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Research Paper

# Life cycle assessment of citronella Oil supply Chain: A comparative two production process methods

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ABSTRACT

Generally, the production processes of citronella (Cymbopogon Nardus) oil refining in Aceh are traditionally carried out, making them less efficient in resource usage. Every activity along the citronella supply chain has an environmental impact due to raw materials, water, and energy resources. Therefore, this study aimed to assess the environmental impacts caused by activities along the citronella oil supply chain based on a life cycle assessment framework. We compared two production process methods, namely a distillation system with one boiler for one kettle and one boiler for three kettles. The environmental impacts measured include greenhouse gas emissions, global warming potential, land use, and air acidification. Research stages involved determining goal and scope, data collection, environmental impact measurement, interpretation, and proposals for improving the production process. The results showed that the production process of a single boiler system for three kettles had an environmental impact lower than the other method. Furthermore, the distillation process and solid waste combustion have a significant impact on the environment, hence they need to be improved. This life cycle assessment of the citronella oil supply chain is the basis for enhancing the production process to reduce environmental impact.



## 1. Introduction

Agriculture-based industries always need to consider the environmental impacts of their activities due to various resources such as energy, water, and land for the continuous supply of raw materials. Therefore, irrespective of the economic profitability of an organization, it can also have negative social impacts on the surrounding community. Citronella industries have high economic value, which involves many actors, namely farmers as raw materials suppliers, processing industries, collectors, and traders or exporters. However, in Aceh, the citronella oil (Cymbopogon Nardus) refining is still carried out using a traditional process that leads to low productivity. This process also causes waste of resources with numerous negative impacts on the environment. Citronella oil is one of the essential oils obtained from the distillation of the leaves and stems of citronella (Cymbopogon Nardus). It has been widely used for various human needs, such as aromatherapy ingredients, room deodorizers, respiratory stimulants, massage oils, insect repellents, beauty products, stress relievers, perfumes, traditional medicines, and fuel oil bio-additives [1]. Generally, citronella oil production yields an average of approximately 1% of the raw materials used, which means that 99% of the produce is waste capable of negatively impacting the environment. Moreover, these raw materials require a large area of land for proper disposal, which can also damage forests. Based on observations, activities along this supply chain tend to impact the environment in solid and liquid waste and gas emissions due to energy sources, water, machinery, and electricity. Inefficient use of resources leads to emissions (waste) and losses capable of polluting the surrounding environment. Therefore, life cycle assessment (LCA) framework can be used to analyze the environmental impacts caused by industrial activities. This method is a mechanism used to analyze and calculate the total environmental impact for each stage of a product life cycle. It starts from preparing raw materials, production processes, sales and transportation, and product disposal [2]. Preliminary studies on citronella oil-focused mainly on its benefits [3, 4] and process technology developments [5]. Moncada et al. (2014) [6] measured the environmental impact of citronella oil production on a laboratory scale, analyzing the added value and financial feasibility of the industry [7, 8], the economics [8], testing the character in the form of nano-emulsion to repel mosquitoes [3], and describing the chemical composition and its antifungal activity [4]. Others include measuring its environmental impact on a laboratory scale during production [6], determining the amount of essential oil in various parts of the plant [9], explaining the business and challenges of essential oil sustainability in Indonesia [10], testing its effectiveness with one and two furnaces [5], the assessing environment impact of chemical fertilizers industry in Iraq [11], analysing environmental value chain of water supply [12], and recycling old rubber tire to decrease the problem of environment [13]. LCA is an approach used to analyze the impact of a product on the environment during its life cycle [14]. Several preliminary studies on LCA in numerous essential or vegetable oils carried out on palm oil [15–19], canola oil [20], olive oil [21–24], linseed oil [16, 25], and sunflower oil [26]. However, no study has been conducted on the environmental impact of the citronella oil supply chain activities. This study uses two methods to analyze the life cycle assessment framework of citronella oil. The first method is a distillation system of one boiler for one kettle, and the second uses one boiler for three kettles. This assessment is the basis for policymakers, producers, and consumers choosing the products and manufacturing processes sustainable for the environment. Subsequently, this study aimed to measure the environmental impact of the citronella oil supply chain and process production by comparing the two methods before providing recommendations to reduce the environmental effects.

