | 6,888,000          |
| 1                                                                       | Ethanol           | 26,800                    | 118.35                  | 3,171,780          |
| 2                                                                       | Vinasse           | 5,000                     | 697.48                  | 3,487,400          |
| Total output energy (MJ)                                                |                   |                           |                         | 6,659,180          |
| Theoretical Energy efficiency = (Output/Input) = 6,659,180/6,888,000    |                   |                           |                         | <b>96.7%</b>       |
| <b>Cogeneration</b>                                                     |                   |                           |                         |                    |
| 1                                                                       | Sugarcane bagasse | 19,000                    | 2286.38                 | 43,441,220         |
| Total input energy (MJ)                                                 |                   |                           |                         | 43,441,220         |
| 1                                                                       | Steam (10 bar)    | 2,776                     | 2399.02                 | 6,659,679          |
| 2                                                                       | Steam (5 bar)     | 2,726                     | 470.39                  | 1,282,283          |
| 3                                                                       | Electricity (MW)  | 86,400                    | 36.62                   | 3,163,968          |
| Total output energy (MJ)                                                |                   |                           |                         | 11,105,930         |
| Theoretical Energy efficiency = (Output/Input) = 11,105,930/43,441,220  |                   |                           |                         | <b>25.56%</b>      |
| Overall energy output (Eout)                                            |                   |                           |                         | <b>31,465,564</b>  |
| Overall energy input (Ein)                                              |                   |                           |                         | <b>153,000,000</b> |
| Overall system theoretical energy efficiency                            |                   |                           |                         | <b>20.58%</b>      |

Considering the fuel exergy input of 197 MW, the useful exergy output, including electricity and steam production, is 67 MW, yielding an exergy efficiency of about 34%. The gap between energy and exergy efficiency arises from irreversibilities in combustion and heat transfer. There is scope for improved heat recovery from waste heat and system optimisation.

### Comparison with Previous Studies

The present study was compared with the existing literature on the integrated sugarcane processing complex by Munagala and Shastri (2023) to evaluate consistency and identify deviations. The study primarily focuses on an integrated sugarcane processing complex with the same product ranges: sugar, ethanol, and cogeneration. The major difference arises in the scale and process model assumptions. Equation (2) represents the gross margin or profitability (%), and equation (3) represents the net present value in terms of interest rate and net cash flow as implemented in the SuperPro Designer (Intelligen, 2023) [23]. Table 5 presents a comparative analysis of the proposed model with the existing literature.

$$\text{Gross Margin or Profitability (\%)} = \frac{\text{Net Profit}}{\text{Revenues}} \times 100 \quad (2)$$

$$NPV = \sum_{k=0}^n \frac{NCF_k}{(1+i)^k} \quad (3)$$

Where,

i=interest rate

NCF<sub>k</sub> = Net cash flow in years, k

n = project lifetime in years

Table 5. Comparison of results for the model developed by munagala and shastri, 2023

| Sl. No.                   | Parameter                   | Munagala and shastri (2023) | Present study |
|---------------------------|-----------------------------|-----------------------------|---------------|
| General Model Details     |                             |                             |               |
| 1                         | Type of Feedstock           | Sugarcane                   | Sugarcane     |
| 2                         | Processing Capacity (TPD)   | 4,344                       | 9,000         |
| 3                         | Sugar Yield (TPD)           | 434.4                       | 738.57        |
| 4                         | Ethanol Yield (TPD)         | 22.32                       | 114.10        |
| 5                         | Sugarcane Bagasse (TPD)     | 1,303.2                     | 2,286         |
| 6                         | Electricity Production (MW) | 18.57                       | 36.62         |
| 7                         | No. of Operating Days       | 150-300                     | 250           |
| Cost Parameters           |                             |                             |               |
| 1                         | CAPEX (million INR)         | 3,793                       | 13,942        |
| 2                         | OPEX (million INR)          | 2,765                       | 11,803        |
| 3                         | Annual Revenues             | 3,546                       | 12,955        |
| 4                         | NPV (million INR)           | -                           | 6,952         |
| 5                         | Profitability (%)           | -                           | 8.89          |
| Selling Price of Products |                             |                             |               |
| 1                         | Sugar (INR/kg)              | 31                          | 40            |
| 2                         | Ethanol (INR/kg)            | 47                          | 61            |
| 3                         | Electricity (INR/kWh)       | 8                           | 2             |

