

Comparative life cycle assessment of fuel-grade bioethanol production from sugarcane, cassava, and corn in Lampung

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ABSTRACT

Bioethanol is a renewable energy source with strategic potential to support the transition to a sustainable, low-carbon energy system. Lampung Province has three major agricultural commodities that can be used as bioethanol feedstocks: sugarcane, cassava, and corn, each with different agronomic characteristics, conversion pathways, and energy requirements. These differences may influence both bioethanol productivity and environmental performance. Therefore, this study compared fuel-grade bioethanol production from sugarcane, cassava, and corn using a cradle-to-gate Life Cycle Assessment (LCA) approach. The assessment integrated mass balance, energy balance, Energy Return on Investment (EROI), and Global Warming Potential (GWP), using a 2-ha cultivation basis and a primary functional unit of 1 L of fuel-grade bioethanol at the plant gate. The results showed that sugarcane produced the highest bioethanol yield at approximately 8,821 L/2 ha, followed by cassava at 8,310 L/2 ha and corn at 2,522 L/2 ha. Sugarcane also had the highest EROI (2.32), compared with 1.62 for cassava and 1.21 for corn. On a 2-ha cultivation basis, total cradle-to-gate GWP was 11,990.00 kg CO₂-eq for sugarcane, 9,296.81 kg CO₂-eq for cassava, and 7,048.95 kg CO₂-eq for corn. However, when normalised to 1 L of fuel-grade bioethanol, cassava showed the lowest GWP at 1.119 kg CO₂-eq/L, followed by sugarcane at 1.359 kg CO₂-eq/L, while corn had the highest value at 2.795 kg CO₂-eq/L. These findings demonstrate a clear trade-off among land-based productivity, energy performance, and carbon intensity, indicating that sustainable feedstock selection should consider both productivity per land area and environmental impact per unit of fuel produced.

Keywords: Bioethanol, fuel grade, life cycle assessment, EROI.

INTRODUCTION

Biofuels are a promising alternative energy source for optimising energy mixes and reducing environmental pollution (Tilman *et al.*, 2009). As an effort to reduce CO₂ emissions, alternative fuels such as biodiesel and bioethanol should be considered to replace fossil fuels (Agung, Naufal and Alam, 2015). Compared with other renewable energy sources, biofuels are highly stable and simple to store. According to the "energy ladder" theory, converting raw biomass resources (e.g., plants and crop waste) into modern energy sources (liquid and gaseous fuels) improves energy quality (Horst and Ã, 2008). However, each energy conversion system requires additional energy and materials.

Bioethanol is a renewable energy source with significant potential to replace fossil fuels in the transportation sector (Ying *et al.*, 2011). Increasing global energy demand, coupled with climate change and limited oil reserves, has prompted many countries, including Indonesia, to develop bioethanol as a more environmentally friendly alternative fuel. Bioethanol can be produced through the fermentation of biomass containing sugars or starch (Gul, Ozdingis and Kocar, 2021) such as sugarcane (*Saccharum officinarum*), cassava (*Manihot esculenta*), and corn (*Zea mays*). These three materials are the main carbohydrate sources widely available in Indonesia, so using them

for bioethanol production is strategic for raw material availability and national energy security.

The bioethanol production processes from these three raw materials have different technical and environmental characteristics. Sugarcane has the advantage of a high sucrose content (Iwuozor, Chizitere and Joshua, 2022) and produces bagasse, which can be used as a process energy source (Meghana and Shastri, 2020). In contrast, bioethanol production from corn and cassava requires additional steps, such as liquefaction and saccharification, to convert starch into fermentable simple sugars (Beluhan, 2023). These differences in process stages affect energy requirements, conversion efficiency, and greenhouse gas (GHG) emissions throughout the life cycle. Therefore, selecting optimal feedstocks for bioethanol production requires a comprehensive analysis that accounts for environmental aspects.

The Life Cycle Assessment (LCA) approach effectively evaluates the environmental impact of a product or process from upstream to downstream. LCA calculations begin with raw material cultivation, then move through extraction and production. In the context of bioethanol, LCA allows for a more objective assessment of energy inputs, GHG emissions, and the net energy efficiency of each production pathway. This analysis can also

identify critical stages in the production chain that contribute most to environmental impacts, providing a basis for process improvement and sustainable energy policy decision-making.

This study aims to conduct a comparative Life Cycle Assessment analysis of fuel-grade bioethanol production from three main feedstocks: sugarcane, corn, and cassava. The study compares energy consumption, net energy efficiency (Energy Return on Investment, or EROI), and the global warming potential (GWP) of each production system. The results are expected to provide an in-depth overview of the environmental performance of each bioethanol production pathway and serve as a scientific basis for determining the most sustainable feedstock for developing Indonesia's bioethanol industry.