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**Nomenclature**

| | | | |
|---|---|---|---|
| *BOD* | Biological oxygen demand | *NCV* | Net calorific value |
| *COD* | Chemical oxygen demand | *GHG* | Greenhouse ga |
| *LCA* | Life cycle assessmen | *GWP* | Global Warming Potentia |
| *ha* | Hectare | | |

## 2. Materials and methods

Data were collected from primary and secondary sources. Primary data were sourced from field observations at the citronella oil mill in Bener Meriah and Aceh Utara, Aceh, Indonesia. Currently, there are numerous citronella oil factories in Bener Meriah Regency, Aceh; however, some operate intermittently. We selected production sites that operate consistently and were willing to provide the required data, including details on the production process flow, raw material requirements, types of energy used, and the quantity of energy consumed. We collected those data for 3 days or 5 times production to know the amount of energy used. Furthermore, the parameters of waste condensate water were tested on as many as 3 samples at the chemical laboratory of Polytechnic Lhokseumawe. The parameters were pH, Fe, Mg, chemical oxygen demand (COD), and biological oxygen demand (BOD). Secondary data sourced from literature are in the forms of net calorific value and gas emission factors. Those data used in this study were primarily obtained from internationally recognized databases (IPCC, 2006; ISO 14044, 2006) and relevant literature. Although these references provide globally accepted default values, region-specific data for Aceh, Indonesia, are not yet available. Therefore, the selected factors were considered as the most suitable proxies for this analysis. Such an approach is also consistent with LCA studies conducted in developing countries where localized emission databases are still limited. Meanwhile, transportation distance from resources to the mill was measured using google maps.

## 3. Results and discussion

### 3.1 Citronella oil supply chain

This study analysed the supply chain of citronella oil in two production areas located in Bener Meriah district and North Aceh. This supply chain generally involves several actors, namely farmers, processors, collectors, traders, and exporters Fig. 1. As providers of raw materials, farmers can sell citronella leaves to the processing industry or process them before being sold to collectors. Generally, farmers rent equipment and processing facilities at a fee, depending on the amount produced. The citronella oil produced is then purchased by the collectors to be sold to exporters. Furthermore, small-scale processing industries also can sell this oil directly to exporters or collectors through medium scale industries depending on the output produced.

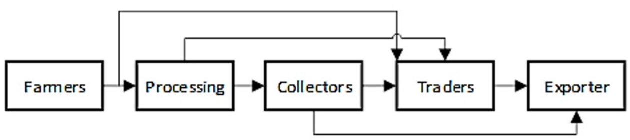


**Figure** 1. Citronella oil supply chain.

### 3.2 The technology of production process

This study compares the environmental impact of the supply chain of two citronella oil distillation methods. The difference between them is in the distillation system. The first method uses a boiler for one kettle whereby the furnace, boiler, and kettle are arranged vertically and fused Fig. 2. The second method uses one boiler for several boilers, with the furnace and boiler placed separately from the kettle Fig. 3.

### 3.3 Production process

Citronella leaves as raw material were harvested, dried in the sun for approximately 1-2 days (depending on sun conditions), and distilled as indicated in the following process.

- Add some quantity of water to a kettle.
- Put the leaves into the kettle until it is complete and then close tightly.
- Channel the steam is coming out of the kettle through the pipe to the condenser section.
- The hot steam is condensed into a liquid to separate the oil and water.
- The condensate water is discharged into the drain, and the oil on the surface water is stored in a container.

