

Life cycle cost of bioethanol bioeconomy of sugarcane bagasse in Indonesia

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ABSTRACT

As one of the largest agricultural industries in Indonesia, the sugarcane industry plays a vital role in realising the potential of second-generation bioethanol production from sugarcane bagasse (SCB). Despite this fact, SCB is not perceived to be a value-added commodity on a domestic scale, and therefore, it is mostly treated as agricultural waste and disposed via open burning. In this study, life cycle cost (LCC) analysis was carried out to assess the potential of SCB as a feedstock for second-generation bioethanol production in Indonesia. By taking a project lifetime of 20 years and using the average SCB yield per year of a local sugarcane factory (203 kton/year), the total SCB bioethanol yield was estimated to be as high as 30.9 ML/year. The corresponding LCC of the SCB bioethanol production project was determined to be \$177.18 million with a payback period of 5.09 years. The levelised cost of bioethanol from SCB (\$0.541/L) was lower than the bioethanol selling price recommended by the General Directorate for Renewable Energy and Energy Conservation (EBTKE) at \$0.766/L, indicating that the SCB bioethanol production project is economically feasible. The findings of this study provide insight into the potential of SCB as a value-added commodity for second-generation bioethanol production in Indonesia, which will encourage local industries and small and medium enterprises (SMEs) to venture into SCB bioethanol production.

1. Introduction

To date, fossil fuels such as coal, gasoline, diesel, and natural gas are the primary sources of energy worldwide. The growing environmental issues linked with the combustion of fossil fuels have made renewable energy sources highly preferable as future alternative energy sources (Riayatsyah et al., 2017). Bioethanol is produced from renewable biomass and it has great potential as an alternative to fossil fuels since it produces lower carbon dioxide (CO₂) emissions compared with fossil fuels (Haji Esmaili et al., 2020). The production of bioethanol has increased over the years. According to the U.S. Department of Energy (U.S. Department of Energy, 2023a,b), bioethanol production is the highest

in the United States of America in 2023, with a total of 15.36 billion gallons. This is followed by Brazil (7.40 billion gallons), the European Union, China, and Canada. The bioethanol production facilities in the United States of America mostly use corn as the feedstock, as shown in Fig. 1 (Kumar and Singh, 2019), while Brazil uses sugarcane for bioethanol production (Nogueira et al., 2023).

Bioethanol or ethyl alcohol (C₂H₅OH) is a well-known biofuel with a relatively high octane number of 108 (Buić et al., 2018; H.B. Aditiya et al., 2016). Bioethanol is considered to be a clean combustion fuel since the combustion of bioethanol emits CO₂ into the atmosphere, which can be reused by the plants from which biomass are derived via photosynthesis (Anwar et al., 2020). Bioethanol is classified as first-generation, second-generation, third generation, and

Abbreviations: DCF, Discounted cash flow; LCC, Life cycle cost; NEB, Net energy balance; SCB, Sugarcane bagasse; SME, Small and medium enterprises; SSF, Simultaneous saccharification and fermentation.

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| Nomenclatures | | | |
|---------------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|--|
| <i>Symbol</i> | <i>Description</i> | <i>Unit</i> | |
| $\hat{\gamma}$ | Inflation rat% | | |
| $\eta_{cellu\ conv.}$ | Efficiency of cellulose conversion and glucose recovery | kg glucose/kg cellulose | |
| $\eta_{glu\ ferm.}$ | Efficiency of glucose fermentation | — | |
| $\eta_{xy\ ferm.}$ | Efficiency of xylose fermentation | — | |
| $\eta_{hemicellu\ conv.}$ | Efficiency of hemicellulose conversion and xylose recovery | kg xylose/kg hemicellulose | |
| $\nu_{ethanol}$ | Specific volume of ethanol | L/kg | |
| <i>AP</i> | Annual sales profit | \$/year | |
| <i>BPC</i> | By-product credit | \$ | |
| <i>BSP</i> | SCB bioethanol selling price | \$/L | |
| <i>CC</i> | Capital cost | \$ | |
| <i>CRF</i> | Capital recovery factor | \$ | |
| <i>EST</i> | SCB bioethanol sales including tax | \$ | |
| $EY_{glucose}$ | SCB bioethanol yield from fermentation of glucose | L/kg SCB | |
| EY_{xylose} | SCB bioethanol yield from fermentation of xylose | L/kg SCB | |
| EY_{total} | Total SCB bioethanol yield | L/kg SCB | |
| <i>EY</i> | Total annual ethanol yield | L/year | |
| <i>FC</i> | Feedstock cost | \$/ton | |
| <i>FP</i> | Feedstock price | \$/ton | |
| <i>i</i> | Project year | — | |
| <i>IRR</i> | Internal rate of return | % | |
| <i>LCC</i> | Life cycle cost | \$ | |
| <i>LCOB</i> | Levelised cost of bioethanol | \$ | |
| <i>MC</i> | Maintenance cost | \$ | |
| <i>MR</i> | Maintenance rat% | | |
| <i>n</i> | Project lifetime years | | |
| $n_{cellulose}$ | Cellulose content | kg cellulose/kg SCB | |
| $n_{hemicellulose}$ | Hemicellulose content | kg hemicellulose/kg SCB | |
| <i>NPV</i> | Net present value | \$ | |
| <i>OC</i> | Operating cost | \$ | |
| <i>OR</i> | Cost of the material or utility needed to produce the SCB bioethanol | \$/year | |
| <i>PC</i> | Average SCB yield per year of the SCB producer | ton SCB/year | |
| <i>PP</i> | Payback period | year | |
| <i>PCF</i> | Present value of cash flow | \$ | |
| <i>PWF</i> | Present worth factor | — | |
| <i>r</i> | Discount rat% | | |
| <i>RC</i> | Replacement cost | \$ | |
| <i>SV</i> | Salvage value | \$ | |
| <i>TBS</i> | Total annual bioethanol sales | \$/year | |
| <i>TPC</i> | Total production cost | \$ | |
| <i>TR</i> | Tax rat% | | |
| $Y_{ethanol}$ | Maximum theoretical bioethanol yield from fermentation of glucose or xylose based on stoichiometric calculations | kg ethanol/kg glucose or kg ethanol/kg xylose | |

fourth-generation bioethanol based on the feedstock. First-generation bioethanol uses starch or sugar from edible crops as the feedstock. Second-generation bioethanol uses lignocellulosic materials from industrial or agricultural wastes, while third-generation bioethanol uses algae as the feedstock. Fourth-generation bioethanol is produced from genetic modification, and it is often called the ‘advanced bioethanol’ (Awogbemi et al., 2021). Bioethanol is typically blended with gasoline for vehicle use. In 2006, most of the fuel stations in Brazil used bioethanol–gasoline blend. These fuel stations advertised the use of bioethanol–gasoline blend, also known as gasohol, which is composed of 25 % ethanol and 75 % gasoline. It is expected that the use of bioethanol in vehicles will significantly increase by 2030 due to the pressing need to

reduce harmful exhaust emissions such as carbon monoxide (CO), nitrogen oxide (NO_x), and unburned hydrocarbons (UHC) (Gradziuk et al., 2021). The Department of Energy in the Philippines predicts that in 2030, the percentage of bioethanol mixed with gasoline will increase to 20 % and can possibly reach 85 % (Department of Energy, 2017). According to the Annual Energy Outlook, it is estimated that biofuel blended with gasoline, diesel, and jet fuel will increase to 9.0 % in 2040. However, this percentage was 7.3 % in 2019 (U.S. Energy Information Administration, 2020).

As a country with significant agricultural sector potential, lignocellulosic biomass has become popular in Indonesia because it can be used as a feedstock for bioethanol production. The use of lignocellulosic

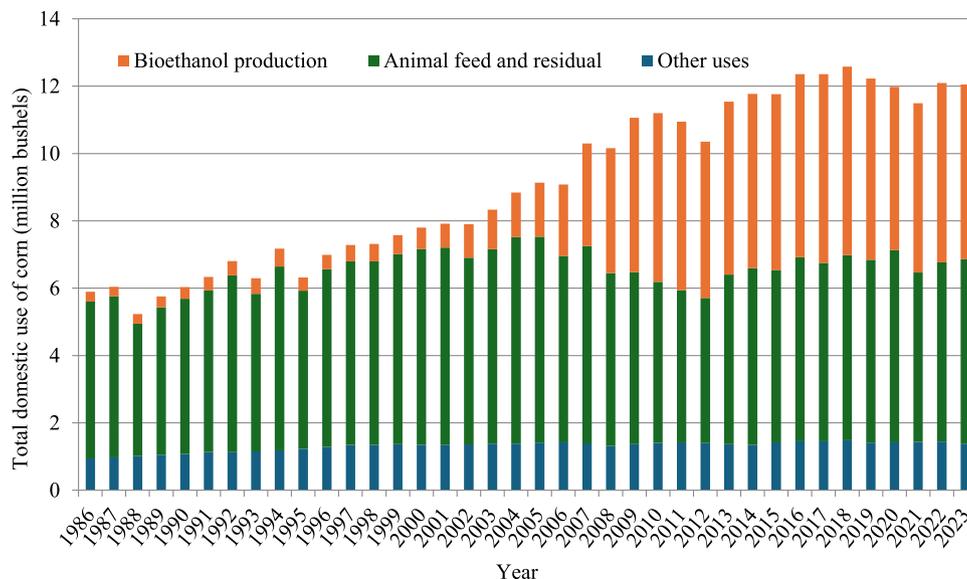


Fig. 1. Breakdown of the total domestic use of corn in the United States of America from 1986 to 2023 (U.S. Department of Energy, 2023b).

biomass derived from plants eliminates competition with human food consumption because they are inedible. According to the Ministry of Industry in Indonesia, there are 64 active sugarcane factories with a total capacity of 100,000 ton of sugarcane per day (Kementerian Perindustrian Republik Indonesia, 2023). With this number, the bioethanol produced from sugarcane bagasse (SCB) is predicted to reach 614.83 ML/year (Restrepo-Serna et al., 2018). Compared with other lignocellulosic materials, SCB has a relatively high bioethanol yield, as shown in Fig. 2 (Pobitra Halder et al., 2019). Hence, SCB has great potential as a feedstock for second-generation bioethanol production.