Furthermore, as shown in Figure 1, the keyword network map shows that global bioethanol research is dominated by three main clusters: the feedstock cluster, the production process cluster (such as fermentation and pretreatment), and the environmental and energy issues cluster. Keywords such as sugarcane, corn, cassava, bioethanol production, energy, and waste appear as large, interconnected nodes, indicating intense research on these aspects. "This pattern demonstrates that raw material selection and understanding the production process are central to

scientific discussions in bioethanol development. Therefore, this research is within the mainstream literature and fills the need for a comparative analysis that integrates these three dominant feedstocks through a Life Cycle Assessment approach to comprehensively assess their environmental performance.

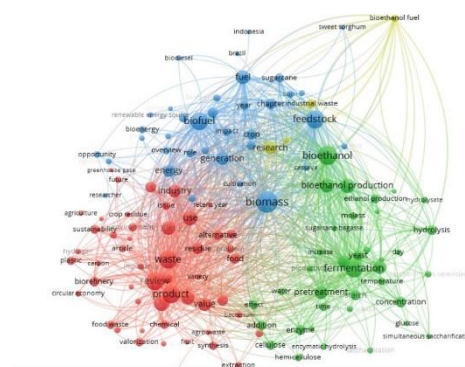


Figure 1. Bibliometric

MATERIAL AND METHODS

This methodology comprehensively evaluates the overall environmental impact of a system or product. Life cycle assessment provides a comprehensive perspective on a system's environmental impact.

This method examines how energy inputs and waste outputs affect the environment, including air, water, soil, and human health. Businesses, legislators, and consumers can use life cycle assessment (LCA) to make informed decisions by gaining a comprehensive understanding of the environmental impacts of goods and services. The procedure reduces environmental impact and promotes sustainability. According to the

International Organisation for Standardisation (ISO) 14040, the LCA methodology is divided into four main stages: defining objectives and scope, inventory analysis, impact assessment, and interpretation (Rebitzer *et al.*, 2004).

Objective and Scope

The initial stage of the LCA involves defining the objectives, scope, functional units, system boundaries, and assumptions. The purpose of this Life Cycle Assessment (LCA) study is to comprehensively assess the environmental impacts resulting from the entire life cycle of the bioethanol production process from three main feedstocks: sugarcane, corn, and cassava. This study aims to compare the environmental performance of these three production pathways to determine the most environmentally friendly and sustainable feedstock. Furthermore, this LCA aims to identify the process stages that contribute most to environmental impacts, such as greenhouse gas emissions, energy consumption, and water use, to pinpoint critical points (hotspots) for improvement. The results are expected to support decision-making by policymakers, bioenergy industry players, and other relevant parties in selecting and improving the efficiency of bioethanol production processes oriented toward environmental sustainability.

This Life Cycle Assessment (LCA) study uses a cradle-to-gate approach, covering all process stages from feedstock cultivation to bioethanol production ready for distribution at the plant, excluding the product's use and end-of-life phases. This boundary system encompasses three main stages: raw material cultivation, transportation, and bioethanol production. The cultivation stage includes planting sugarcane, corn, and cassava, as well as the use of fertilisers, pesticides, irrigation water, and the mechanical energy required for land preparation and plant maintenance. The transportation stage involves moving raw materials from the farmland to the bioethanol processing facility and accounts for fuel consumption and emissions generated during distribution. The production stage includes a series of technical processes, from raw material preparation (milling, cooking, and hydrolysis) to fermentation (converting sugars to ethanol) and distillation to obtain high-quality bioethanol. The study also accounts for electricity, heat, and water use within the plant, as well as the management of liquid and solid waste such as vinasse, bagasse, and cassava and corn residues. Using this cradle-to-gate approach, the study identifies environmental burdens up to the production stage, providing a comprehensive picture of the

bioethanol process's efficiency and sustainability across feedstocks.

Life Cycle Inventory

The Life Cycle Inventory (LCI) is the second phase of Life Cycle Assessment and involves systematically collecting, quantifying, and calculating material and energy inputs and environmental outputs associated with a product system (Rebitzer et al., 2004; Islam, Ponnambalam, and Lam, 2016). According to ISO 14044, the LCI should align with the defined goal, functional unit, and system boundary and provide a transparent basis for the subsequent Life Cycle Impact Assessment (ISO, 2006).

In this study, the inventory was developed for the three cradle-to-gate bioethanol pathways based on sugarcane, cassava, and corn. The inventory was organised into three major stages: feedstock cultivation, transportation, and bioethanol conversion. The cultivation inventory included fertiliser application, pesticides, diesel consumption for field operations, electricity use, and field emissions associated with agricultural activities. The transportation inventory included the amount of biomass transported and the fuel consumption associated with transporting harvested feedstocks from the cultivation area to the bioethanol processing facility. The conversion-stage inventory included raw material preparation, milling,

clarification where applicable, liquefaction and saccharification for starch-based feedstocks, fermentation, distillation, dehydration, utilities, and waste treatment.