Compared to the process model developed by Munagala and Shastri (2023), the proposed model operates at a realistic industrial scale in the Indian context—the scale-up results in higher production of sugar, ethanol and electricity from cogeneration. The results of the proposed model are benchmarked with the previous literature reported by Munagala and Shastri (2023). The comparative results indicate that large-scale integrated sugarcane processing complexes achieve improved economic performance, yielding positive NPV and higher profitability than the previously reported model. The proposed study aligns with the existing literature regarding process configuration and economic trends. The major deviation of the ethanol selling price is due to the scale of the process model and other cost assumptions.

The proposed study was developed to reflect the actual industrial operation and was parameterized using data consistent with Indian sugar industry practices. The steady-state process model was assumed for all unit operations, representing continuous operation during the crushing season. The equipment performance parameters, steam consumption and power generation efficiencies were selected based on actual industrial operating ranges. The economic parameters, such as capital cost correlations and utility prices, were adopted from SuperPro Designer's default settings and adjusted using Indian benchmarks to ensure realistic cost estimates. These assumptions enable reproducibility while maintaining consistency with industrial practices.

### Scenario Analysis

The Indian sugar mills generally operate on a seasonal basis, i.e., the number of operating days is directly linked to the sugarcane harvesting seasons. Thus, it is strategically important to increase the number of operating day windows for enhanced sugar and ethanol production. Sugarcane harvesting in India generally takes place from November to April each year. The major drawback of the sugarcane processing complex is that the facility remains idle for the rest of the year. The other costs associated with the sugarcane processing complex, such as loans and other expenses, are incurred throughout the year. In India, most sugarcane processing mills focus solely on conventional sugar production, limiting their revenue streams.

The integrated sugar mill is a step toward the sugar industry's transformation into integrated, diversified biorefineries that produce a variety of products. The main issue with the integrated sugarcane processing

complex is that, although molasses is used to produce ethanol year-round, sugar is only produced during certain seasons. The annual operating days for such models range from 250 to 300 days.

The diversified year-round operations, higher profit margins, and better resource use are all made possible by the integrated approach. Therefore, in terms of productivity, economics and resource use, an integrated approach is more sustainable. Additionally, it supports the country's contemporary energy and policy objectives. The effect of operational days on key economic metrics, including gross margin, ROI, payback period, and IRR, is illustrated in figure 4.