Various studies have been carried out on the production of second-generation bioethanol. Aditiya et al. (2015) investigated the effect of acid pre-treatment on bioethanol production using rice straw as the feedstock. By combining acid pre-treatment with enzymatic hydrolysis, the total bioethanol yield obtained from the fermentation stage was 52.75 %, which was significantly higher than the total bioethanol yield obtained from fermentation of rice straw pre-treated with acid (11.26 %) (H. B. Aditiya et al., 2015). Chriswardana et al. (2021) optimised the production of second-generation bioethanol from durian seeds via alkaline hydrolysis. They determined the optimum conditions to achieve the highest bioethanol yield with the lowest production cost. The optimum conditions were determined as follows: (1) hydrolysis time: 60 min, (2) temperature: 80 °C, (3) substrate loading: 50 g/L, and (4) sodium hydroxide (NaOH) concentration: 0.522 M. The reducing sugar concentration was 2.140 g/L, which produced a theoretical bioethanol concentration of 1.094 g/L (Theofany Harley Chriswardana et al., 2021).

The assessment of cost and economic viability is typically conducted for a specific region of interest, leveraging the region's agricultural strengths to establish a sustainable supply chain. Vasilakou et al. (2023) conducted techno-economic analysis of second-generation bioethanol production using corn stover in Belgium. Their study compared production scales of 156 and 667 ktonnes/year under various pretreatment methods, including dilute acid, steam explosion, alkaline and liquid hot water. The results indicated that final costs were generally lower at a larger scale (~USD 0.83–1.15/L) compared to smaller-scale production (~USD 1.14–1.63/L). Feedstock costs were the primary driver of overall bioethanol production costs, as additional cost stover imports were required to sustain large-scale operations. In Kenya, Ngigi et al. (2023) assessed second-generation bioethanol production using domestic Sial sorghum stalks for an industrial-scale facility, processing up to 300,000 kg/h biomass. Their findings revealed bioethanol costs ranging from USD 0.81–1.54 per litre, influenced by factors such as feedstock and enzyme costs, discount rates and capital investments. In Canada, Onu Olughu et al. (2023) conducted a techno-economic analysis for an industrial bioethanol plant using switchgrass as the feedstock, with a processing capacity of 2 ktonnes per day. The study reported an overall bioethanol production cost of USD 1.44/L, with fungal pretreatment

contributing the most at 49.85 % of the total cost, equivalent to USD 0.72/L. They also concluded that the plant's net present value was highly sensitive to feedstock cost, glucose and xylose yields and the bioethanol selling price.

Lili Zhao et al. (2015) investigated the feasibility of bioethanol production from corn stover in China. Several scenarios were created to determine which plan resulted in the most effective process from an energy and economic perspective. The results revealed that bioethanol production from corn stover could not be commercialised in China as the bioethanol production cost was higher than the wholesale price of corn stover bioethanol (Lili Zhao et al., 2015). (M. Hanif et al. (2017) performed energy analysis and environmental assessment of bioethanol production from cassava in Malaysia. The type of cassava used was Sri Kanji 1, which was chosen due to its high potential to be converted into bioethanol. The fuel energy content and fuel-cycle energy consumption were accounted for in the energy analysis. The energy content of the resultant fuel (cassava fuel ethanol) was compared with the energy consumed during the bioethanol production process. They concluded that it is economically feasible to produce bioethanol from Sri Kanji 1 cassava in Malaysia owing to the positive net energy balance (NEB), and the project is perceived to be an energy-efficient project (M. Hanif et al., 2017). In a similar study, M. Hanif et al. (2016) conducted life cycle cost (LCC) analysis for a bioethanol production project using the same feedstock, and the results indicate that the project is economically feasible.

Focusing on second-generation production from sugarcane, Sganzerla et al. (2022) performed cost analysis of subcritical water pre-treatment for bioethanol production from sugarcane straw and bagasse, where a sugarcane mill was used as a case study. Seven scenarios were created to assess the feasibility of implementing the subcritical water pre-treatment in the sugarcane mill. The results indicate that the cost of raw materials can be reduced to zero by sourcing the raw materials from the factory itself. The lowest bioethanol production cost was achieved by reducing factory costs, labour costs, and steam prices by 50 %, with a value of \$5.45/L. Nevertheless, the bioethanol production cost was higher than the bioethanol selling price in Brazil by a factor of 10. Based on the results, they concluded that there is a need to significantly improve the technical aspects of the subcritical water pre-treatment of sugarcane straw and bagasse before the process is upscaled to a commercial scale for bioethanol production.

Studies by (Fu et al., 2022; Hu et al., 2018) have also shown that the lignin-rich residues produced as a by-product of bioethanol production from SCB also have great potential for the production of other value-added products, extending the economic valorisation of SCB. Through pyrolysis, the lignin-rich residues can be the precursor of bio-oil, biogas, and biochar production, elevating their potential (Dessie et al., 2023). Lignin (which is derived from lignin-rich residues) has shown potential as one of the key ingredients in cosmetics owing to its antioxidant activity and capability to absorb ultraviolet rays. In addition, lignin appears promising for biomedical applications such as wound dressings, drug delivery, and tissue engineering (Ekielski and Mishra, 2021). More detailed reviews on the integration of advanced technologies with cost-effective methods for bioenergy crops are provided by Zhang et al. (2023) and Wang et al. (2024). Further studies highlighting the technical and economic benefits of sugarcane bagasse and waste are summarised in Table 1.

Even though there is a significant number of studies on the production of second-generation bioethanol from a variety of lignocellulosic feedstocks, little is known regarding the production of second-generation bioethanol from SCB in Indonesia based on a techno-economic perspective. The production of SCB bioethanol is still in its infancy in this country. Hence, the objective of this study to assess the economic feasibility of SCB bioethanol production in Indonesia using LCC analysis. To achieve this objective, the theoretical SCB bioethanol yield is first estimated based on the SCB yields obtained from fermentation of the glucose and xylose components of the SCB. The general and

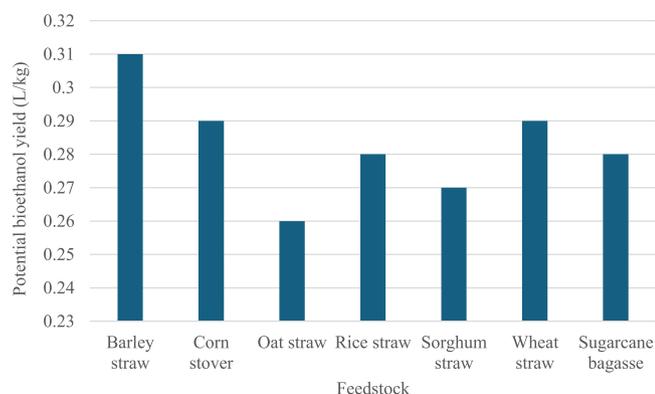


Fig. 2. Potential bioethanol yields from various lignocellulosic feedstocks (Pobitra Halder et al., 2019).

Table 1

Comparative summary of second-generation bioethanol production studies using sugarcane bagasse, emphasising its competitiveness as a feedstock for bioethanol production.

| Author, year and reference | Study focus | Result |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Gubicza et al., 2016) | This research establishes a techno-economic model for a commercial bioethanol facility with a capacity of 83 million litres per year, utilising data from pilot plant and laboratory experiments. The evaluation of economic feasibility is conducted through one experimental case and five hypothetical scenarios, focussing on the comparison of heat, electricity, fertiliser production, and associated production costs. | Feedstocks and capital costs represent 23–28 % and 40–49 % of the Minimum Ethanol Selling Price (MESP), respectively. The sensitivity analysis indicated that ethanol yield is the primary factor influencing MESP, with MESP values varying between 50.38 and 62.72 US cents per litre. |
| (Papong et al., 2017) | The study examines the environmental effectiveness of the bioethanol life cycle, focusing on the greenhouse gas emissions (GHG), eutrophication (EP), direct land use change (dLUC), and water impact potential (WIP), the deployment of process-based and input-output analytical techniques. | As compared to gasoline, bioethanol has lower greenhouse gas (GHG) emissions of 26–39 kg CO ₂ -eq/GJ; however, the indirect land-use change (dLUC) effects cause an increase in GHG emissions by 10–73 %. Additionally, bioethanol shows more pronounced results in terms of eutrophication potential (EP) and water impact (WIP). Socio-economically, bioethanol creates 15–18 extra jobs and contributes to 30–45 % of direct revenue in the agricultural sector; however, it also adds an increased fatality risk for employees. |
| (Amezcu-Allieri et al., 2019) | The study considers the technoeconomic integration along with the life cycle assessment of the sugar manufacturing process with a focus on energy co-generation using fuel produced from oil or bagasse for a southern Mexican sugar mill. | Compared to fuel oil, the use of bagasse (capacity: 2852 tons/day) results in lower costs (5.5 vs. 14 USD/GJ) and a significantly smaller environmental impact (2528 vs. 20,200 PEI/GJ). This biofuel supports positive synergies in the environment-water-food-energy nexus. |
| (Dibazar et al., 2024) | This research examined the sugarcane bagasse ethanol lifecycle along the lines of farming, transportation, and production. The alternatives compared were direct fermentation, bagasse burning for electricity, and simultaneous generation of both. | The production of bioethanol from bagasse requires an input of 27.13 MJ/L and provides an output of 40.44 MJ/L. The key drivers of the environmental load are electricity, diesel, and nitrogen fertiliser. |
| (Buthelezi et al., 2025b) | This study provides a detailed evaluation of techno-economic and financial viability involved with three separate routes for the conversion of biological biomass into fuel: production of bioethanol through fermentation, generation of biogas by anaerobic digestion (AD), and biohydrogen production through dark fermentation (DF). | The Aspen Plus simulation processes 51,840 kg/hour of bagasse (SCB). The economic evaluation uses discounted cash flows (28 % tax, 12 % discount rate, 20 % straight-line depreciation/5 years) assuming a 25-year plant life. Dark Fermentation (DF) is the most profitable method (NPV of USD 67.41 million, BPP of 3.3 years, |

Table 1 (continued)

| Author, year and reference | Study focus | Result |
|----------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| | | ROI of 1.51, PI of 7.95). Meanwhile, bioethanol production is declared unfeasible (negative NPV) and unable to recover the initial investment. |

techno-economic specifications for the LCC analysis are then identified. LCC analysis is then performed and the economic feasibility of the SCB bioethanol production project is evaluated based on the net present value (NPV), levelised cost of bioethanol (LCOB), payback period (PP), and internal rate of return (IRR). This study does not only assess the potential of SCB as a feedstock for bioethanol production in Indonesia but also provide insights into the economic feasibility of the SCB bioethanol production project, which can be used as a reference by the key stakeholders of the local bioethanol industry.