Material flows were quantified through mass-balance calculations for each major unit operation, whereas energy requirements were determined from the energy consumption associated with the respective processing stages. The inventory also accounted for the main products, process residues, and emissions generated within the system boundary. These included fuel-grade ethanol as the principal product; bagasse from sugarcane processing; cassava peel and solid residues; corn residues; fermentation CO₂; liquid residues from distillation; and other process wastes. We recorded biomass residues as separate inventory flows so we could evaluate their treatment and potential utilisation consistently, without double-counting their contribution to the energy balance.

For comparison, we first compiled the inventory data on a 2 ha cultivation basis to establish feedstock production and land-based productivity. We then normalised the inventory results to the primary functional unit of 1 L of fuel-grade bioethanol at the plant gate to enable equivalent comparisons of the three pathways, despite differences in ethanol yield. For each inventory item, we documented the activity

data, measurement unit, calculation basis, and data source to ensure traceability and reproducibility. Where direct measurements were unavailable, we used secondary data or literature-supported parameters and explicitly identified them in the calculation procedure.

The resulting LCI therefore provides the quantitative link between feedstock cultivation, transportation, process material and energy requirements, ethanol production, residue generation, and environmental releases. This inventory serves as the basis for calculating Global Warming Potential (GWP) in the Life Cycle Impact Assessment stage.

Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the Life Cycle Assessment phase in which the inventory flows identified in the Life Cycle Inventory (LCI) are translated into potential environmental impacts. This stage provides a systematic framework for evaluating the environmental significance of resource consumption and emissions associated with a product system (Rebitzer et al., 2004). LCIA approaches are generally classified into midpoint and endpoint methods. Midpoint methods evaluate environmental impacts at an intermediate stage of the cause-and-effect chain, such as global warming, acidification, or eutrophication, whereas endpoint methods evaluate broader damage to human health,

ecosystems, and natural resources (Pang et al., 2015; Goedkoop & Effting, n.d.).

In this study, the LCIA focused on the Global Warming Potential (GWP) as the principal environmental impact category because greenhouse gas emissions are directly relevant to evaluating the environmental performance of bioethanol as a renewable transportation fuel. GWP was expressed in kilograms of carbon dioxide equivalent (kg CO₂-eq) and included greenhouse gas emissions associated with feedstock cultivation, fertiliser production and application, field N₂O emissions, agricultural operations, electricity consumption, pesticide use, feedstock transportation, bioethanol conversion processes, utilities, and waste treatment.

We calculated the GWP contribution of each inventory activity by combining the corresponding activity data with the appropriate emission or characterisation factor. The general calculation was expressed as:

$$GWP = AD \times EF$$

where GWP is the greenhouse gas impact associated with the activity, expressed in kg CO₂-eq; AD_i is the activity data representing the quantity of material or energy consumed; and EF is the corresponding emission or characterisation factor. We then aggregated contributions from individual activities to determine the

total cradle-to-gate GWP for each bioethanol production pathway.

We first calculated environmental impacts on a 2 ha cultivation basis to represent the total greenhouse gas burden associated with the feedstock production and conversion system. Because the three feedstocks produced different quantities of fuel-grade bioethanol from the same cultivation area, the resulting GWP was subsequently normalised to the primary functional unit of 1 L of fuel-grade bioethanol at the plant gate. This normalisation enables a consistent comparison of the carbon intensity of sugarcane-, cassava-, and corn-based bioethanol, while the 2 ha results provide supplementary information on land-based environmental burden.

We also evaluated each life-cycle stage to identify environmental hotspots across the three production pathways. These stages included fertiliser-related emissions, field N₂O emissions, agricultural energy and field operations, pesticides and transportation, and the bioethanol conversion process. The hotspot analysis identified the processes that contribute most to total GWP and highlighted opportunities to reduce greenhouse gas emissions within each bioethanol pathway.

This study did not apply endpoint weighting or aggregate results into a single environmental score because it evaluates climate-change impacts through GWP. Consequently, the

LCIA results are interpreted as comparative carbon-footprint indicators for the three bioethanol production pathways within the defined cradle-to-gate system boundary.

RESULTS AND DISCUSSION

Mass Balance of The Bioethanol Process: Bioethanol from Sugarcane.

The sugarcane bioethanol production process for fuel blending begins with raw material preparation. The process harvests and cleans 180 tons (180,000 kg) of sugarcane to remove leaves and other impurities. The sugarcane stalks are then cut and crushed using a crusher and mill to extract the juice. This milling process produces approximately 126,000 kg of raw sugarcane juice and 54,000 kg of bagasse. Based on the revised mass-balance calculation, the raw juice contains approximately 12 wt% total sugars, equivalent to approximately 15,120 kg of sugars.