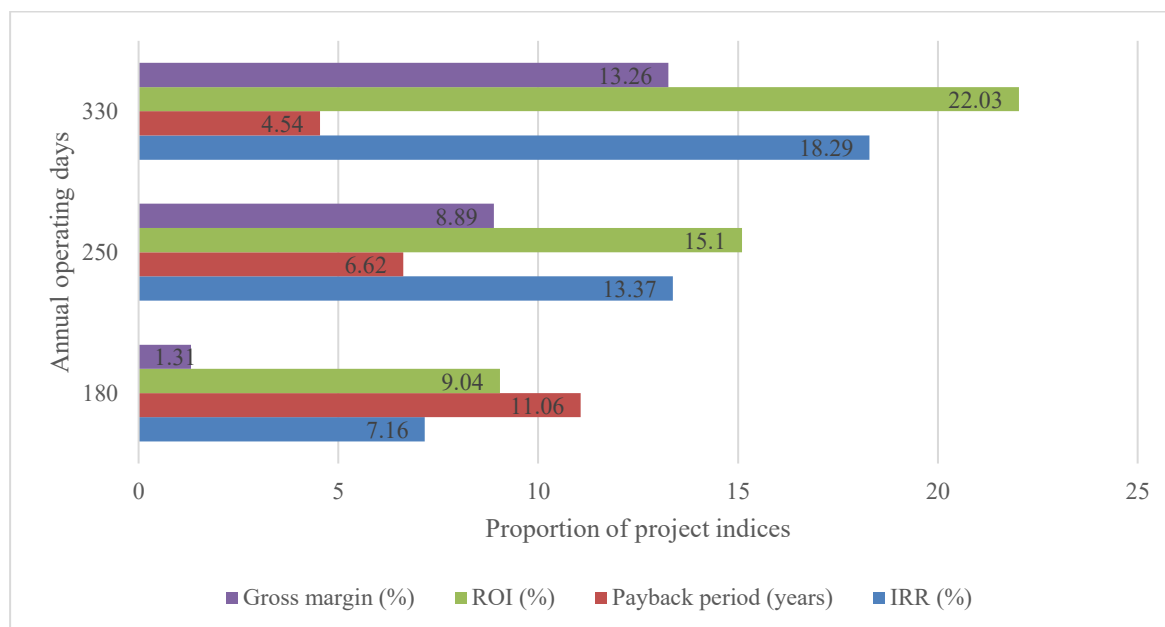


Figure 4. Effect of annual operating days on project indices of the integrated sugarcane processing complex

## DISCUSSION

The proposed process model for techno-economic analysis of an integrated sugarcane processing complex for ethanol production indicates that the process is economically viable under Indian conditions, primarily due to the well-established agro-industrial infrastructure and availability of feedstock. The integration of a molasses-based ethanol distillery with a sugar mill enhances overall plant profitability by efficiently utilizing molasses and other by-products within the same processing complex. The results suggest that sugarcane costs are the primary driver of ethanol production costs. The major benefit of the integrated sugarcane processing complex is its energy self-sufficiency through cogeneration of electricity from sugarcane bagasse.

The ethanol yield observed in the present study aligns with the typical industrial benchmarks, indicating that the process is technically mature and optimized. Higher plant capacity and improved process efficiency could lead to lower unit production costs through economies of scale. The findings from the techno-economic analysis of a sugarcane processing complex reinforce the strategic importance of 1G ethanol in India's biofuel program in achieving the blending targets. However, the long-term sustainability may be influenced by competition with sugar production. Therefore, 1G ethanol remains a commercially viable pathway; integrating with advanced 2G ethanol technologies will be crucial for future scalability and sustainability.

The proposed process model is based on the sugarcane processing complex operating under Indian industrial and regulatory conditions; therefore, the findings may not be directly transferable to other regions. Although informed by actual plant data, the analysis relies on steady-state process simulation, which involves making simplifying assumptions. In addition, economic parameters such as sugarcane prices, chemical costs, and energy tariffs are subject to market volatility, which may affect economic outcomes under real operating conditions.

## CONCLUSION

This study examines the techno-economic feasibility of an integrated sugarcane processing complex in India. The integrated approach can enhance profitability by reducing unit production costs. Therefore, the results from an integrated sugarcane processing complex with a processing capacity of 9,000 TPD of sugarcane can yield 738.57 TPD of sugar crystals, 140 KLPD of ethanol, and 36.62 MW of captive power. From an economic perspective, the proposed model demonstrates strong feasibility, with an ROI of 15.10%, an IRR of 13.37%, an NPV of 6,952 million INR, and a payback period of 6.62 years. The results demonstrate a good fit with the operating characteristics of India's current sugar industrial complexes. Integrated sugar industry complexes can significantly contribute to rural development, national energy security, and economic diversification in sugar-growing regions. The waste streams from the sugarcane processing complex, such as sugarcane bagasse, vinasse, and press mud, can be effectively redirected for further energy valorisation, enhancing energy efficiency and promoting a sustainable circular economy. Future research should focus on expanding the valorisation pathways of sugarcane bagasse for 2G ethanol and biogas production, while further integrating 1G ethanol production. Additionally, the proposed model's process data could enable a more comprehensive life-cycle assessment of the process's environmental impact, including the agricultural phase. Thus, transforming traditional sugar complexes into integrated sugar mills can improve the economic viability of ethanol production in India and significantly contribute to achieving the nation's Sustainable Development Goals.

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