2. Methodology

2.1. Overview of the methodology

The overall methodology adopted in this study consisted of four phases, as shown in Fig. 3. In the first phase, the relevant data pertaining to production of value-added products from SCB in Indonesia were gathered from the published literature as well as reports, which served as the basis to perform the LCC analysis. The average SCB yield per year of a local sugarcane factory in Lumajang, East Java, Indonesia, was used as the basis for the SCB supply rate in the LCC analysis. It shall be noted that despite the production of sugarcane juice on a commercial scale by the local sugarcane factory, the SCB generated from sugarcane juice extraction has never been used to create value-added products such as bioethanol. At present, the SCB is predominantly used as a source of fibre in cattle feed or treated as an agricultural waste, where the SCB is typically disposed by open burning.

The second phase of this study involved determining the SCB bioethanol yields from the glucose and xylose components in the SCB using the theoretical approach described by Janick and Whipkey (2002). The average SCB yield per year of the local sugarcane factory in Lumajang, East Java, Indonesia, was used to estimate the total SCB bioethanol yield. This is done intentionally to ensure that the results are tailored for the local businesses in Indonesia. In addition, the theoretical approach presented in this study serves as a guideline for local small and medium enterprises (SMEs) to perform LCC analysis with different production scales and capacities.

The third phase of this study involved the LCC analysis, where the LCC was calculated in detail based on the total SCB yield. The cost analysis was conducted for a typical bioethanol production scenario employing steam explosion pre-treatment and enzymatic hydrolysis, within the defined system boundary illustrated in Fig. 4. The LCC analysis began with the procurement of the SCB and ended with the evaluation of profits from SCB bioethanol sales. The analysis also accounted for the fuel requirement in SCB logistics as part of the operating cost. This included transporting SCB within an assumed 3 km radius from the bioethanol production plant. The LCC analysis involved a series of calculations, including estimations of the capital cost, feedstock cost, operating cost, maintenance cost, and salvage value. These costs were calculated using the discounted cash flow (DCF) model to incorporate the future value of money (Azmi et al., 2023; Riayatsyah, 2018; Riayatsyah et al., 2017). For revenue, the study considers the financial income from bioethanol sales as the primary product. This approach is intended to capture the true economic potential of SCB in projecting the domestic market for second-generation bioethanol in Indonesia.

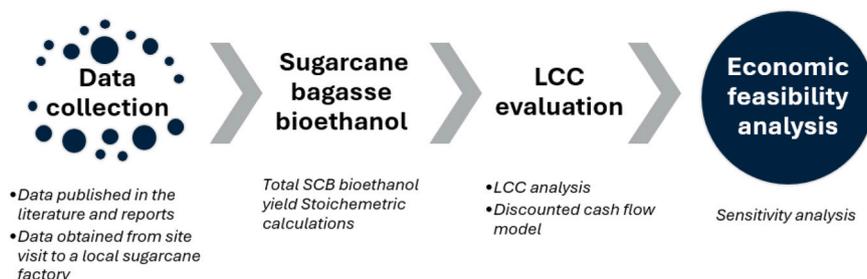


Fig. 3. Outline of the methodology adopted in this study.

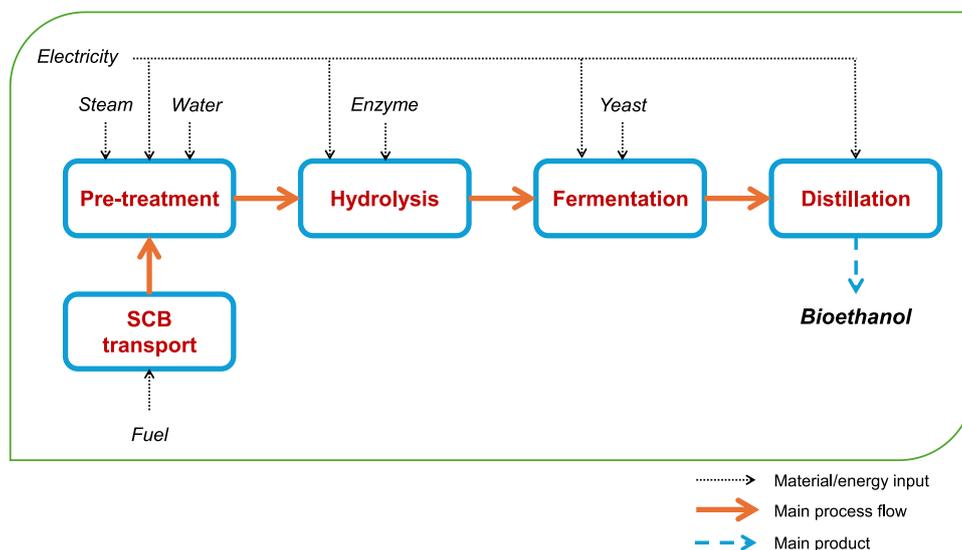


Fig. 4. The main working boundary for the life cycle cost analysis in this study.

The final phase of this study involved performing an economic feasibility analysis based on the LCC calculations. The contributions of the capital cost, feedstock cost, operating cost, maintenance cost, and salvage value to the levelised cost of bioethanol (LCOB) from SCB were analysed. In addition, to gain insight into the economic feasibility of the SCB bioethanol production project for local SMEs, sensitivity analysis was performed to assess the sensitivity of the projected internal rate of return (IRR) to the changes in the SCB bioethanol selling price. The phases of this study are elaborated in detail in the following sections.

In general, factors such as production volume, raw material availability, and transportation efficiency have a significant influence on SCB prices, with variations likely to occur between provinces. In this study, the economic parameters, including SCB prices and electricity tariffs, are restricted to observed local data from East Java, Indonesia, in order to reflect the market potential of the region of interest. East Java, which accounts for 45 % of the nation’s sugarcane production, is recognised as the largest sugarcane-producing province in Indonesia, as illustrated in Fig. 5 (Badan Pusat Statistik, 2023). Nevertheless, data on SCB market prices across the country remain scarce due to the limited availability of publications and literature. Since the SCB cost is incorporated into the projected bioethanol selling price, any variation in SCB costs can be captured through the sensitivity analysis of the bioethanol selling price in relation to the critical economic indicators examined in the final phase of this study.

2.2. Estimation of the total SCB bioethanol yield

The average SCB yield per year was used in this study based on the field data provided by a local sugarcane factory in Lumajang, East Java, Indonesia. On average, the sugarcane factory generates 203 kton of SCB

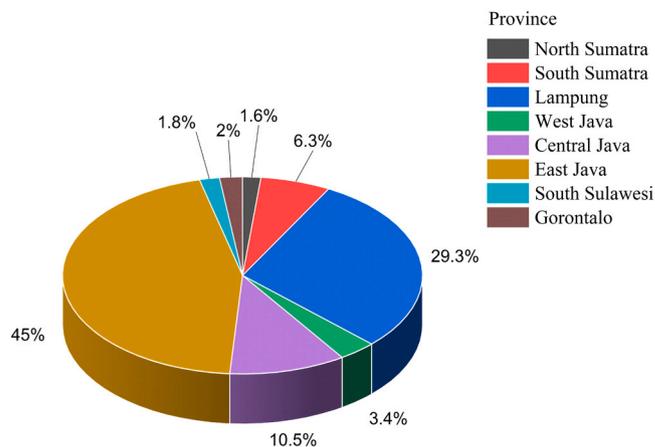


Fig. 5. Shares of Indonesia’s sugarcane plantation production across major provinces.

as agricultural wastes per year, which served as the basis of to estimate the total SCB bioethanol yield of the SCB bioethanol production facility in this study. The composition of the SCB according to per cent by weight (% (w/w)) was also provided by the sugarcane factory, as tabulated in Table 2. The cellulose and hemicellulose components were of main interest in estimating the total SCB bioethanol yield, owing to the formation of simple monomers (glucose and xylose) from complex sugars. The SCB bioethanol is mainly produced as the product of fermentation of the glucose and xylose monomers derived from the SCB. Using yeast as the fermentation agent, the fermentation of glucose (C₆H₁₂O₆) results to

Table 2

Composition of the sugarcane bagasse (SCB) according to per cent by weight.

| Component | Value (% (w/w)) |
|---------------|-----------------|
| Cellulose | 37.45 |
| Hemicellulose | 23.84 |
| Lignin | 16.02 |
| Protein | 2.79 |
| Water | 5.94 |
| Ash | 10.84 |

the production of ethanol (C_2H_5OH) and CO_2 , whereas the fermentation of xylose ($C_5H_{10}O_5$) yields ethanol and CO_2 as the products (Sudiyani et al., 2019):

The theoretical approach of Janick and Whipkey (2002) and Amores et al. (2013) was adopted in this study to estimate the total SCB bioethanol yield. In this approach, the SCB bioethanol yields from cellulose and hemicellulose were determined based on the main conversion activities, which were the conversion of complex sugars (cellulose and hemicellulose) into simple monomers (glucose and xylose) and the fermentation of glucose and xylose to form ethanol. The factors influencing the bioethanol conversion efficiency were also included. The SCB bioethanol yield obtained from fermentation of glucose was estimated using Eq. (1) (Janick and Whipkey, 2002):

$$EY_{glucose} = n_{cellulose} \times \eta_{cellu\ conv.} \times Y_{ethanol} \times \eta_{glu\ ferm} \times \nu_{ethanol} \quad (1)$$

where $EY_{glucose}$ is the SCB bioethanol yield from the fermentation of glucose (L/kg SCB), $n_{cellulose}$ is the cellulose content (0.3745 kg cellulose/kg SCB), $\eta_{cellu\ conv.}$ is the efficiency of cellulose conversion and glucose recovery (0.866 kg glucose/kg cellulose), $Y_{ethanol}$ is the theoretical maximum bioethanol yield based on stoichiometric calculations (0.51 kg bioethanol/kg glucose), $\eta_{glu\ ferm}$ is the efficiency of glucose fermentation (0.65), and $\nu_{ethanol}$ is the specific volume of bioethanol (1.284 L/kg) (Amores et al., 2013).