In the clarification stage, 126,000 kg of raw sugarcane juice is treated with lime (Ca(OH)₂) at approximately 0.15% of the juice mass, corresponding to approximately 189 kg. Lime addition neutralises acidity, coagulates impurities, and facilitates sedimentation. Clarification occurs at approximately 105°C. During this process, the juice generates approximately 2,520 kg of process mud. Including the added lime, the total filter-cake/mud output is

approximately 2,709 kg. The sediment contains approximately 756 kg of trapped sugar, corresponding to about 5% of the initial sugar content. Therefore, approximately 14,364 kg of fermentable sugars remain available in the clarified juice. After sedimentation and filtration, approximately 123,480 kg of clarified sugarcane juice is obtained and subsequently used as the main feedstock for fermentation. This purification stage improves juice quality, stabilises pH, and reduces fermentation-inhibiting compounds, supporting efficient conversion of sugar into ethanol.

The next stage is fermentation, which represents the main biochemical conversion of sugar in the clarified sugarcane juice into ethanol. A total of 123,480 kg of clarified juice is introduced into the fermentation reactor without additional dilution water because the sugar concentration is considered suitable for alcoholic fermentation.

Saccharomyces cerevisiae yeast is added at approximately 0.2% of the juice mass (246.96 kg) and acts as the biocatalyst that converts fermentable sugars into ethanol and carbon dioxide (Stewart, 2014). Fermentation is carried out at approximately 35°C and pH 4.5–5.0 for 48 h under anaerobic conditions. Based on stoichiometric conversion and a fermentation yield of approximately 90%, the process produces approximately 6,962.81 kg of ethanol and 6,652.80 kg of CO₂.

Approximately 387.8 kg of new yeast-cell biomass is formed during fermentation, resulting in approximately 634.8 kg of total yeast biomass in the fermentation broth, including the initial inoculum.

Taking into account the initial yeast addition and the release of CO₂, the total mass of fermented liquid, or “beer,” after fermentation is approximately 117,074.16 kg. This fermented beer contains ethanol, water, residual sugars, yeast biomass, and other dissolved and suspended organic compounds and is subsequently transferred to the distillation unit.

The distillation process is carried out on approximately 117,074.16 kg of fermented beer. This stage recovers ethanol and concentrates it to approximately 95% (w/w) (Saini, Chandel, and Kant, 2020). Using an overall downstream ethanol recovery of 99.7%, approximately 6,941.92 kg of ethanol is recovered. At a target concentration of 95% (w/w), the resulting hydrous ethanol distillate has a total mass of approximately 7,307.29 kg, consisting of approximately 6,941.92 kg of ethanol and 365.36 kg of water. The remaining bottom stream is approximately 109,766.87 kg and contains water, residual sugars, yeast biomass, dissolved and suspended solids, and approximately 20.89 kg of unrecovered ethanol.

The 95% (w/w) hydrous ethanol is subsequently processed in a

molecular sieve-based dehydration unit to obtain fuel-grade ethanol. The dehydration feed is therefore 7,307.29 kg, consisting of 6,941.92 kg of ethanol and 365.36 kg of water. To produce fuel-grade ethanol with a purity of 99.5% (w/w) (Makertihartha, Dharmawijaya, and Wenten, 2016), the final product mass is approximately 6,976.81 kg, consisting of 6,941.92 kg of ethanol and approximately 34.88 kg of water. Consequently, the dehydration stage removes approximately 330.48 kg of water.

After dehydration, the sugarcane pathway produces approximately 6,976.81 kg, or 8,821 L, of 99.5% fuel-grade bioethanol, ready for use as a renewable fuel blend.

Bioethanol Process from Cassava.

The bioethanol production process from cassava begins with raw material preparation. The process uses 50 tons (50,000 kg) of fresh cassava as the raw material. The fresh cassava is washed to remove soil, sand, and other impurities using approximately 5,000 kg of clean water, equivalent to about 10% of the fresh cassava mass. After washing, the outer peel is removed, generating about 8,000 kg of cassava peel, or 16% of the fresh cassava mass. Consequently, approximately 42,000 kg of clean cassava remains for further processing.

The 42,000 kg of clean cassava is then crushed into a pulp to facilitate

mixing with water and enzymes during the liquefaction and saccharification stages. Approximately 112,000 kg of process water is added, resulting in a total slurry mass of approximately 154,000 kg. The resulting homogeneous cassava slurry is subsequently subjected to enzymatic hydrolysis to convert starch into fermentable glucose.

