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Life Cycle Assessment and Emission Mass Balance of Cassava-Based Bioethanol: A Feasibility Analysis of Environmental Impacts from Upstream to Downstream in Indonesia

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Abstract

Bioethanol is a promising alternative biofuel for reducing gasoline consumption. Indonesia's bioethanol industry is expanding to achieve the energy mix target through Pertamax Green 95. The government also focuses on energy transition and environmental concerns, especially in the transportation sector. This research aims to inventory and assess the impacts of bioethanol production from cassava in Indonesia and analyze the feasibility of bioethanol consumption in vehicle exhaust emissions. The research method utilizes Life Cycle Assessment (LCA) and emission mass balance as the essential analytical tools. The LCA analysis refers to SNI ISO 14040:2016 and SNI ISO 14044:2017, with a cradle-to-gate scope using ReCiPe 2016 Midpoint (H) to assess the potential environmental impact of Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD) and Terrestrial Acidification (TAC). Whereas vehicle emission feasibility is analyzed using the emission mass balance method to calculate emission concentrations. The research result shows the environmental impacts per liter of bioethanol production from cassava were GWP 11.88 kg CO2 eq, SOD 5.9x10-6 kg CFC11 eq, and TAC 0.04 kg SO2 eq. Emission feasibility analysis signifies that bioethanol combustion vehicles are lower than conventional gasoline. Therefore, it indicates energy and environmental added value through its life cycle.

Keywords: *bioethanol; cassava; Live Cycle Assesment (LCA); emission mass balance, vehicle energy transition*

1. Introduction

Premium gasoline (C_8H_{18}) is a petroleum fuel and remains the primary choice for the public in Indonesia. According to the 2022 Oil and Gas Statistics, gasoline production in Indonesia reached 93,000 barrels of oil in 2021 (Ditjen Migas KESDM RI, 2022). The widespread use of petroleum, particularly gasoline, has contributed to the depletion and limitation of raw material sources and has adverse environmental impacts. In the transportation sector, gasoline consumption in Indonesia has consistently increased, reaching 13,013,926 kL in 2022 (BPS, 2023).

The production of gasoline necessitates acquiring raw materials, involving the extraction of natural resources, which often leads to environmental degradation, such as large-scale drilling and extensive land use. Given this environmental damage, significant efforts in environmental revitalization, both costly and time-consuming, are also required. This has drawn the government's attention towards transitioning to using alternative energy sources that are environmentally friendly and abundant.

Biofuels, particularly bioethanol, present a potential alternative as an additive or substitute for gasoline. According to the Ministry of Energy and Mineral Resources of The Republic of Indonesia (2022), bioethanol production in Indonesia reached 40,000 kiloliters in 2021. Additionally, under the renewable energy strategy within the national energy mix, bioethanol production is targeted to reach 450,000 kiloliters by 2025 (Ditjen EBTKE KESDM RI, 2020). The government is promoting the Pertamax Green 95 or Ethanol 5% (E5) program to achieve this target. According to Dinata & Kartawiria (2021), the conversion rate of bioethanol cassava-based can reach 180 liters per ton. When considering the environmental impact of emissions, the comparison between gasoline and bioethanol is quite significant. However, emissions represent only the downstream environmental impact. To evaluate the overall environmental impact comprehensively, it is essential to include an assessment of the upstream processes and the entire life cycle of bioethanol.

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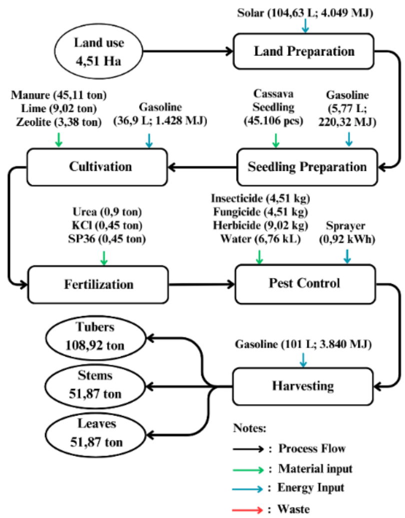