The SCB bioethanol yield obtained from the fermentation of xylose was estimated using Eq. (2) (Janick and Whipkey, 2002):

$$EY_{xylose} = n_{hemicellulose} \times \eta_{hemicellu\ conv.} \times Y_{ethanol} \times \eta_{xy\ ferm} \times \nu_{ethanol} \quad (2)$$

where EY_{xylose} is the SCB bioethanol yield from the fermentation of xylose (L/kg SCB), $n_{hemicellulose}$ is the hemicellulose content (0.2384 kg hemicellulose/kg SCB), $\eta_{hemicellu\ conv.}$ is the efficiency of hemicellulose conversion and xylose recovery (0.14 kg xylose/kg hemicellulose), $Y_{ethanol}$ is the theoretical maximum bioethanol yield based on stoichiometric calculations (0.51 kg ethanol/kg xylose), $\eta_{xy\ ferm}$ is the efficiency of xylose fermentation (0.65), and $\nu_{ethanol}$ is the specific volume of bioethanol (1.284 L/kg). The total SCB bioethanol yield (EY_{total}) was estimated to be 30.9 ML based on the average SCB yield per year provided by the local sugarcane factory.

2.3. General and techno-economic specifications

The general and techno-economic specifications used in this study were taken from the published literature as well as from the field data provided by the local sugarcane factory in Lumajang, East Java, Indonesia. The production capacity of the SCB bioethanol production facility (i.e., the maximum SCB bioethanol yield that can be achieved in a year using the available resources in the facility) was based on the average SCB yield per year of the SCB producer since SCB was selected as the primary feedstock of the facility. The general specifications of the SCB bioethanol production facility are summarised in Table 3.

The techno-economic specifications were derived from similar published works with the necessary adjustments made based on the production capacity of the SCB bioethanol production facility, and the details are presented in Table 4. *Saccharomyces cerevisiae* and

Table 3

General specifications of the SCB bioethanol production facility.

| Specification | Value | Note |
|---------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------------|
| Project lifetime | 20 years | The value was assumed. |
| Average SCB yield per year of the SCB producer | 203,000-ton SCB/year | The value was based on the SCB yield of a local sugarcane factory in Lumajang, East Java, Indonesia. |
| Production capacity of the SCB bioethanol production facility | 100 % | The value was assumed. |

Scheffersomyces stipites were selected as the fermentation agents to ferment glucose and xylose derived from the cellulose and hemicellulose components of the SCB, respectively. The working capital was estimated based on one year's worth of feedstock costs. The working capital was assumed to cover the operating costs required during start-up (excluding the capital cost) and included on-hand cash, credit for accounts payable, and other initial operating costs (Towler and Sinnott, 2012). The working capital was incurred in the year prior to the start of operations of the SCB bioethanol production facility (i.e., year 0). The salvage value was determined based on the replacement cost, which was assumed to incur at the end of the project lifetime of the SCB bioethanol production project (i.e., 20 years). All costs and prices of other components used in this study were converted into U.S. dollars (\$).

MFPU – Million filter paper unit; *hL* – Hectoliter, typical units for yeast measurement and is equivalent to 100 L.

This study focuses on the fundamental economic potential of SCB bioethanol for Indonesia market, stemmed from the significant utilisation rate of sugar cane seen from the favourable accessibility to the plantation (Fig. 5). Because of this, the profitability element of this study is exclusively derived from the sales of SCB bioethanol and salvage value (SV). To demonstrate the competitiveness of SCB bioethanol, the outcomes from this economic analysis will be also benchmarked with the suggested bioethanol price by the Indonesian government and with the subsidised gasoline price effective in the Indonesian fuel market.

2.4. Life cycle cost analysis

LCC analysis is an economic assessment method used to evaluate the total cost of a project throughout the project lifetime. In this study, the LCC analysis of the SCB bioethanol production facility was performed using the following equations (M. Hanif et al., 2016).

Present worth factor

The present worth factor (*PF*) is the current value of money, which is the cash flow's equivalency in a certain period with a specific discount rate. The *PF* was calculated using Eq. (3), where i is the project year and r is the discount rate:

$$PF = \frac{1}{(1+r)^i} \quad (3)$$

2.4.1. Capital cost

The capital cost (*CC*) of the SCB bioethanol production facility covers the initial costs for constructing the facility and installing the necessary equipment so that the facility can operate, such as the costs of land acquisition, building construction, and equipment installation and testing. The capital cost is typically determined by the production capacity of the facility. In this study, the capital cost was estimated based on the average SCB yield per year of the SCB producer (*PC*) (Howell, 2005; Riayatsyah et al., 2017), as follows:

$$CC = -430.13 PC^2 + 205,235PC + 2696000 \quad (4)$$

Feedstock cost

The total feedstock cost (*FC*) was calculated based on the feedstock price (*FP*, which is the SCB price), inflation rate (γ), discount rate (r), project year (i), and project lifetime (n), as follows:

Table 4
List of techno-economic specifications used in this study.

| Specification | Description | Value | Unit cost (\$) | Unit | Reference |
|----------------------------|---------------------------------|------------------------------|----------------|-------------------|---------------------------------------------|
| Feedstock cost | SCB price | 203,000 ton/year | 10.60 | \$/ton | (JPNN, 2014) |
| Operating cost (logistics) | Fuel consumption | 1.597 ML/year | 0.636 | \$/L | (Ardyanto, 2020; E. Chikishev et al., 2019) |
| Operating cost (materials) | Enzymes | 4.872 M MFPU/year | 1.34 | \$/MFPU | (Mesa et al., 2020) |
| | <i>Saccharomyces cerevisiae</i> | 116.4 kton/year | 8 | \$/hL | (Mesa et al., 2020) |
| | <i>Scheffersomyces stipites</i> | 7.023 kton/year | 0.01 | \$/hL | (Mesa et al., 2020) |
| Operating cost (utilities) | Steam | 203 kton/year | 1.51 | \$/ton | (Chandel et al., 2019; TLV Group, 2020) |
| | Water | 812,000 m ³ /year | 0.89 | \$/m ³ | (PAM Jaya, 2023) |
| | Electricity | 13,297 MWh/year | 95.68 | \$/MWh | (Chandel et al., 2019; PLN Indonesia, 2023) |
| Operating cost (wages) | Wages paid to the workers | 263 workers | 139.82 | \$/month | (Dzulfaroh, 2020) |
| Maintenance rate | Factored into the capital cost | 2 | — | % | (M. Hanif et al., 2016) |
| Replacement cost | — | — | 10,000,000 | \$ | (Riayatsyah, 2018) |
| Discount rate | Assumed | 7 | — | % | |
| Inflation rate | — | 1.59 | — | % | (Bank Sentral Republik Indonesia, 2023) |

$$FC = \sum_{i=1}^n \frac{FP(1 + \gamma)^i}{(1 + r)^i} \tag{5}$$

2.4.2. Operating cost

The operating cost (OC) covers the costs of all materials and utilities needed to process the SCB. In this study, the operating cost included the costs for enzymes, yeast, electricity, water, and steam used for SCB bioethanol production. The operating cost in this study was determined by taking the cost of the material or utility needed to produce the SCB bioethanol (OR) under the account of present worth factor (PWF) of the respective year, which then was summed over the project lifetime.

2.4.3. Maintenance cost

The total maintenance cost (MC) was determined using Eq. (6) based on the service and periodic maintenance costs, which can be calculated as a percentage (MR) of the capital cost (CC), and were assumed to remain constant over the project lifetime:

$$MC = \sum_{i=1}^n \frac{MR \times CC}{(1 + r)^i} \tag{6}$$

2.4.4. Salvage value

The salvage value is the remaining value of the assets of the project after the project has reached its end of life. In this study, the replacement cost (RC, which is the cost of replacing the assets of the SCB bioethanol production facility) was used to estimate the salvage value (SV) instead of the capital cost. This is because, intuitively, the salvage value of the SCB bioethanol production facility at the end of the project lifetime is decided by the capital cost at the end of the project lifetime after depreciation is deducted. A constant yearly depreciation rate (d) was assumed. The salvage value was determined using the following equation:

$$SV = RC \times (1 - d)^{n-1} \tag{7}$$

2.4.5. Life cycle cost

The total life cycle cost (LCC) of the SCB bioethanol production facility was calculated using Eq. (8), where CC is the capital cost, OC is the operating cost, MC is the maintenance cost, FC is the feedstock cost, SV is the salvage value that is applied at the end of project lifetime n, r is the discount rate, and i is the project year.

$$LCC = CC + \sum_{i=1}^n \frac{OC_i + MC_i + FC_i}{(1 + r)^i} - \frac{SV}{(1 + r)^n} \tag{8}$$

2.4.6. Total annual bioethanol sales

The total annual bioethanol sales (TBS) is determined based on the set bioethanol selling price. In this study, it was assumed that there were complete and consistent sales from the annual SCB bioethanol production. The TBS was calculated using Eq. (9), where BSP is the SCB

bioethanol selling price, EY is the annual SCB bioethanol yield, r is the discount rate, and i is the project year:

$$TBS = \frac{BSP \times EY}{(1 + r)^i} \tag{9}$$

In this study, the economic feasibility of the SCB bioethanol production project was assessed using four main indicators: net present value (NPV), levelised cost of bioethanol (LCOB), payback period (PP), and internal rate of return (IRR). The PP was calculated by neglecting the effect of inflation on the feedstock price. The IRR was calculated by determining the discount rate at which the NPV equalled to zero. The other economic feasibility indicators (NPV and LCOB) of the SCB bioethanol production facility were calculated using the Eqs. (10)-(12). PCF in this context is the present value of cash flow, which was obtained by subtracting the SCB bioethanol sales including tax (EST) with the total production cost (TPC). The total production cost in this study was evaluated by reducing the total life cycle cost (LCC) with salvage value (SV).

$$\text{Net present value : } NPV = \sum_{i=1}^n PCF - CC \tag{10}$$

$$\text{Levelised cost of bioethanol : } LCOB = \frac{CRF \times LCC}{EY} \tag{11}$$

$$\text{Capital recovery factor : } CRF = \frac{r(1 + r)^n}{(1 + r)^n - 1} \tag{12}$$

2.4.7. Payback period

The economic feasibility of the SCB bioethanol production facility can be evaluated using a simple method called the payback period (PP). In simple terms, the payback period can be interpreted as the time required for the SCB bioethanol production facility to generate sufficient cash flow to recover its initial investment cost. By taking the initial investment cost as the capital cost (CC), the PP was calculated as the ratio of capital cost to net annual income of SCB bioethanol production facility after deducting first year's total operation (LCC₁), sales and corporate taxes using the following equation:

$$PP = \frac{CC}{TBS - LCC_1 - (AP \times TR)} \tag{13}$$

where TBS is the total annual bioethanol sales, AP is the annual sales profit, and TR is the tax rate.