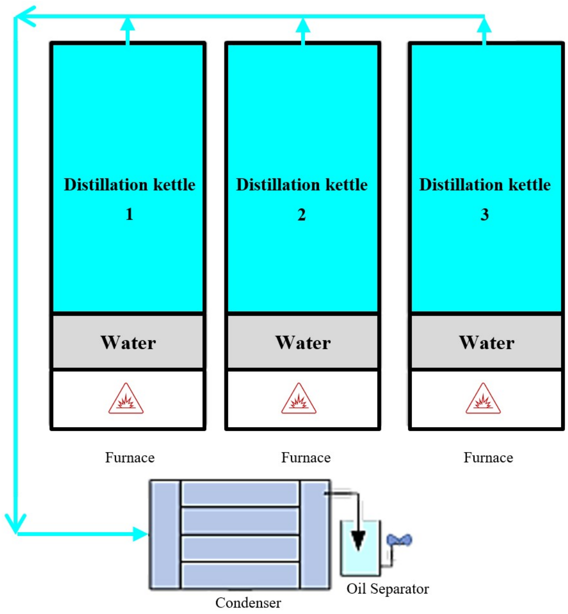


**Figure** 2. Production process of citronella oil for method 1 (one boiler for one kettle).

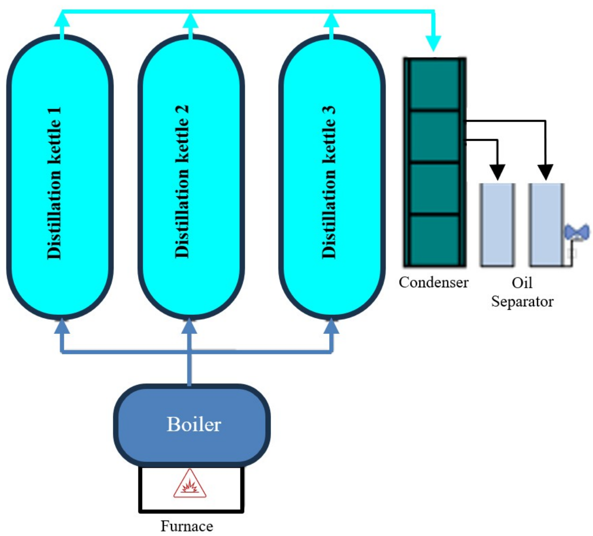


**Figure** 3. Production process of citronella oil for method 2 (one boiler for three kettles).

### 3.4 Life cycle assessment of citronella Oil

#### 3.4.1 Goal and scope

The purpose of in this study is to assess environmental impact through the citronella oil-supply chain activities for the two production process methods based on LCA framework. The measured environmental impacts include greenhouse gas emissions, global warming potential, land use, and acidification. Two production process methods were studied, namely 1) one boiler for one boiler and 2) one boiler for three boilers Fig. 2 and 3. The scope of the system studied is starting from citronella cultivation, processing to agents. Citronella is a plant that can be harvested repeatedly, in general every three months. The scope of cultivation studied in this study is from the harvesting process to the next harvest. After harvesting, farmers carry out maintenance to prevent grass growth by giving herbicides.

### 3.4.2 Definition of functional unit

For consistency, the parameters and units used for this assessment were determined. Table 1 shows the parameters and units applied in this study for both methods. In this study, the amount of resources required to refine citronella oil is based on the production of 1,000 kg of citronella oil. This functional unit is based on real production scales, specifically the number of deliveries to the collecting agent. The average daily production capacity is 66 kg of citronella oil, which means it takes 16 days to produce this amount. Resource requirements to produce 1000 kg of citronella oil as shown in Table 2.

### 3.4.3 Input-output allocation

The allocation of inputs and outputs is based on all required materials produced from farmers to exporters during the citronella oil-supply chain activities. The allocation of input-output and the production processes for 2 methods are similar. Besides gas emissions, processing activities produce solid and liquid waste that negatively impacts the environment.