In the liquefaction and saccharification stage, 154,000 kg of cassava slurry is introduced into the reactor. Liquefaction is carried out at approximately 85°C (Martín et al., 2017), with the addition of approximately 44 kg of α -amylase to break down starch granules into shorter dextrin molecules. After approximately 1 h of liquefaction, the temperature is reduced to approximately 60°C, which is considered suitable for the saccharification stage (Fiana & Asben, 2022). Approximately 66 kg of glucoamylase is then added to convert dextrans into glucose. Therefore, the total enzyme addition is approximately 110 kg.

The total mass entering the hydrolysis and saccharification stage is approximately 154,110 kg, consisting of 154,000 kg of slurry and 110 kg of enzymes. During heating and hydrolysis, approximately 2,200 kg of water is assumed to evaporate. Consequently, the process yields approximately 151,910 kg of saccharified slurry. Based on the

revised mass balance, this stream contains approximately 14,250 kg of glucose, together with water, non-starch solids, and enzyme-related solids.

The fermentation process begins with approximately 151,910 kg of saccharified slurry. The slurry is cooled to approximately 30–35°C and inoculated with *Saccharomyces cerevisiae*. Approximately 90% of the available glucose, equivalent to about 12,825 kg, is converted during fermentation, while approximately 1,425 kg of residual glucose remains unfermented. Based on the stoichiometric conversion of glucose, approximately 6,559.29 kg of ethanol and 6,265.71 kg of carbon dioxide (CO₂) are produced. The fermentation system releases the CO₂.

After accounting for CO₂ release, the remaining fermentation broth has a total mass of approximately 145,644.29 kg. The broth consists of ethanol, residual glucose, water, non-starch solids, enzymes, and other dissolved or suspended components. This fermentation broth is subsequently transferred to the distillation unit to separate and concentrate the ethanol.

The distillation and dehydration stages produce fuel-grade bioethanol with high ethanol purity (Patil, 2016). In the distillation stage, the fermented broth is heated, and the ethanol is concentrated to approximately 95% (w/w). Using an overall downstream ethanol recovery of 99.7%,

approximately 6,539.61 kg of ethanol is recovered, while approximately 19.68 kg of ethanol remains unrecovered in the process stream. At 95% (w/w), the resulting hydrous ethanol distillate has a total mass of approximately 6,883.80 kg, consisting of approximately 6,539.61 kg of ethanol and 344.19 kg of water.

The remaining bottom stream from the distillation column is approximately 138,760.49 kg and contains water, residual glucose, non-starch solids, enzyme-related solids, and unrecovered ethanol. The 95% (w/w) hydrous ethanol distillate is then processed in a molecular sieve dehydration unit to further reduce its water content.

During dehydration, the ethanol concentration is increased from 95% to 99.5% (w/w). Because the dehydration stage primarily removes water rather than producing additional ethanol, the ethanol mass remains approximately 6,539.61 kg. The resulting fuel-grade product has a total mass of approximately 6,572.47 kg, consisting of approximately 6,539.61 kg of ethanol and 32.86 kg of water. Therefore, the dehydration stage removes approximately 311.33 kg of water.

Following distillation and dehydration, the cassava pathway produces approximately 6,572.47 kg, or about 8,310 L, of 99.5% fuel-grade bioethanol.

Bioethanol Process from Corn.

The bioethanol production process from corn begins with raw material preparation. The process processes 10,000 kg of corn through hulling to separate the kernels from the non-kernel fractions. This stage produces approximately 6,930 kg of clean kernels, 70 kg of screening waste, and approximately 3,000 kg of corn cob, husk, and other non-kernel residues. Thus, the total mass output from the hulling stage is consistent with the initial 10,000 kg of corn input.

The 6,930 kg of clean kernels is subsequently milled using a dry-milling process. Assuming a milling loss of approximately 2% of the clean kernel mass, or 138.6 kg, approximately 6,791.4 kg of corn flour is obtained. The corn flour is then mixed with 12,677.3 kg of process water, producing approximately 19,468.7 kg of corn slurry for the subsequent liquefaction and saccharification stages.

In the liquefaction stage, 19,468.7 kg of corn slurry is introduced into the reactor, and approximately 5.8 kg of α -amylase is added. The slurry is heated to approximately 85–90°C for about 2 h to disrupt the starch granules and convert the starch into shorter dextrin chains. Next, approximately 17.5 kg of glucoamylase is added during saccharification. The temperature is reduced to approximately 60°C, which is considered suitable for corn starch saccharification (Salsabilla &

Fahrurroji, 2021). The reaction is continued for approximately 5 h.

Based on the revised mass balance, the corn flour contains approximately 5,833.3 kg of dry matter, of which approximately 4,096.75 kg is starch. Assuming approximately 95% starch hydrolysis, about 3,891.91 kg of starch is hydrolysed, while approximately 204.84 kg remains unconverted. The hydrolysed starch produces approximately 4,324.33 kg of glucose. After accounting for enzyme addition and approximately 2.0 kg of process or evaporative loss, the total mass of the saccharified slurry is approximately 19,490 kg.