3. Results and discussion

3.1. Results of the life cycle cost analysis

The breakdown of the LCC for the SCB bioethanol production facility is presented in Table 5. It was assumed that the SCB bioethanol

Table 5
Detailed breakdown of the life cycle cost for SCB bioethanol production across a 20-year project lifetime.

| Component | Value (\$) |
|-----------------------------------------|--------------------|
| Capital cost, CC | 26,538,835 |
| Feedstock cost, FC | 30,692,501 |
| Operating cost, OC | 115,557,862 |
| Maintenance cost, MC | 5644,244 |
| Salvage value, SV | 1350,852 |
| Total life cycle cost (LCC) (\$) | 177,182,590 |

production facility was independently funded, and therefore, there were no costs of debts (i.e., loans and interest associated with loans) in the capital cost. At the end of the project lifetime, a salvage value was added to the LCC, relieving \$1.35 million into the cash flow. The LCC of the SCB bioethanol production facility was estimated to be \$177.18 million after 20 years of operation. It is expected that the LCC will decrease after taking into account the by-product of the SCB bioethanol production facility such as the sales of CO₂.

In comparison with another study on SCB bioethanol production (Buthezezi et al., 2025a), the reported capital, feedstock and operating costs were significantly lower than in the present study. This difference is explained by the longer project lifetime considered in that study and the assumption of zero cost for SCB as the primary feedstock component. Furthermore, although that study achieved a higher annual bioethanol yield, it concluded with a substantial overall project loss of \$51.52 million. This outcome contrasts with the present study, which, despite incorporating SCB costs into the feedstock component, achieved a positive financial outcome. Similarly, a separate study on bioethanol production from bread waste (Hafyan et al., 2024) reported a negative NPV despite a relatively high minimum selling price of \$2.55/L. These comparisons highlight that the SCB-based process developed in the present study demonstrates stronger financial resilience and market competitiveness than several alternative feedstocks reported in the literature.

Another study utilising oil palm waste and rubberwood waste (Hossain et al., 2021) reported LCC values of \$24.3 million and \$15.2 million respectively, which were considerably lower than in the present study. This difference can be attributed to the much smaller production scale (25.3 ML/year) and lower recurring operating cost (\$11.8 million). These reduced values are reasonable given the simplified analysis approach adopted in that study, which did not incorporate a detailed breakdown of recurring feedstock, operating and maintenance costs. As these cost components are the dominant contributors to the LCC, their accurate estimation is essential for producing reliable economic evaluations. The comparative evidence reinforces that the SCB-based process presented in this study is not only technically viable but also economically competitive when assessed against other second-generation bioethanol pathways.

Fig. 6 shows the annual contribution of the feedstock cost, operating

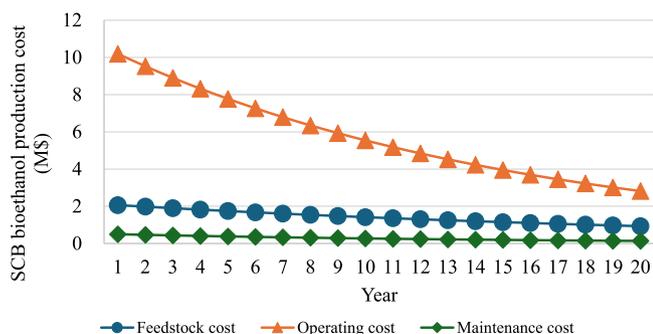


Fig. 6. Effect of the feedstock cost, operating cost, and maintenance cost on the SCB bioethanol production cost throughout the project lifetime.

cost, and maintenance cost to the LCC of the SCB bioethanol production facility. It can be observed that the operating cost declined significantly over the project lifetime due to the scale of the SCB bioethanol production facility, where the operating cost was sensitive to the annual discount rate. It is worth noting that the feedstock cost is different from the other components when subjected to the discount rate, and this is due to the effect of the inflation rate on the feedstock price. However, due to the incomparable scale, the overall present value of the feedstock price was not significantly different from the present value of the operating cost.

The operating cost had the most pronounced effect on the projected annual cash flow, which is indeed expected as the operating cost reflects the expenses incurred in operating the SCB bioethanol plant, such as the costs of logistics, materials, and wages. This is also reflected in Fig. 7. The operating cost contributed to the largest share of the LCC (65.2%), followed by the feedstock cost (17.3%), capital cost (15%), and maintenance cost (3.2%) over the project lifetime of 20 years. It can also be observed from Fig. 7 that there was a relief of \$1.35 million, as indicated by the reduction in the LCC by 0.8%.

3.2. Economic feasibility of the SCB bioethanol production project

The economic feasibility of the SCB bioethanol production project was assessed based on the levelised cost of bioethanol (LCOB), which can be determined by the summation of costs associated with SCB bioethanol production throughout the project lifetime divided by the total amount of SCB bioethanol produced during this period. In this study, the LCOB was determined using the DCF method, taking into account the capital recovery factor. The LCOB from SCB was determined to be \$0.541/L, as shown in Fig. 8. The operating cost was the most dominant contributor to the LCOB (\$0.353/L). This was followed by the feedstock cost and capital cost, with a contribution of \$0.094/L and \$0.081/L, respectively. The LCOB obtained in this study agreed with the LCOB reported by Gubicza et al. (2016), where the SCB bioethanol production cost was within a range of \$0.5038–0.6272/L. The LCOB obtained in this study (\$0.541/L) was deemed to be favourable than the LCOB from SCB in Brazil, which was \$1.33/L (Chandel et al., 2019). This discrepancy is indeed expected because of the differences in the fundamental unit costs (i.e., the costs involved to produce 1 L of bioethanol) involved in the LCC analysis, which are influenced by national regulations, policies, and standards. For instance, the feedstock and labour costs to produce 1 L of SCB bioethanol in Indonesia were lower than those in Brazil, resulting in

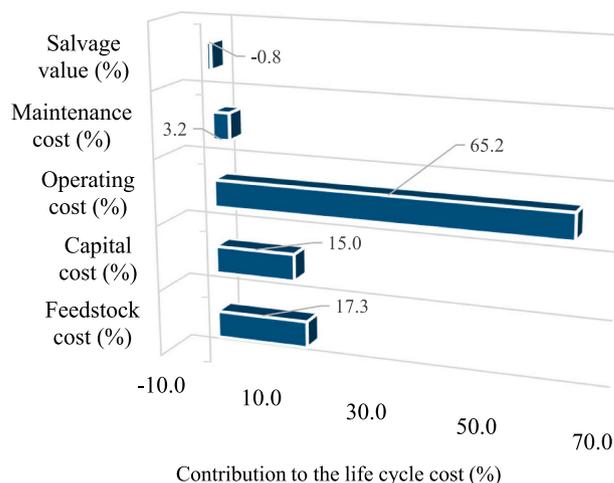


Fig. 7. Contributions of the salvage value, maintenance cost, operating cost, capital cost, and feedstock cost to the LCC. The salvage value represents the income received by the SCB bioethanol production facility after factoring depreciation, and therefore it has a negative contribution on the LCC.

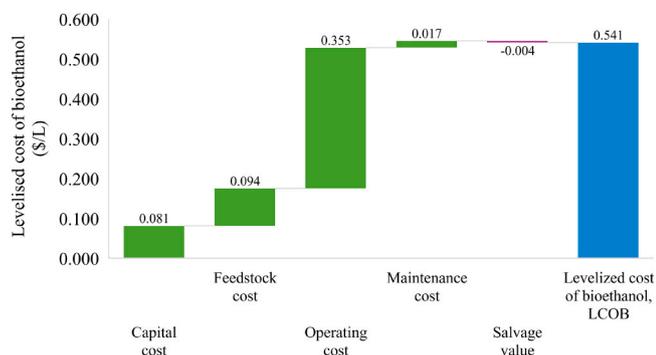


Fig. 8. Contributions of the capital cost, feedstock cost, operating cost, maintenance cost, and salvage value to the levelised cost of bioethanol (LCOB) from SCB. The salvage value has a negative contribution to the LCOB.

a stark contrast in the LCOB values between the two countries.

The LCOB from SCB obtained in this study is attractive for the bioethanol market in Indonesia because it is lower than the bioethanol selling price (\$0.766/L) recommended by the General Directorate for Renewable Energy and Energy Conservation (EBTKE), Indonesia (Direktorat Jenderal Energi Baru, 2023). This will enable local SMEs to achieve a decent profit margin from the SCB bioethanol production facility. It shall be highlighted that the bioethanol price set by the EBTKE is for first-generation bioethanol production from sugarcane, which is slightly higher than the LCOB from SCB, which is a second-generation bioethanol. The lower LCOB from SCB is certainly an advantage since the use of SCB as feedstock eliminates the competition with food sources and makes use of SCB (which is an agricultural waste) to produce a beneficial product (bioethanol), which is a cleaner fuel than fossil fuels. The LCOB from SCB obtained in this study was also lower than the LCOB from biobased CO₂ from a pulp mill (\$1.05/L) (Kosonen, 2020) and LCOB from organic wastes (\$2.2/L) (Kwon and Han, 2021).