Figure 1. Plantation inventory flow diagram

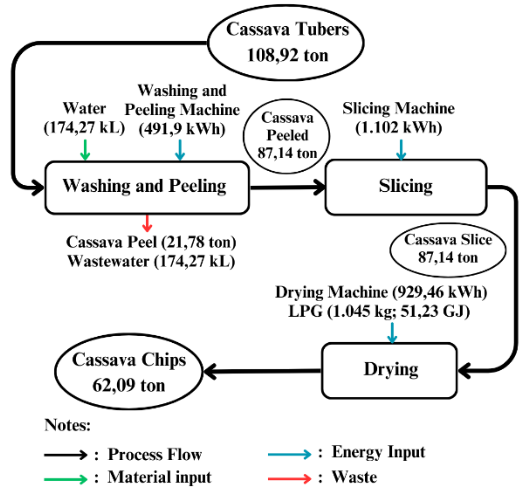

Figure 2. Chips processing inventory flow diagram

Previous research plays a significant role in advancing knowledge and differentiates from the current study. However, these studies yielded divergent conclusions, potentially due to differences in methodologies, scope, and system boundaries. This research references prior studies, including Papong and Malakul (2010), which conducted a life-cycle energy and environmental analysis of bioethanol production from cassava in Thailand using the LCA tool CML 2000. Another relevant study by Lyu et al. (2020) performed a life cycle assessment of bioethanol production from whole-plant cassava using an integrated process, focusing on a case study in China and utilizing GaBi software for LCA.

Both studies indicate points to specific aspects for improvement, particularly in the life cycle inventory, which lacks specificity and detail in collecting data such as cultivation, cassava chip processing, and ethanol production. Incomplete inventory data can impact the accuracy of environmental impact assessments. Then, these studies only report environmental emissions from a cradle-to-gate perspective, based on LCA software calculations. Therefore, the novelty of this research includes a focus on study case in Indonesia, with a more detailed life cycle inventory specifying all inputs and outputs for each process stage from cradle to gate. Additionally, this study calculates the exhaust emissions estimation of bioethanol at the downstream stage, using mass balance calculations to assess its feasibility for transportation use, particularly in motorcycles.

This research aims to conduct a Life Cycle Inventory (LCI), analyze the Life Cycle Impact Assessment (LCIA), and calculate the Specific Energy Consumption (SEC) of bioethanol production from cassava in Indonesia. It also analyzes the feasibility of bioethanol consumption in vehicle exhaust emissions.

2. Materials and Methods

The tools and materials used in this study include SimaPro software version 9.4.0.3, Microsoft Excel, and primary and secondary data obtained from various literature sources on the bioethanol life cycle and vehicle exhaust emissions in Indonesia.

The Life Cycle Assessment (LCA) method consists of four steps. The first step is the goal and scope definition. This LCA study aims to analyze the potential environmental impact of the life cycle of cassava-based bioethanol in Indonesia, with a focus on West Java. The scope of the study is cradle-to-gate, encompassing cassava cultivation, cassava chips production, bioethanol production, and product transportation. This study follows the guidelines outlined in SNI ISO 14040:2016 and SNI ISO 14044:2017.

The second step is Life Cycle Inventory (LCI) analysis, which involves quantification and compilation of data. This study focuses on a bioethanol production capacity of 100 liters per day, with a functional unit of 1 liter of bioethanol at 99% concentration. Cassava cultivation data is based on a case study in Cimanggu Village, Sukabumi, West Java, while bioethanol production data is from BSIP TRI Sukabumi. The quantification of data helps calculate the energy, material inputs, and outputs for each process. The third step is the Life Cycle Impact Assessment (LCIA). The LCIA of bioethanol is analyzed using ReCiPe 2016 Midpoint (H) (100 years impact measurement). The environmental impact categories studied include global warming potential (GWP), stratospheric ozone depletion (SOD), and terrestrial acidification (TAC). The last step is interpretation. Interpretation aims to analyze and discuss the collected data, including LCI and LCIA results. These results will be interpreted using contribution analysis (hotspot analysis).