The fermentation stage begins with approximately 19,490 kg of saccharified corn slurry. The slurry is cooled to approximately 30–35°C and maintained under anaerobic conditions. *Saccharomyces cerevisiae* is added at approximately 2% of the available glucose mass, corresponding to approximately 86.49 kg of yeast, while nutrients and buffering agents are added at approximately 0.5% of the glucose mass, corresponding to approximately 21.62 kg.

Based on approximately 90% conversion of the available glucose, approximately 3,891.90 kg of glucose is fermented, while approximately 432.43 kg remains as residual glucose. The biochemical conversion of glucose produces approximately 1,990.43 kg of ethanol and 1,901.47 kg of carbon dioxide (CO₂). The

fermentation system releases the generated CO₂.

After accounting for the addition of yeast and nutrients and the release of CO₂, the total mass of the fermentation broth is approximately 17,696.64 kg. The fermented broth contains ethanol, residual glucose, water, unconverted starch, non-starch solids, enzymes, yeast, nutrients, and other dissolved or suspended compounds. The fermentation broth is subsequently transferred to the distillation stage for ethanol separation and concentration.

In the distillation stage, ethanol is concentrated to approximately 95% (w/w). Based on an overall downstream ethanol recovery of 99.7%, approximately 1,984.46 kg of ethanol is recovered, corresponding to an ethanol loss of approximately 5.97 kg. At a target concentration of 95% (w/w), approximately 2,088.90 kg of hydrous ethanol distillate is obtained, consisting of approximately 1,984.46 kg of ethanol and 104.45 kg of water.

The remaining bottom stream from the distillation column is approximately 15,607.74 kg and consists primarily of water, residual glucose, unconverted starch, non-starch solids, yeast biomass, nutrients, and unrecovered ethanol. The 95% (w/w) hydrous ethanol distillate is subsequently transferred to a molecular sieve dehydration unit to obtain fuel-grade ethanol.

During dehydration, the ethanol concentration is increased from 95% to

99.5% (w/w). Because the dehydration stage primarily removes water rather than generating additional ethanol, the recovered ethanol mass remains approximately 1,984.46 kg. The final fuel-grade ethanol product has a total mass of approximately 1,994.43 kg, consisting of approximately 1,984.46 kg of ethanol and 9.97 kg of water.

Consequently, the dehydration process removes approximately 94.47 kg of water. After distillation and dehydration, the corn pathway produces approximately 1,994.43 kg, equivalent to approximately 2,522 L, of 99.5% fuel-grade bioethanol, ready for use as a renewable fuel blend.

The energy output from the main product was calculated from the mass of recovered fuel-grade ethanol and its lower heating value. Based on the revised mass balance, the energy contained in the ethanol product was approximately 186.25 GJ for sugarcane, 175.46 GJ for cassava, and 53.24 GJ for corn. Sugarcane therefore produced the highest ethanol energy output, followed by cassava and corn.

Energy Balance

Table 1. Energy balance calculation results.

Process	Sugarcane (GJ)	Cassava (GJ)	Corn (GJ)
Input Energy			
Pretreatment	2.00	5.15	0.72
Clarification	37.80	–	–
Liquefaction	–	38.62	4.88
Saccharification	–	4.97	–
Cooling before fermentation	–	4.77	0.72
Distillation	39.39	46.20	30.12
Dehydration	1.20	8.29	7.59
Total energy input	80.39	108.00	44.03
Output Energy			
Main product: fuel-grade ethanol	186.25	175.46	53.24
Bagasse gross energy content ¹	364.50	–	–
Total Energy output	186.25	175.46	53.24
EROI	2.32	1.62	1.21

Sugarcane processing also generated approximately 54,000 kg of bagasse, with an estimated gross energy content of 364.50 GJ. In the original calculation, we added this entire energy content directly

to the ethanol energy output. In the revised energy accounting, however, we treat bagasse separately because it can be used as an internal boiler fuel to provide process heat.

Consequently, we do not credit its gross energy content as an external energy output in the base-case EROI calculation to avoid double counting. Any surplus bagasse remaining after satisfying internal thermal requirements may be utilised for further energy recovery or as a lignocellulosic feedstock for second-generation bioethanol production; however, this potential pathway is outside the system boundary of the present base-case analysis.

Energy Return on Investment (EROI) represents the ratio between the useful energy contained in the principal energy product and the energy required to produce it. In the present comparative analysis, EROI was calculated consistently for all three feedstocks using the energy content of fuel-grade ethanol as the useful energy output:

$$EROI = \frac{E_{Ethanol}}{E_{Process\ input}} \quad (1)$$

Where EDout is the energy content of all products, while Vj is the energy that comes out and can be reused. EDin is the total energy entering the system. The results show that the EROI of sugarcane is 6.74, cassava is 1.63, and corn is 1.24. These values are the same as the results of previous research, where E_{ethanol} is the lower-heating-value energy contained in the recovered fuel-grade ethanol, and

$E_{\text{process input}}$ represents the total process energy required within the defined conversion boundary.