**Table 1.** The parameters and units applied in this study.

| Type of Operation | Type of Resources | Units |
|---|---|---|
| Citronella agricultural | Land | *ha* |
| Plant cultivation | Herbicide | *liter* |
| Transportation from agricultural to mill | Biodiesel | *kg* |
| Input | Citronella grass | *kg* |
| | Condenser cooling water | $m^3$ |
| | Boiler water | $m^3$ |
| Distillation process | Wood biomass | *kg* |
| | Electricity | *kwh* |
| Water pump | Electricity | *kwh* |
| Transportation from mill to agent | Biodiesel | *kg* |
| Transportation from biomass to mill | Biodiesel | *kg* |
| Electricity used (others) | Electricity | *kwh* |
| Output | Citronella oil | *kg* |
| | Liquid waste | $m^3$ |
| | Solid waste | *kg* |

**Table 2.** Resource requirements to produce 1000 *kg* of citronella oil.

| Type of Resources | Units | Method 1 | Method 2 |
|---|---|---|---|
| Land | *ha* | 37.50 | 37.50 |
| Herbicide | *liter* | 225.00 | 225.00 |
| Biodiesel | *kg* | 71.66 | 71.66 |
| Citronella grass | *kg* | 100,000 | 100,000 |
| Condenser cooling water | $m^3$ | 1234.29 | 1944 |
| Boiler water | $m^3$ | 124.56 | 117.975 |
| Wood biomass | *kg* | 53,570 | 41,670 |
| Electricity | *kwh* | 252.00 | — |
| Electricity | *kwh* | — | 281.61 |
| Biodiesel | *kg* | 62.10 | 83.82 |
| Biodiesel | *kg* | 34.125 | 10.23 |
| Electricity | *kwh* | 14.112 | 17.64 |
| Citronella oil | *kg* | 1000 | 1000 |
| Liquid waste | $m^3$ | 1358.85 | 2061.98 |
| Solid waste | *kg* | 99000 | 99000 |

### 3.4.4 Life cycle inventory (LCI)

In this section, we collected data regarding the resources needed to carry out activities along the citronella oil supply chain, from farmers to exporters. According to Sukamto et al. (2011), [27], the average yield of citronella oil is between 0.8-1.2%. Based on observations and interviews with citronella oil processing actors for the two production process methods, there is no significant difference in the amount of yield produced. In this study, to simplify the analysis, we assumed the yield of citronella oil produced for both methods is 1%. Before being processed, the raw materials were dried in the sun for 1-2 days, where they still contained 62.02% water [28]. The resource requirements needed to produce 1000 kg of citronella oil can be seen in Table 1. The three outputs resulting from the distillation process are citronella oil, solid waste, and liquid waste. The net calorific value (NCV) is needed for each energy used to measure the environmental impact. Gas emissions from electricity use are based on missions generated at power plants. Generally, power plants in Indonesia use steam power, where coal is the source of fuel. The NCV and emission factors of each gas produced can be seen in Table 3. From observations on the supply chain activities of citronella oil for both methods, we identified that the sources of greenhouse gas (GHG) emissions are transportation, distillation, electricity use, and solid waste combustion. We used data from Table 4 to calculate emissions from each activity by multiplying fuel consumption by NCV and the emission factor.

**Global Warming Potential (GWP):**
GWP is a measure to compare the potential of GHG in heating the earth for a certain period and is equated with the potential value of $CO_2$ gas. The greater the GWP, the more significant the role of the gas in global warming in a certain period. The GWP value can be used to convert non- $CO_2$ emission data into $CO_2$ equivalent emission data ($CO_2$eq). In this study, the conversion factor of non-$CO_2$ to $CO_2$eq gas based on IPCC-SAR (1995) is the GWP value of $CH_4$ and $N_2O$ emissions, respectively 21 and 310. The GWP value in the citronella oil supply chain for both methods can be seen in Appendix 1. Appendix 1 and Fig. 4 show that the citronella oil-production process for method 1 has a higher total GWP than method 2. This is because method 1 still uses the traditional distillation system, one furnace for one kettle. This system requires more wood fuel because it has to operate three stoves to cook three boilers. The supply chain activity with the largest GWP comes from the distillation process, both methods 1 and 2. This matter is because this activity requires a large amount of biomass fuel, so it produces massive gas emissions. In the distillation process, the GWP value of method 1 is higher than method 2. This indicates that the use of fuel in method 1 is greater than method 2. The second largest GWP generated from solid waste combustion activities. This is because the production process only produces 1% citronella oil from the total input of raw materials, and the remaining 99% becomes waste. Both production process methods deal with solid waste by burning it openly.