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The specific energy consumption (SEC) method determines the energy required to produce bioethanol at each life cycle stage per 1 liter of bioethanol. The SEC calculation focuses on the energy content or heat energy of the fuels used (equation 1). The energy content for the fuels consists of solar 38.7 MJ/L (Kitani et al., 1999), gasoline 38.2 MJ/L (Kitani et al., 1999), LPG 49.14 MJ/kg (Prasetyo, 2023), and electricity 3.6 MJ/kWh (Kitani et al., 1999).

$$SEC\ in\ Joule\left(\frac{MJ}{L}\right) = \frac{Total\ main\ energy\ consumption\ (MJ)}{Total\ of\ bioethanol\ production\ (L)} \quad (1)$$

Emissions from material balance are determined by the amount of material entering the process, the amount leaving the process, and the products produced. Fuel analysis is an example of a material balance. Emissions are calculated by applying the law of conservation of mass. The presence of certain elements in in the fuel can be used to estimate the presence of those elements in the emission stream emissions (Deputy for Environmental Pollution Control, 2013). The emissions can be calculated using an emission mass balance approach, as shown in equation 2-4. This calculation is based on the concept of stoichiometry in combustion reactions, which measures the content of specific elements in the fuel to estimate the emissions that will be formed from combustion reactions.

$$Fuel\ mass\ flow\ rate\left(\frac{g}{h}\right) = Fuel\ consumption\left(\frac{L}{h}\right) \times Density\left(\frac{g}{L}\right) \quad (2)$$

$$Elemental\ mass_{(C,H,N,O,S)}\left(\frac{g}{h}\right) = Mass\ (\%) \times Fuel\ mass\ flow\left(\frac{g}{h}\right) \quad (3)$$

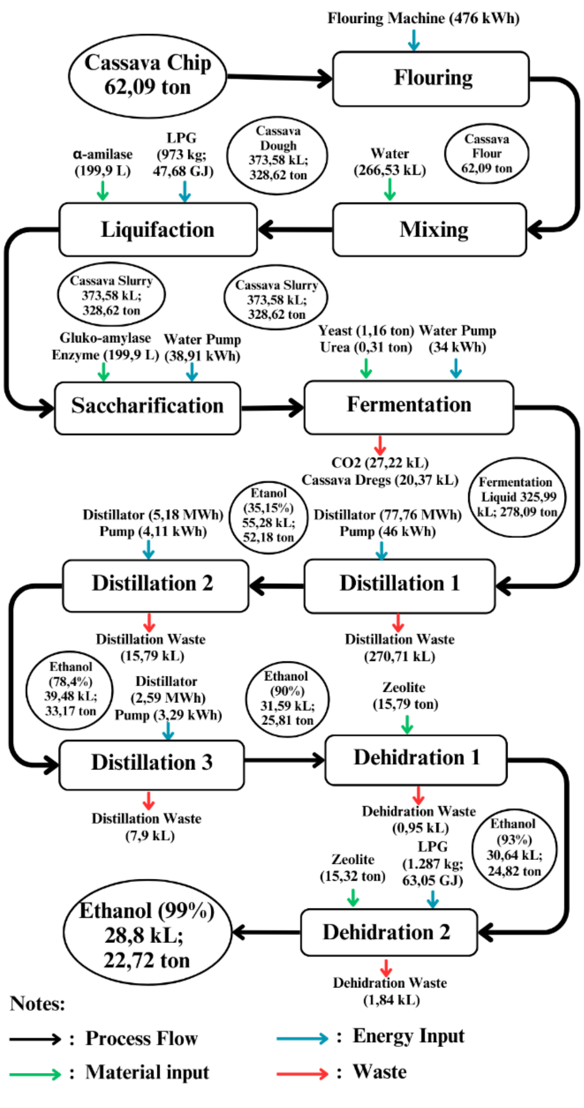

Figure 3. Bioethanol processing inventory flow diagram

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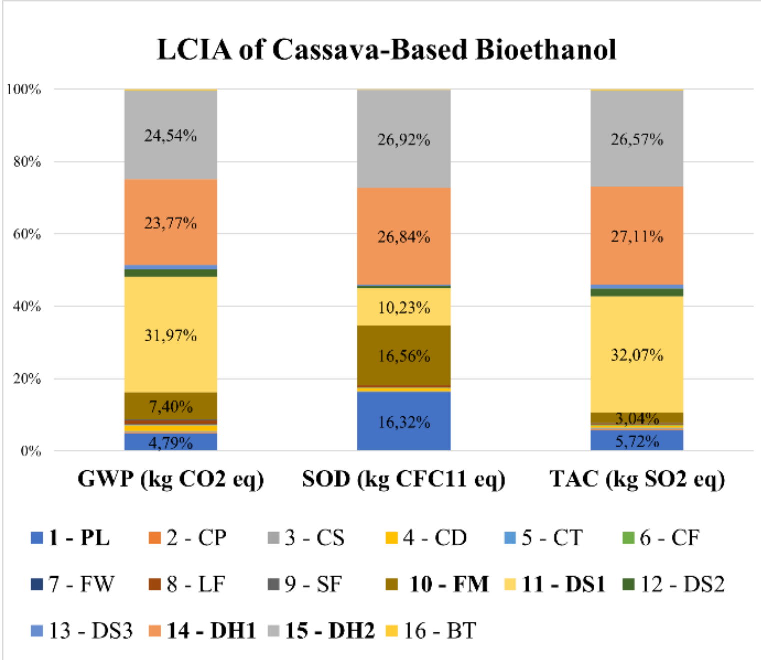