The economic feasibility of the SCB bioethanol production facility was also assessed based on other indicators, namely, the payback period (PP), net present value (NPV), and internal rate of return (IRR), and the results are summarised in Table 6. The NPV of the SCB bioethanol production facility was calculated to be \$31,776,711 based on an SCB bioethanol selling price of \$0.70/L. This results in a profit margin of \$0.066/L, totalling to a profit of \$60,567,680 (after tax deduction) for a project lifetime of 20 years. The PP was estimated to be 5.09 years, which was slightly shorter than the PP obtained by Kosonen (Kosonen, 2020). Hence, it can be expected that local SMEs can recoup their initial investment costs shortly after the SCB bioethanol production facility has operated for 5 years.

3.3. Sensitivity analysis of the economic feasibility indicators to the SCB bioethanol selling price

To further assess the economic feasibility of SCB bioethanol production in Indonesia, it is necessary to analyse the sensitivity of the economic feasibility indicators (payback period (PP), net present value (NPV), and internal rate of return (IRR)) of the SCB bioethanol production project to changes in the SCB bioethanol selling price. Fig. 9 shows the projected PP, NPV, and IRR resulting from an SCB bioethanol

Table 6
Summary of the economic feasibility indicators based on an SCB bioethanol selling price of \$0.70/L.

| Economic feasibility indicator | Value | Unit |
|------------------------------------|------------|------|
| Levelised cost of bioethanol, LCOB | 0.541 | \$/L |
| Net present value, NPV | 31,776,711 | \$ |
| Payback period, PP | 5.09 | year |
| Internal rate of return, IRR | 11.72 | % |

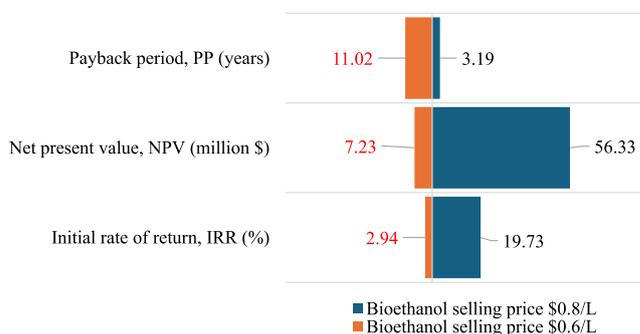


Fig. 9. Sensitivity of the payback period (PP), net present value (NPV), and internal rate of return (IRR) to changes in the SCB bioethanol selling price.

selling price of ±\$0.10/L from the bioethanol selling price of \$0.70/L recommended by the EBTKE, Indonesia. The results indicate that a slight shift in the SCB bioethanol selling price has a marked effect on the PP, NPV, and IRR. Increasing the SCB bioethanol selling price by \$0.10/L shortened the PP from 5.09 years to 3.19 years.

In contrast, decreasing the SCB bioethanol selling price by \$0.1/L prolonged the PP to 11.02 years, which was more than double of the original PP of 5.09 years. Likewise, a similar trend can be observed for the projected NPV and IRR. Increasing the SCB bioethanol selling price by \$0.10/L increased the NPV and IRR by a significant margin (with a value of \$56.33 million and 19.73 %, respectively), indicating that the SCB bioethanol production project is highly profitable since the NPV represents the difference between the present value of cash inflows and the present value of cash outflows over the project lifetime of 20 years and the IRR involves determining the discount rate that makes the present value of future cash inflows equal to the initial investment cost. If the IRR exceeds the initial investment cost, this indicates that the SCB bioethanol production project is profitable, i.e., the higher the IRR, the more profitable the project. In contrast, the NPV and IRR dropped to \$7.23 million and 2.94 %, respectively, when the SCB bioethanol selling price was decreased to \$0.6/L, indicating a significant reduction in the profitability of the project.

Fig. 10 shows the effects of the SCB bioethanol selling price on the PP and IRR, which can be used by local SMEs in determining the best SCB bioethanol selling price that will boost profitability and reduce the PP. It can be observed that the IRR increased almost linearly with an increase in the SCB bioethanol selling price and selling price at less than \$0.57/L should be avoided because it will result in a negative IRR, indicating that the SCB bioethanol production project is no longer profitable. The PP was also affected by the SCB bioethanol selling price, as indicated by the declining exponential trend, where the effect was more pronounced for a selling price of less than \$0.63/L. In addition, it is evident that as the IRR approaches 0 %, the PP is maximum, which is highly undesirable.

The IRR is typically used to assess the profitability of a project, where

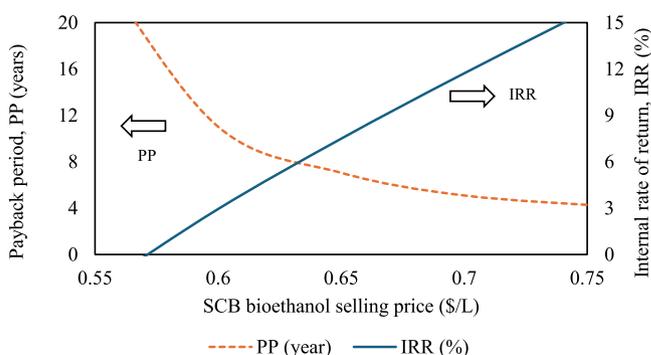


Fig. 10. Sensitivity of the projected payback period (PP) and internal rate of return (IRR) to changes in the SCB bioethanol selling price.

an IRR of 11.72 % indicates that the project is expected to generate a return that exceeds the required return, which will make the project particularly attractive to potential investors. For this reason, the effect of SCB bioethanol selling price on the projected IRR is further examined, as shown in Fig. 11. The bioethanol selling price (\$0.766/L) recommended by the EBTKE, Indonesia, was taken as the upper limit to ensure competitiveness of the SCB bioethanol in the market, and it can be seen that the SCB biodiesel production project could achieve a positive IRR when the SCB bioethanol selling price was within a range of \$0.57–0.766/L, as indicated by the shaded region in Fig. 11. The SCB bioethanol selling price should not be lower than \$0.57/L as this leads to negative IRR, which confirms the findings in Fig. 10. In addition, an SCB bioethanol selling price of more than \$0.766/L will boost the IRR to more than 17.05 %, which will be particularly attractive to investors. However, this strategy may be impractical for the bioethanol market in Indonesia. Indonesia is a price-sensitive market and therefore, it is crucial to determine the best bioethanol selling price in order to encourage and promote the use of bioethanol as a vehicle fuel in this country. The production of SCB bioethanol appears to be a promising strategy in Indonesia in parallel with the bioethanol blending mandates (Setiawan, 2022). Furthermore, when compared with Indonesia’s subsidised gasoline price, Peralite (RON90) at USD 0.66/L (Kurniawan, 2023), SCB bioethanol demonstrates a competitive position in the fuel market. This is evident from the recommended price range, which aligns closely with the Peralite price. At price parity with Peralite, SCB bioethanol production could still achieve an internal rate of return of up to 7.5 %, with only a small price difference of USD 0.10/L from the selling price suggested by EBTKE.

The projected IRR for SCB bioethanol production was also compared with the projected IRR obtained by Harsono et al. (2015) for second-generation bioethanol production from Arabica coffee wastes in East Java, Indonesia. Their projected IRR (8.96 %) was lower than that obtained in this study (11.72 %). The higher IRR for SCB bioethanol production can be attributed to the higher LCOB (\$0.541/L) and shorter PP (5.09 years) compared with the LCOB for Arabica coffee waste bioethanol production (\$0.48/L) and PP (~10 years) (Harsono et al., 2015). Fig. 11 also shows the LCOB from SCB reported by Chandel et al. (2019) (\$1.33/L) and the average LCOB from SCB obtained by Gubicza et al. (2016) (\$0.566/L).

The results of the sensitivity analysis highlight the importance of setting the SCB bioethanol selling price appropriately in order to achieve a positive IRR. The SCB bioethanol production project appears to be promising with decent profit margins for the bioethanol market in

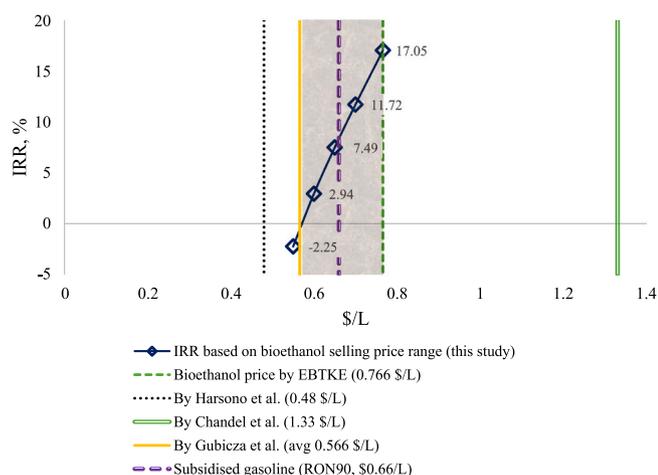


Fig. 11. Influence of SCB bioethanol selling price on the projected internal rate of return (IRR), with comparison to bioethanol production costs reported in other studies and to Indonesia’s subsidised gasoline price. The shaded area represents the recommended range for SCB bioethanol selling prices.

Indonesia, and setting the SCB bioethanol selling price to below the bioethanol selling price recommended by the EBTKE will give this commodity a competitive edge over other fuels. The LCC analysis conducted in this study provide insight into the economic feasibility of SCB bioethanol production facility to local SMEs and key stakeholders of the bioethanol market in Indonesia. Based on the results, the SCB bioethanol production project will appeal to the key stakeholders of the bioethanol industry in Indonesia such as SCB producers, SCB bioethanol manufacturers, vehicle manufacturers, government agencies, research institutions, and end users. The increase in the number of key stakeholders involved in the SCB bioethanol production project will propel the bioethanol market in Indonesia and increase the competitiveness of SCB bioethanol with fossil fuels. However, there is a need to exercise caution in interpreting the LCC of SCB bioethanol production owing to differences in the SCB feedstock prices, wage standards, and accessibility to advanced technologies in the SCB bioethanol production facility (e.g., advanced fermentation techniques such as simultaneous saccharification and fermentation (SSF), consolidated bioprocessing, and genetic engineering), which may vary significantly from one region to another in Indonesia. These factors will influence the economic feasibility of the SCB bioethanol production project to an appreciable extent.