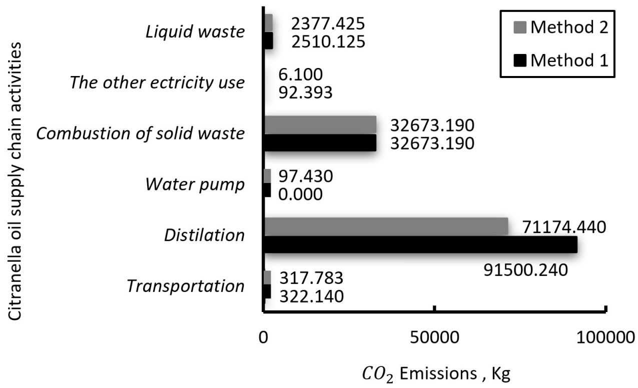


**Figure 4.** Global warming potential.

**Acidification Potential**:
Acidification is the process of acidification of the air derived from gas emissions of $SO_2$, $NOx$, and $NH_3$ converted to $SO_2$ (eq). According to Heijungs et al. (1992) [29], we can obtain the conversion value to $SO_2$ (eq) by converting 1 kg NOx to 0.7 kg $SO_2$ (eq) dan 1 kg NH3 to 1.88 kg $SO_2$ (eq). Table 4 shows emission factors of $SO_2$ and NOx based on IPCC (2006). The amount of energy consumption is multiplied by the net calory value and the emission factor, thereby leading to gas emissions, which cause acidification. Furthermore, the acidification potential is obtained by multiplying it by the equivalent $SO_2$ conversion factor Fig. 5. Figure 6 shows the highest acidification potential in the distillation process for methods 1 and 2. Method 1 produces greater $SO_2$ gas emissions than method 2 because the distillation system is less efficient, using 1 boiler to heat 3 kettles.

**Land Use:**
Determination of emissions on land use is based on the amount of carbon stock obtained from above and below-ground biomass. The higher the amount of biomass on the land, the higher the carbon stock. The amount of carbon stock in living plant bodies (biomass) in land can describe the amount of $CO_2$ in the atmosphere that plants absorb. Citronella is a type of plant whose maintenance does not require the application of fertilizers or pesticides. The use of citronella land is is categorized as uncultivated agricultural land so that the carbon stock based on IPCC (2006) is 50.74 tons ($C/ha$) for 50 years. From Table 3, we can see that the citronella land area of 37.5 ha was able to absorb or reduce GHG emissions by 34,883.75 kg $CO_2$. Reducing GHG emissions from agricultural

**Table 3.** Conversion net calorie value and emission factors.

| No. | Inventory | Net calorie valu | Emission factor | | | Sources |
|---|---|---|---|---|---|---|
| | | | $CO_2$ | $CH_4$ | $N_2O$ | |
| 1 | Biodiesel | 27 TJ.Gg-1 | 70.800 Kg $CO_2$ TJ-1 | 3 Kg $CH_4$ TJ-1 | 0.6 Kg $N_2O$ TJ-1 | [30] |
| 2 | Biomass | 0.000015 TJ.Kg-1 | 112.000 Kg $CO_2$ TJ-1 | 30 Kg $CH_4$ TJ-1 | 4 Kg $N_2O$ TJ-1 | [30] |
| 3 | Electricity | — | 96100 Kg $CO_2$ TJ-1 | 1 Kg $CH4$ TJ-1 | 1.5 Kg $N_2O$ TJ-1 | [30] |
| 4 | Combustion of wood | — | 0.1 Kg $CO_2$ Kg-1 | 0.033 Kg $CH_4$ Kg-1 | — | [31] |
| 5 | Liquid waste | — | — | 0.21 kg $CH_4/kg$ COD | — | [30] |

land use for method 1 to 92,214.338 kg $CO_2$ eq and method 2 to 71,762.618 $CO_2$ eq.