Figure 4. Process's contribution to each impact.

$$Emission\ mass\left(\frac{g}{h}\right) = \frac{Mr\left(\frac{g}{mol}\right)}{Ar\left(\frac{g}{mol}\right)} \times Elemental\ mass\left(\frac{g}{h}\right) \quad (4)$$

Certain assumptions will be made to approximate actual results. The emission calculations were obtained under two combustion conditions: emissions from complete combustion (CO_2, H_2O, SO_2) expressed in g/h (gram per hour) and emissions from incomplete combustion (CO and HC) expressed in % and ppm (part per million) as shown in equation 5-6. These emission results will be compared to the motor vehicle emission standards specified in the Ministry of Environment and Forestry Regulation 8/2023.

$$Carbon\ mass_{(complete\ combustion)}\left(\frac{g}{h}\right) = 90\% \times Carbon\ mass\left(\frac{g}{h}\right) \quad (5)$$

$$Carbon\ mass_{(incomplete\ combustion)}\left(\frac{g}{h}\right) = 10\% \times Carbon\ mass\left(\frac{g}{h}\right) \quad (6)$$

3. Results and Discussion

3.1. Life Cycle Inventory (LCI) Analysis

The inventory of main processes includes cassava cultivation, cassava chips production, bioethanol production, and transportation. The inventory analysis in this study is based on a bioethanol production capacity of 100 liters per day. **Table 1** presents the inventory for the main products.

Referring to **Table 1**, the quantification of the main products is based on the following yields: 0.464 liters of bioethanol per kilogram of cassava chips (Leng et al., 2008) and 0.57 kilograms of cassava chips per kilogram of tubers (Nugroho et al., 2018). The total cultivated area required is 4.51 hectares, based on a cassava tubers productivity of 24.15 tons per hectare in Cikembar, Sukabumi (BPS Sukabumi Regency, 2022). **Table 2** shows the specific inventories for input and output.

This is a flow diagram depicting the life cycle of bioethanol production from cassava, illustrating the mass or volume balance between input inventory and output at each process unit, as shown in **Figures 1, 2, and 3**.

The database sources used in SimaPro for the LCI of each input and output are summarized in **Table 3**. The LCI database indicates that the Ecoinvent 3 database is predominantly utilized because it offers diverse datasets and comprehensive global inventory coverage for all commodities.

3.2. Specific Energy Consumption (SEC)

Table 4 presents the results of the SEC calculation based on the total fuel energy consumption in the cassava

Table 1. Main products inventory.

Product	Per Day	Per Year
Fresh cassava tubers (tons)	0.45	108.92
Cassava chips (tons)	0.216	62.09
Bioethanol 99% (kL)	0.1	28.8

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Table 2. Detail input and output inventory