3.4. Policy-based market opportunities in Indonesia

The Indonesian government’s biofuel strategy from 2025 to 2035 mandates the establishment of a 5 per cent bioethanol blend, or E5, beginning in 2023. This directive is formalised through a presidential regulation that promotes domestic sugar self-sufficiency while supporting renewable energy sources via bioethanol supply, as illustrated in the roadmap presented in Fig. 12. The E5 blend implementation commenced in 2023, initially targeting the gasoline market with an octane rating of 95 in the province of East Java. Government regulations, including those issued by EBTKE, guide the implementation and acceleration of bioethanol use as a biofuel. The increase in bioethanol blending is a key reference point for achieving the national renewable energy mix target of 23 per cent by 2025. The mandatory 5 per cent bioethanol blending is planned to expand nationwide in 2025 for the non-public service obligation market, specifically non-subsidised gasoline. Further increases to a 10 per cent blend are scheduled for the period between 2029 and 2035 ((BPS), 2024; (USDA), 2025), as shown in Fig. 13.

Despite these ambitious targets, infrastructure limitations in eastern Indonesia may delay the nationwide adoption of E5 until 2035. To address this, additional policy support is required. This includes the collocation of small and medium enterprises (SMEs) in partnership with sugar mills to develop blending infrastructure, exemplified by the Pertamina Biohub model. Additionally, leveraging Indonesia’s carbon trading scheme through carbon-linked pricing could provide financial incentives by securing premiums for sugarcane bagasse’s low carbon footprint. These measures aim to bridge the infrastructure gap and accelerate the adoption of bioethanol blends across the country.

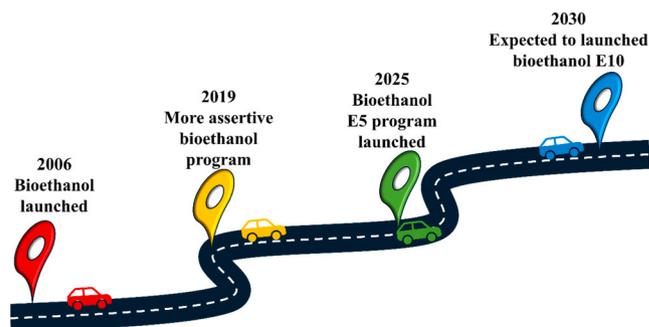


Fig. 12. Roadmap for bioethanol implementation in Indonesia.

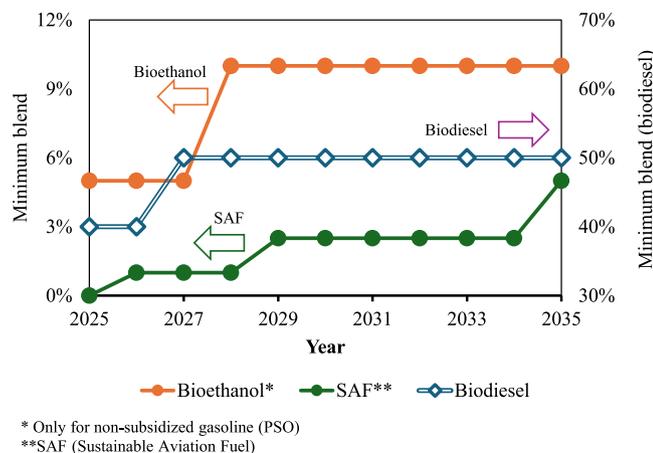


Fig. 13. Biofuel blending strategy and trajectory in Indonesia ((USDA), 2025).

The successful implementation of Indonesia's bioethanol blending targets hinges not only on regulatory mandates but also on addressing regional infrastructure disparities and fostering strategic collaborations. Enhancing supply chain capabilities, incentivising low-carbon feedstock utilisation, and strengthening policy frameworks will be critical to realising the full potential of bioethanol as a renewable fuel. Continued investment and coordinated efforts among government, industry, and local stakeholders are essential to ensure that bioethanol contributes effectively to Indonesia's energy transition and sustainability goals.

4. Conclusion

Life cycle cost (LCC) analysis of second-generation bioethanol production from sugarcane bagasse (SCB) in Indonesia has been presented in this study. The results indicate that the SCB bioethanol production facility is an economically feasible project with an LCC of \$177.18 million for a project lifetime of 20 years and a payback period of 5.09 years. By setting the SCB bioethanol selling price to \$0.70/L, the levelised cost of bioethanol (LCOB), net present value (NPV), and internal rate of return (IRR) for the SCB bioethanol production facility were estimated to be \$0.541/L, \$31,776,711, and 11.72 %, respectively, indicating that the project is economically feasible in Indonesia. In addition, the LCOB from SCB (\$0.541/L) was lower than the bioethanol selling price recommended by the General Directorate for Renewable Energy and Energy Conservation (EBTKE) at \$0.766/L and the subsidised RON90 price at \$0.66/L, indicating that the SCB bioethanol is competitive. Based on the results of the sensitivity analysis, the SCB bioethanol selling price should be within a range of \$0.570–0.766/L, which will yield a positive NPV. This study provides a valuable economic model for the key stakeholders of the renewable energy sector in Indonesia. To enhance the robustness of the LCC analysis, future studies should be carried out to identify the key factors that can limit SCB bioethanol production on a commercial scale and devise strategies to boost the efficiency of SCB bioethanol production. Such studies are crucial to advance the production and use of SCB bioethanol in Indonesia's energy landscape, which is currently dominated by fossil fuels.

CRedit authorship contribution statement

Aditiya Harjon Bahar, Teuku Meurah Indra Riayatsyah, and Chitra Ismi Sofila Nadia: Writing – Original draft, Formal analysis, Investigation, Visualisation, Methodology, Resources. Arridina Susan Silitonga: Conceptualisation, Supervision, Data curation, Writing – Review and editing, Validation. Abdi Hanra Sebayang and Topan Erlangga: Validation.

Declaration of Competing Interest

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

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Data availability

The data that has been used is confidential.

References

- Aditiya, H.B., Mahlia, T.M.I., Chong, W.T., Nur, Hadi, Sebayang, A.H., 2016. Second generation bioethanol production: a critical review. *Renew. Sustain. Energy Rev.* 66, 23.
- Aditiya, H.B., Sing, K.P., Hanif, M., Mahlia, T.M.I., 2015. Effect of acid pretreatment on enzymatic hydrolysis in bioethanol production from rice straw. *Int. J. Technol.* 8 (1).
- Amezcuá-Allieri, M.A., Martínez-Hernández, E., Anaya-Reza, O., Magdaleno-Molina, M., Melgarejo-Flores, L.A., Palmerín-Ruiz, M.E., Eguía-Lis, J.A.Z., Rosas-Molina, A., Enriquez-Poy, M., Aburto, J., 2019. Techno-economic analysis and life cycle assessment for energy generation from sugarcane bagasse: case study for a sugar mill in Mexico. *Food Bioprod. Process.* 118, 281–292.
- Amores, I., Ballesteros, I., Manzanares, P., Sáez, F., Michelena, G., Ballesteros, M., 2013. Ethanol production from sugarcane bagasse pretreated by steam explosion. *Electric Journal of Energy & Environment.*
- Anwar, M., Fayyaz, A., Sohail, N., Khokhar, M., Baqar, M., Yasar, A., Rasool, K., Nazir, A., Raja, M., Rehan, M., 2020. CO₂ utilization: turning greenhouse gas into fuels and valuable products. *J. Environ. Manag.* 260, 110059.
- Ardyanto, F., 2020. Harga solar industri HSD Pertamina terkini dan kriteria kualitasnya. *Liputan 6* (6) (Liputan).
- Awogbemi, O., Kallon, D.V.V., Onuh, E.I., Aigbodion, V.S., 2021. An overview of the classification, production and utilization of biofuels for internal combustion engine applications. *Energies* 14, 5687.
- Azmi, A., Sebayang, A.H., Harjon, A., 2023. Life cycle cost analysis and payback period of 12-kW wind turbine for a remote telecommunications base station. *Aceh Int. J. Sci. Technol.* 12, 304–316.
- Badan Pusat Statistik, 2023. Statistik Tebu Indonesia 2023. Badan Pusat Statistik Indonesia.
- Bank Sentral Republik Indonesia, 2023. BI consumer price index. Bank Sentral Republik Indonesia.
- BPS), B.P.S., 2024. Indonesia Sugarcane Statistic.
- Busić, A., Mardetko, N., Kundas, S., Morzak, G., Belskaya, H., Ivancić Šantek, M., Komes, D., Novak, S., Šantek, B., 2018. Bioethanol production from renewable raw materials and its separation and purification: a review. *Food Technol. Biotechnol.* 56, 289–311.
- Buthelezi, A.S., Chetty, M., Mohammadi, A.H., 2025a. Techno-Economic Assessment of Biofuels Production From Sugarcane Bagasse. *Energy Science & Engineering* n/a.
- Buthelezi, A.S., Chetty, M., Mohammadi, A.H., 2025b. Techno-Economic Assessment of Biofuels Production From Sugarcane Bagasse. *Energy Science & Engineering.*
- Chandel, A.K., Albarelli, J.Q., Santos, D.T., Chundawat, S.P., Puri, M., Meireles, M.A.A., 2019. Comparative analysis of key technologies for cellulosic ethanol production from Brazilian sugarcane bagasse at a commercial scale. *Biofuels Bioprod. Bioref.* 13, 994–1014.
- Chikishev, E., Fisher, A., Alontsev, V., 2019. Optimization of the work of road transport with the help of navigation equipment on the example of "Mostostroy-11", JSC, TF "Mostostroyad-36. *IOP Conf. Series Materials Science Engineering* 582, 7.
- Chriswardana, Theofany Harley, Mulyaningsih, Yheni, Mulyaningsih, Yhana, Bahar, Aditiya Harjon, Indra Riayatsyah, T.M., 2021. Optimization of sugar production from durian seeds via alkaline hydrolysis for second-generation bioethanol production. *Clean. Energy* 13.
- Department of Energy, 2017. Ethanol Policy and Ethanol Industry Overview - Philippines. Department of Energy, Seoul.
- Dessie, W., Luo, X., He, F., Liao, Y., Duns, G.J., Qin, Z., 2023. Lignin valorization: a crucial step towards full utilization of biomass, zero waste and circular bioeconomy. *Biocatal. Agric. Biotechnol.* 51, 102777.
- Dibazar, A.S., Aliasghar, A., Behzadnezhad, A., Shakiba, A., Pazoki, M., 2024. Energy cycle assessment of bioethanol production from sugarcane bagasse by life cycle