Based on the revised calculation, the EROI values were 2.32 for sugarcane, 1.62 for cassava, and 1.21 for corn. Therefore, the energy-performance ranking was: Sugarcane > Cassava > Corn

All three pathways exhibited EROI values greater than unity, indicating that the energy contained in the produced ethanol exceeded the process energy required for its production. Sugarcane showed the highest EROI because of its relatively high ethanol output compared with its process energy requirement. In addition, the availability of bagasse provides an important opportunity for internal process-energy substitution and further valorisation, although these additional benefits were not included in the base-case EROI.

Life Cycle Impact Assessment

Table 2 presents the fertiliser activity data recorded for cultivating sugarcane, cassava, and corn within the 2-ha system boundary. These values represent the actual amounts of fertiliser applied during field cultivation and therefore constitute inventory data rather than greenhouse gas emissions. Total fertiliser inputs were 8,200 kg for sugarcane, 7,050 kg for cassava, and 845 kg for corn. The substantially higher total inputs for sugarcane and cassava mainly resulted from applying 6,000 kg of

manure to each crop, whereas manure was not applied to corn cultivation. In contrast, mineral fertiliser amounts varied among the three feedstocks according to their respective field management practices. Sugarcane received the highest urea input (1,050 kg) and was the only crop receiving ZA fertiliser (720 kg), while cassava and corn each received 600 kg of urea. SP-36 and KCl were applied at comparatively lower rates across all cultivation systems.

These differences in fertiliser activity data matter because they establish the agricultural input profiles used in the subsequent life-cycle impact calculations. However, the total mass of fertiliser applied should not be interpreted directly as the magnitude of environmental impact. Different fertiliser types have different nutrient compositions and emission factors, and nitrogen-containing fertilisers can additionally contribute to direct and indirect N_2O emissions after field application. Therefore, the activity data in Table 2 were subsequently converted into fertiliser-related greenhouse gas emissions using the corresponding emission factors, while field N_2O emissions were calculated separately to avoid double counting. This distinction clearly separates the life cycle inventory (LCI) from the resulting life cycle impact assessment (LCIA).

Table 2. Fertilizer Activity Data for 2 ha Cultivation Area

Fertilizer	Sugarcane (kg/2 ha)	Cassava (kg/2 ha)	Corn (kg/2 ha)
Manure	6,000	6,000	–
SP-36	250	150	125
KCl	180	300	120
Urea	1,050	600	600
ZA	720	–	–
Total fertiliser applied	8,200	7,050	845

Table 3 presents greenhouse gas emissions associated with producing fuel-grade bioethanol from sugarcane, cassava, and corn. The fertiliser-related emissions reported under Parameter A represent the upstream emissions associated with the mineral fertilisers used during cultivation. Although Table 2 includes manure application as activity data, we did not assign an upstream production burden because we treated manure as an agricultural residue under the cut-off approach. Therefore, manure is not presented separately under Parameter A. Nevertheless, we included nitrogen introduced through manure application in calculating direct and indirect field N₂O emissions under Parameter B. This treatment avoids assigning an artificial production burden to an agricultural residue

while ensuring that emissions associated with its field application are not omitted.

On the common 2-ha cultivation basis, total cradle-to-gate greenhouse gas emissions were 11,990.00 kg CO₂-eq for sugarcane, 9,296.81 kg CO₂-eq for cassava, and 7,048.95 kg CO₂-eq for corn. Thus, when comparing production systems on an equal land-area basis, corn has the lowest absolute greenhouse gas emissions, while sugarcane has the highest. However, this land-based comparison does not account for the substantial differences in bioethanol productivity among the three feedstocks.

The contribution of individual life-cycle stages differed considerably among the three production pathways. For sugarcane, field N₂O emissions were the largest contributor, accounting for approximately 33.7% of total GWP, followed by the bioethanol conversion process (28.4%) and fertiliser-related emissions (25.0%). The relatively high cultivation-stage burden of sugarcane was linked to higher nitrogen inputs, particularly from urea and ZA, which contributed to both upstream fertiliser-related emissions and direct and indirect N₂O emissions after field application. The contribution of manure-derived nitrogen was also included in the field N₂O calculation, although no upstream production emissions were allocated to the manure itself.

In contrast, the bioethanol conversion stage was the dominant contributor for cassava and corn, accounting for approximately 54.0% and 49.7% of their total emissions, respectively. The comparatively high

conversion-stage burden for cassava reflects its greater energy requirement for liquefaction, saccharification, distillation, and dehydration.