No	Input	Output	Total per Year	Unit	Amount per L Bioethanol	Unit
1.	Main raw material	Cassava seeds	45,100	pcs	1.56	pcs
		Cassava tubers	108.92	tons	3.78	kgs
		Cassava chips	62.09	tons	2.15	kgs
2.	Supporting raw material	Water	447.57	kL	15.54	L
		Alfa-amilase	199.90	L	0.007	L
		Gluko-amilase	199.90	L	0.007	L
		Animal manure	45.11	tons	1.57	kgs
		Urea	0.90	tons	0.03	kgs
		SP-36	0.45	tons	0.02	kgs
		KCL	0.45	tons	0.02	kgs
		Zeolite	34.49	tons	1.20	kgs
		Agricultural lime	9.02	tons	0.31	kgs
		Insecticide	4.51	kgs	$1.5x10^{-4}$	kgs
		Fungiside	4.51	kgs	$1.5x10^{-4}$	kgs
		Herbiside	9.02	kgs	$3.1x10^{-4}$	kgs
		Yeast	1.16	tons	0.040	kgs
		Urea	0.31	tons	0.011	kgs
3.	Electricity	Electricity	89.65	MWh	3.11	kWh
4.	Transportation	Chips distribution	1,055	tkm	0.04	tkm
5.	Liquid fuel	Gasoline	106.31	L	0.004	L
		Solar	141.54	L	0.005	L
6.	Gaseous fuel	LPG	2,260	kg	0.078	kg
7.	Main product and by-product	Bioethanol 99%	28.80	kL	1	L
		Cassava stems	51.87	tons	1.80	kgs
		Cassava leaves	22,55	tons	0.78	kgs
8.	Waste treatment	Cassava skin	21.78	tons	0.76	kg
		Cassava dregs	29.54	tons	1.03	kg
		DS & DH wastewater	81.76	kL	2.84	L
		Transportation to refineries	7,089	tkm	0.31	tkm

Table 3. LCI database sources

No	Database Sources	Dataset Amount
1.	*Database* Ecoinvent 3	16
2.	*Database* Agri-footprint	4
3.	*Database* USLCI	3

Table 4. SEC value in the cassava bioethanol life cycle

Main Fuel	Total Use	Unit	*Energy Content* (MJ/unit)	SEC per L Bioethanol (MJ/L)
Solar	141.54	L	38.7	0.19
Bensin	106.31	L	38.2	0.14
LPG	3,306	kg	49.14	5.64
Listrik	89.64	kWh	3.6	11.21
SEC Total (MJ/L bioethanol)				**17.18**

Table 5. Environmental impact categories analyzed

No	Impact Category	Code
1.	Global Warming Potential	GWP
2.	Stratospheric Ozone Depletion	SOD
3.	Terrestrial Acidification	TAC

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Based on **Table 4**, the SEC value of the primary energy sources in the bioethanol life cycle, including diesel fuel, gasoline, LPG, and electrical energy, is 17.8 MJ per liter of bioethanol produced.

3.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) focuses on three environmental impact categories and evaluates 16 specific processes, including cassava cultivation, chips production, bioethanol production, and transportation. **Table 5** presents the environmental impact categories, and **Table 6** presents the specific processes.

Table 7 shows the total environmental impact for all main processes, presented annually and per liter of bioethanol. **Figure 4** shows the percentage contribution of each process to each impact category. **Table 8** shows each process's impact value over its annual life cycle.

3.3.1. Global Warming Potential (GWP)

Global warming potential (GWP) contributes

Table 6. The specific processes assessed

Nr.	Process	Code
1.	Plantation	PL
2.	Cassava-skin Peeling	CP
3.	Cassava Slicing	CS
4.	Cassava Drying	CD
5.	Chips Transportation	CT
6.	Chips Fouring	CF
7.	Flour Watering	FW
8.	Liquification	LF
9	Saccharification	SF
10	Fermentation	FM
11	Distillation 1	DS1
12	Distillation 2	DS2
13	Distilation 3	DS3
14	Dehidration 1	DH1
15	Dehidration 2	DH2
16	Bioetanol Transportation	BT

Table 7. The total environmental impact

Impact Category	Unit	Total per Year	Total per L Bioethanol
GWP	kg CO_2 eq	342,221	11.88
SOD	kg CFC11eq	0.17	$5.9x10^{-6}$
TAC	kg SO_2 eq	1,285	0.04

Table 8. The specific impact of each process per year

Year	Code	GWP	SOD	TAC
1	PL	16,378	0.027	73.48
2	CP	783	1.4×10^{-4}	2.97
3	CS	1,548	2.4×10^{-4}	5.84
4	CD	5,418	1.4×10^{-3}	7.75
5	CT	183	6.5×10^{-5}	0.70
6	CF	669	1.0×10^{-4}	2.52
7	FW	49	1.4×10^{-5}	0.30
8	LF	4,067	1.1×10^{-3}	2.91
9	SF	880	4.9×10^{-12}	1.80
10	FM	25,326	2.7×10^{-2}	39.06
11	DS1	109,404	1.7×10^{-2}	412.27
12	DS2	7,294	1.1×10^{-3}	27.49
13	DS3	3,649	5.6×10^{-4}	13.75
14	DH1	81,353	4.4×10^{-2}	348.42
15	DH2	83,990	4.4×10^{-2}	341.52
16	BT	1,228	4.4×10^{-4}	4.68