- approach using the fermentation conversion process. *Biomass.. Convers. Biorefinery* 14, 20679–20698.
- Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi, 2023. Harga Indeks Pasar Bahan Bakar Nabati (HIP BBN) Jenis Bioetanol Bulan Juni 2023. Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi.
- Dzulfaroh, A.N., 2020. UMK Jawa Timur 2020 Disahkan, Tertinggi Rp 4,2 Juta, Terendah Rp 1,9 Juta. *Kompas*.
- Ekielski, A., Mishra, P.K., 2021. Lignin for bioeconomy: the present and future role of technical lignin. *Int. J. Mol. Sci.* 22, 63.
- Fu, Y., Gao, H., Yu, H., Yang, Q., Peng, H., Liu, P., Li, Y., Hu, Z., Zhang, R., Li, J., Qi, Z., Wang, L., Peng, L., Wang, Y., 2022. Specific lignin and cellulose depolymerization of sugarcane bagasse for maximum bioethanol production under optimal chemical fertilizer pretreatment with hemicellulose retention and liquid recycling. *Renew. Energy* 200, 1371–1381.
- Gradziuk, P., Jończyk, K., Gradziuk, B., Wojciechowska, A., Trociewicz, A., Wysokiński, M., 2021. An economic assessment of the impact on agriculture of the proposed changes in EU biofuel policy mechanisms. *Energies* 14, 6982.
- Gubicza, K., Nieves, I.U., Sagues, W.J., Barta, Z., Shanmugam, K.T., Ingram, L.O., 2016. Techno-economic analysis of ethanol production from sugarcane bagasse using a liquefaction plus simultaneous saccharification and co-fermentation process. *Bioresour. Technol.* 208, 42–48.
- Hafyan, R.H., Mohanarajan, J., Uppal, M., Kumar, V., Narisetty, V., Maity, S.K., Sadhukhan, J., Gadkari, S., 2024. Integrated biorefinery for bioethanol and succinic acid co-production from bread waste: Techno-economic feasibility and life cycle assessment. *Energy Convers. Manag.* 301, 118033.
- Haji Esmaeili, S.A., Sobhani, A., Szmerekovsky, J., Dybing, A., Pourhashem, G., 2020. First-generation vs. Second-generation: a market incentives analysis for bioethanol supply chains with carbon policies. *Appl. Energy* 277, 115606.
- Halder, Pobitra, Azad, Kalam, Shah, Shaheen, Sarker, E., 2019. Prospects and technological advancement of cellulosic bioethanol ecofuel production. *Adv. EcoFuels a Sustain. Environ.* 26.
- Hanif, M., Mahlia, T.M.I., Aditiya, H.B., Chong, Nasruddin, W.T., 2016. Techno-economic and environmental assessment of bioethanol production from high starch and root yield sri kanji 1 cassava in Malaysia. *Energy Rep.* 2, 8.
- Hanif, M., Mahlia, T.M.I., Aditiya, H.B., Bakar, M.S.A., 2017. Energy and environmental assessments of bioethanol production from sri kanji 1 cassava in Malaysia. *Biofuel Res. J.* 13, 8.
- Harsono, S.S., Salahuddin, Fauzi, Purwono, M., Soemarno, G.S., Kissinger, D., 2015. Second generation bioethanol from arabica coffee waste processing at smallholder plantation in ijen plateau region of east java. *Procedia Chem.* 14, 408–413.
- Hossain, N., Mahlia, T.M.I., Miskat, M.I., Chowdhury, T., Barua, P., Chowdhury, H., Nizamuddin, S., Ahmad, N.B., Zaharin, N.A.B., Mazari, S.A., 2021. Bioethanol production from forest residues and life cycle cost analysis of bioethanol-gasoline blend on transportation sector. *J. Environ. Chem. Eng.* 9, 105542.
- Howell, S., 2005. Time to take the biodiesel plunge? *Render Mag.* 10–14.
- Hu, M., Yu, H., Li, Y., Li, A., Cai, Q., Liu, P., Tu, Y., Wang, Y., Hu, R., Hao, B., Peng, L., Xia, T., 2018. Distinct polymer extraction and cellulose DP reduction for complete cellulose hydrolysis under mild chemical pretreatments in sugarcane. *Carbohydr. Polym.* 202, 434–443.
- Janick, J., Whipkey, A., 2002. Ethanol from cellulose: a general review, trends in new crops and new uses. *ASHS Press*.
- Jaya, P.A.M., 2023. Tarif air minum. *PAM Jaya*.
- JPNP, 2014. Jual ampas tebu, PTPN x garap korsel, JPNN. Pt. Jaringan Pemberitaan Nusantara Negeriku, Jakarta.
- Kementerian Perindustrian Republik Indonesia, 2023. Direktori Perusahaan Industri. Kementerian Perindustrian Republik Indonesia.
- Kosonen, P., 2020. Techno-economic study of bioethanol production as a carbon capture and utilization process, *Bioengineering*. Tampere.
- Kumar, D., Singh, V., 2019. Chapter 22 - Bioethanol Production From Corn, in: Serna-Saldivar, S.O. (Ed.), *Corn (Third Edition)*. AACC International Press, Oxford, pp. 615–631.
- Kurniawan, D., 2023. Harga BBM Pertamina per 1 Desember 2023, Pertamina dan Dextlite Turun. *Tempo*. Tempo.
- Kwon, O., Han, J., 2021. Waste-to-bioethanol supply chain network: a deterministic model. *Appl. Energy* 300, 117381.
- U.S. Department of Energy, 2023b. U.S. Corn Production and Portion Used for Fuel Ethanol, Feed, and Other Uses.
- Mesa, L., Martínez, Y., Celia de Armas, A., González, E., 2020. Ethanol production from sugarcane straw using different configurations of fermentation and techno-economic evaluation of the best schemes. *Renew. Energy* 156, 377–388.
- Ngigi, W., Siagi, Z., Kumar, A., Arowo, M., 2023. Predicting the techno-economic performance of a large-scale second-generation bioethanol production plant: a case study for Kenya. *Int. J. Energy Environ. Eng.* 14, 95–108.
- Nogueira, G.P., Hernandez, T.A.D., Petrielli, G.P., Chagas, M.F., Junqueira, T.L., McManus, M., Leak, D., Franco, T.T., Dias, M.O.S., Cavaliero, C.K.N., 2023. The effect of pretreatment choice on cellulosic ethanol production from sugarcane straw: an insight into environmental impact profile and GHG emissions mitigation potential in Brazil. *Biomass.. Bioenergy* 175, 106895.
- Onu Olughu, O., Tabil, L.G., Dumonceaux, T., Mupondwa, E., Cree, D., Li, X., 2023. Technoeconomic analysis of a fungal pretreatment-based cellulosic ethanol production. *Results Eng.* 19, 101259.
- Papong, S., Rewlaw-ngoeng, C., Itsubo, N., Malakul, P., 2017. Environmental life cycle assessment and social impacts of bioethanol production in Thailand. *J. Clean. Prod.* 157, 254–266.
- PLN Indonesia, 2023. Tarif adjustment. PLN Indonesia.
- Restrepo-Serna, D.L., Martínez-Ruano, J.A., Cardona-Alzate, C.A., 2018. Energy efficiency of biorefinery schemes using sugarcane bagasse as raw material. *Energies* 11, 3474.
- Riayatsyah, T.M.I., 2018. Techno-economics Analysis of Biodiesel Production from Non-edible Reutealis trisperma Oil, Department of Mechanical Engineering. University of Malaya, Kuala Lumpur, p. 138.
- Riayatsyah, T.M.I., Ong, H.C., Chong, W.T., Aditya, L., Hermansyah, H., Mahlia, T.M.I., 2017. Life cycle cost and sensitivity analysis of reutealis trisperma as non-edible feedstock for future biodiesel production. *Energies* 10, 877.
- Setiawan, V.N., 2022. Bioetanol Bisa Jadi Bahan Bakar, Kapan RI Mau Ngembangin? *CNBC Indonesia*.
- Sganzerla, W.G., Lachos-Perez, D., Buller, L.S., Zabet, G.L., Forster-Carneiro, T., 2022. Cost analysis of subcritical water pretreatment of sugarcane straw and bagasse for second-generation bioethanol production: a case study in a sugarcane mill. *Biofuels Bioprod. Bioref.* 16, 435–450.
- Sudiyan, Y., Aiman, S., Mansur, D., 2019. Perkembangan bioetanol G2: teknologi dan perspektif. *Lipi Press*.
- TLV Group, 2020. *Steam Unit Cost*. TLV.
- Towler, G., Sinnott, R., 2012. *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*, 2nd ed. Butterworth-Heinemann.
- U.S. Department of Energy, 2023a. *Global Ethanol Production*.
- U.S. Energy Information Administration, 2020. EIA projects U.S. biofuel production to slowly increase through 2050. *U.S. Energy Information Administration*.
- USDA, U.S.Do.A., 2025. After a Decade Indonesia is Updating Its Biofuel Roadmap.
- Vasilakou, K., Nimmeggers, P., Thomassen, G., Billen, P., Van Passel, S., 2023. Assessing the future of second-generation bioethanol by 2030 – a techno-economic assessment integrating technology learning curves. *Appl. Energy* 344, 121263.
- Wang, M., Wang, Y., Liu, J., Yu, H., Liu, P., Yang, Y., Sun, D., Kang, H., Wang, Y., Tang, J., Fu, C., Peng, L., 2024. Integration of advanced biotechnology for Green carbon. *Green. Carbon* 2, 164–175.
- Zhang, R., Gao, H., Wang, Y., He, B., Lu, J., Zhu, W., Peng, L., Wang, Y., 2023. Challenges and perspectives of Green-like lignocellulose pretreatments selectable for low-cost biofuels and high-value bioproduction. *Bioresour. Technol.* 369, 128315.
- Zhao, Lili, Zhang, Xiliang, Xu, Jie, Ou, Xunmin, Chang, Shiyan, Wu, M., 2015. Techno-Economic analysis of bioethanol production from lignocellulosic biomass in China: Dilute-Acid pretreatment and enzymatic hydrolysis of corn stover. *Energies* 8, 22.