Table 3. GWP emissions of fuel-grade bioethanol production from different feedstocks

Components	Sugarcane (kg CO ₂ -eq)	Cassava (kg CO ₂ -eq)	Corn (kg CO ₂ -eq)
A. Fertiliser-related emissions			
SP-36	48.78	29.27	24.39
KCl	45.04	75.06	30.02
Urea	2,208.28	1,261.87	1,261.87
ZA	691.29	—	—
Subtotal A	2,993.38	1,366.20	1,316.29
B. Field N ₂ O emissions			
Direct N ₂ O emissions	2,882.88	1,346.20	1,184.04
Indirect N ₂ O – volatilization	396.76	211.66	177.61
Indirect N ₂ O – leaching/runoff	761.08	355.40	312.59
Subtotal B¹	4,040.72	1,913.26	1,674.23
C. Energy and field operations			
Diesel tractor	536.00	402.00	321.00
Electricity	85.00	34.00	51.00

Components	Sugarcane (kg CO ₂ -eq)	Cassava (kg CO ₂ -eq)	Corn (kg CO ₂ -eq)
Subtotal C	621.00	436.00	372.00
D. Pesticides and transportation			
Pesticides	25.00	10.00	10.00
Harvest transportation	900.00	550.00	170.00
Subtotal D	925.00	560.00	180.00
E. Bioethanol conversion process			
Pretreatment	—	—	163.40
Clarification	152.50	—	—
Liquefaction	—	275.30	275.30
Saccharification	—	278.06	116.50
Fermentation	450.00	267.10	343.10
Distillation	2,209.78	2,591.82	1,689.73
Dehydration	67.32	465.07	425.80
Utilities	255.10	616.00	245.10
Waste treatment	275.20	528.00	247.50
Subtotal E	3,409.90	5,021.35	3,506.43
TOTAL A+B+C+D+E	11,990.00	9,296.81	7,048.95
Bioethanol production (L/2 ha)	8,821	8,310	2,522
GWP (kg CO ₂ -eq/L ethanol)	1.359	1.119	2.795

Corn had the lowest total emissions per 2 ha, partly because of its smaller cultivation and processing scale; however, its substantially lower bioethanol yield changes the interpretation when results are expressed relative to the amount of fuel produced.

Based on the revised mass balances, sugarcane, cassava, and corn produced approximately 8,821, 8,310, and 2,522 L of fuel-grade bioethanol per 2 ha, respectively. When normalised to the primary functional unit of 1 L of bioethanol, the corresponding GWP values were 1.359 kg CO₂-eq/L for sugarcane, 1.119 kg CO₂-eq/L for cassava, and 2.795 kg CO₂-eq/L for corn. Consequently, the environmental ranking based on the product-oriented functional unit differs from that obtained using land area alone. Cassava exhibited the lowest GWP per litre of bioethanol, followed by sugarcane, while corn showed the highest emission intensity. Although corn generated the lowest absolute emissions per 2 ha, its lower ethanol productivity resulted in a substantially higher carbon footprint per unit of fuel produced.

CONCLUSIONS

This study demonstrates that the environmental and energy performance of fuel-grade bioethanol from sugarcane, cassava, and corn depends strongly on the basis of comparison. Based on the revised

mass balance for an equal cultivation area of 2 ha, sugarcane produced the highest amount of fuel-grade bioethanol at approximately 8,821 L, followed by cassava at 8,310 L and corn at 2,522 L. Sugarcane also showed the highest energy performance, with an EROI of 2.32, compared with 1.62 for cassava and 1.21 for corn. Although all pathways had EROI values above unity, the results indicate substantial differences in how efficiently process energy is converted into ethanol energy.

The environmental ranking differed depending on the functional basis applied. On a 2-ha cultivation basis, total cradle-to-gate GWP was 11,990.00 kg CO₂-eq for sugarcane, 9,296.81 kg CO₂-eq for cassava, and 7,048.95 kg CO₂-eq for corn, making corn the pathway with the lowest absolute emissions per unit of cultivated land. However, when normalised to the primary functional unit of 1 L of fuel-grade bioethanol, cassava exhibited the lowest GWP at 1.119 kg CO₂-eq/L, followed by sugarcane at 1.359 kg CO₂-eq/L, while corn had the highest value at 2.795 kg CO₂-eq/L because of its substantially lower ethanol productivity. Field N₂O and fertiliser-related emissions were major contributors to the sugarcane pathway, whereas the bioethanol conversion stage was the dominant contributor for cassava and corn. Overall, the results highlight a clear trade-off among land-based

productivity, energy efficiency, and carbon intensity, indicating that feedstock selection for sustainable bioethanol development should consider both agricultural productivity and environmental performance per unit of fuel produced. Improvements in nitrogen-fertiliser management, field-emission control, and conversion-process energy efficiency are therefore important strategies for reducing the carbon footprint of bioethanol production in Indonesia.

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