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342,221 kg CO2 equivalent per year, or 11.88 kg CO_2 eq per liter of bioethanol, as detailed in **Table 7**. According to the impact percentage graph in **Figure 4** and the specific impact in each process in **Table 8**, the process units with the highest contributions are distillation 1 (DS1) with 109,404 kg CO_2 eq (31.97%), dehydration 2 (DS2) with 83,990 kg CO_2 eq (24.54%), and dehydration 1 (DH1) with 81,353 kg CO_2 eq (23.77%).

Further analysis using SimaPro characterization shows that the significant GWP contribution from distillation 1 (DS1) is primarily due to 99% of the impact of distillatory electrical energy consumption. The impact of dehydration 2 (DH2) is mainly attributable to 93% of zeolite use and 6% of LPG consumption. In dehydration 1 (DH1), the impact is also predominantly due to zeolite use, contributing 99% CO_2.

3.3.2. Stratospheric Ozone Depletion (SOD)

Stratospheric ozone depletion (SOD) contributes 0.17 kg CFC-11 eq per year, or 5.9 x 10^{-6} kg CFC-11 eq per liter of bioethanol, as shown in **Table 7**. **Figure 4** illustrates that the most prominent contributions come from dehydration 2 (DH2) (0.04 kg CFC-11 eq, 26.92%), dehydration 1 (DH1) (0.04 kg CFC-11 eq, 26.84%), fermentation (0.03 kg CFC-11 eq, 16.56%), and cassava tubers cultivation (0.03 kg CFC-11 eq, 16.32%).

The high SOD impact in dehydration 2 (DH2) and dehydration 1 (DH1) is due to 99% contribution from zeolite use. In fermentation, yeast use (53%) and cassava pulp waste (35%) are major contributors. For cassava tubers cultivation, the largest contributions are from urea fertilizer (26%), zeolite use (18%), KCl fertilizer (17%), and SP-36 fertilizer (13%).

3.3.3. Terrestrial Acidification (TAC)

Terrestrial acidification (TAC) contributes 1,285 kg SO_2 eq per year, or 0.04 kg SO_2 eq per liter of bioethanol, as detailed in **Table 7**. **Figure 4** indicates that the process units with the highest contributions are distillation 1 (DS1) (412.27 kg SO_2 eq, 32.07%), dehydration 1 (DH1) (348.42 kg SO_2 eq, 27.11%), and dehydration 2 (DH2) (341.52 kg SO_2 eq, 26.57%).

The significant TAC impact from distillation 1 (DS1) is due to 99% of the impact from electricity and pump use. The impact of dehydration 1 (DH1) is attributed to 99% of zeolite use. In dehydration 2 (DH2), the contribution is 98% from zeolite use and 1% from LPG use.

3.3.4. Hotspot Process Involved in Environmental Impact

Distillation is the first hotspot process impacting GWP and TAC due to electricity consumption. Based on SimaPro analysis calculation, for every 1 kWh produced, the potential contribution is 1.40 kg CO_2 eq and 0.0052 kg SO_2 eq, which are largely driven by electricity generation. This electricity is produced through the combustion of fossil fuels, which generates key emissions, including carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) (Triatmojo et al., 2024).

Dehydration is the second hotspot process impacting GWP, SOD, and TAC. For every 1 kg produced, the contributions are 5.15 kg CO_2 eq, 2.81x10^{-6}

Table 9. Ultimate analysis of gasoline (Gaur & Reed, 1998)

Elements	%	Mass (g/h)
C	85.50	422.01
H	14.40	71.08
N	0.00	0.00
S	0.10	0.49
O	0.00	0.00

Table 10. Ultimate analysis of bioethanol (Gaur & Reed, 1998)

Elements	%	Mass (g/h)
C	52.20	276.05
H	13.00	68.75
N	0.00	0.00
S	0.00	0.00
O	34.80	184.04

Table 11. Comparison of CO and HC emissions in gasoline, bioethanol, and emission standard (Ministry of Environment and Forestry of the Republic of Indonesia No. 8 of 2023)

Parameter	Gasoline	Bioethanol	Emission Standards
CO (%)	3.26	2.85	3.00
HC (ppm)	5.99	5.23	1000

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kg CFC-11 eq, and 0.022 kg SO_2 eq, largely driven by zeolite production activities. The zeolite production process requires significant energy, particularly for heating during the synthesis or drying stages. The use of fossil-based fuels in zeolite production leads to the combustion of these fuels, resulting in the release of GWP and TAC emissions: carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NOx). In terms of SOD emissions, it results from the use of chemicals in zeolite synthesis, including compounds that can damage the ozone layer, such as chlorofluorocarbons (CFCs) (Yancey et al., 2022).

The results of this study are similar to those of Papong and Malakul (2010), both indicating that 90% to 93% of the global warming impact from the hotspot controbution, ethanol production. Besides, when comparing the findings with those of Lyu et al. (2020), differences in impact values are observed. Lyu et al. reported a global warming potential of approximately 1.73 kg CO_2 per liter of bioethanol and an acidification potential of 0.0043 kg SO_2 per liter. In this study, the global warming potential is 11.88 kg CO_2 per liter, and the acidification potential is 0.04 kg SO_2 per liter. These differences can be attributed to several factors. One possible reason is the difference in the life cycle inventory data compilation, as indicated by variations in energy consumption. Lyu et al. (2020) reported a specific energy consumption (SEC) of around 7.99 MJ/L, while this study recorded an SEC of 17.18 MJ/L. Additionally, the life cycle impact assessment methodologies differ; this study used the ReCiPe Midpoint H method, whereas Lyu et al. (2020) employed the CML 2016 method.

3.4.Vehicle Emissions Feasibility Analysis

Emission calculations using mass balance were conducted based on the ultimate fuel analysis. According to BPS (2023b), the growth rate of motorcycles in Indonesia reached 4.11%, making them the most prevalent type of vehicle compared to others. Therefore, this emission calculation focuses on motorcycle transportation. In this calculation, a combustion efficiency of 90% is assumed. The accumulated emissions come from complete combustion (CO_2, H_2O, SO_2) and incomplete combustion (CO and HC), as shown in **Table 9**.

For motorcycles commonly used in Indonesia, with an average engine speed of 4,000 rpm, gasoline (C_8H_{18}) consumption is 0.667 L/h (liter per hour) (Rifal & Rauf, 2018) and density of 740 g/L (gram per liter) (Ejilah et al., 2017) the mass of each element contained in the fuel can be calculated.

The emissions produced from the complete combustion of gasoline include 1,392.64 g/h of CO_2, 639.68 g/h of H_2O, and 0.99 g/h of SO_2. For the emissions resulting from incomplete combustion, it is assumed that 10% of the unburned fuel results in 7% CO and 3% HC. This yields emission results of 3.26% CO (68.93 g/h) and 5.99 ppm HC (12.66 g/h).

Subsequently, calculations were performed to switch fuel from gasoline to bioethanol, as shown in **Table 10**. Since bioethanol has a different calorific value than gasoline, with the same condition, the fuel consumption is 0.678 L/h (Rifal & Rauf, 2018), and density of 780 g/L (Ejilah et al., 2017).

The emissions produced from the complete combustion of bioethanol fuel include 910.08 g/h of CO_2 and 618.74 g/h of H_2O. Meanwhile, the emissions resulting from incomplete combustion include 2.85% CO (45.09 g/h) and 5.23 ppm HC (8.29 g/h). Based on these emission results, the types of emissions that can be compared and regulated are those from incomplete combustion (CO and HC).

Compared to the motor vehicle emission standards regulation shown in **Table 11**, the CO levels from gasoline are still above the standard, whereas the CO emissions from bioethanol are lower. In contrast, the HC emissions from both fuels are well below the standard. Additionally, bioethanol does not produce SO_2 emissions due to the absence of sulfur in this biofuel.

4. Conclusion

The inventory for the cassava-based bioethanol life cycle produced 28.8 kL/year and the total specific energy consumption (SEC) is 17.18 MJ/L. The environmental impacts per liter of bioethanol are as follows: GWP of 11.88 kg CO_2 eq; SOD of 5.9×10^{-6} kg CFC-11 eq; and TAC of 0.04 kg SO_2 eq. The emission results from gasoline use do not meet the emission standards for the CO parameter, while the emission results from bioethanol are lower than those from gasoline.

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