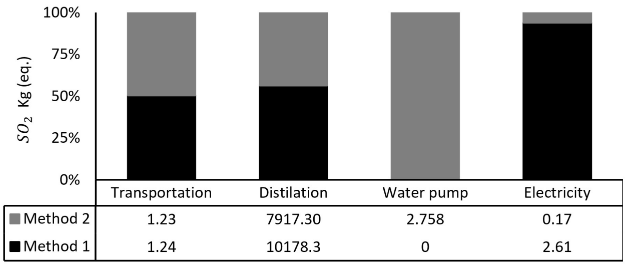


**Figure 5.** Acidification potential of citronella oil supply chain activities.

**Table 4.** Emission factors of $SO_2$ and $NOx$ based on IPCC (2006).

| Type of Resources | Emission factors | | |
|---|---|---|---|
| | $SO_2+SO_3$ | $NOx(Kg/TJ)$ | $NH_3$ |
| Biodiesel | n.a | 146 | n.a |
| Wood | 0.20% | 100 | n.a |
| Electricity | 8.1 gr $SO_2/kwh$ | 250 | n.a |

3.4.5 Interpretation

Based on the environmental impact assessment of activities through the citronella oil supply chain, methods 1 and 2 show that the distillation process produces high GHG emissions. Therefore, the distillation process needs to be considered or prioritized for improvement. From the calculation of environmental impacts, method 2 has a lower global warming and acidification potential than method 1. Subsequently, to reduce emissions, the production process of method 1 needs to be replaced by method 2 because it is more efficient. Another alternative to reduce GHG emissions from the distillation process is to replace fuel with other options. For example, we use natural gas instead. Based on the IPCC (2006) [32], we found that the emission factors for $CO_2$, $CH_4$, and $N_2O$ gas for the use of natural gas were 15.3 $kg/GJ$, 19.807 $kg/TJ$, and 0.204 $kg/TJ$, respectively. From this value, the GWP for natural gas was obtained as shown in Table 5. Several alternatives for solid waste treatment can be carried out to reduce the environmental impact. In this study, we compared enclosed and open composting systems. Estimating GHG emissions for both methods uses the upper limit of emission factors sourced from the IPCC (2006) [32]. The results of the calculation of GHG emissions for the two alternative solid waste composting technologies in Table 6 show that the emissions are the smallest when using composting with a closed system. Therefore, the closed composting method is an alternative to reduce GHG emissions from burning solid waste. Furthermore, closed-system composting can produce high-quality compost that can be used as organic fertilizer. Previous research has shown that this system not only reduces waste but also improves soil fertility, which can subsequently increase citronella yields [8]. The GHG emissions results for the proposed improvement of the production process by replacing wood fuel with natural gas and performing closed composting of solid waste are shown in Table 7. The GHG emissions of the proposed improvement show a reduction of 81.41% for method 1 and 80.61%. The proposed improvement does not take into account the costs incurred to replace wood fuel with natural gas. Suppose the use of natural gas is expensive and increases operational costs. In that case, the decision-maker can increase the efficiency of the boiler furnace, thereby reducing the use of biomass. It should be noted that the emission factors and net calorific values applied in this study were not derived from direct measurements in Aceh but from global default references (IPCC 2006, ISO 14044, etc.). While these sources are widely recommended when local data are unavailable, the results may differ if region-specific factors are developed in the future. Consequently, the findings presented here should be interpreted as indicative rather than absolute values, and future research is encouraged to establish local emission databases for citronella oil production in Aceh, Indonesia.

**Table 5.** GWP for natural gas usage.

| Type of Resources | Method 1 | Method 2 |
|---|---|---|
| NCV of Natural Gas grass | 48 TJ/Gg | 48 TJ/Gg |
| Natural Gas Requirement | 16741 kg | 13022 kg |
| $CO_2$ Emission (kg) | 12,294.59 | 9563.357 |
| $CH_4$ Emission (kg) | 15.916 | 12.380 |
| $N_2O$ Emission (kg ) | 0.164 | 0.1275 |
| GWP (kg) $CO_2, eq.$ eq | 12679.67 | 9862.862 |

**Table 6.** Estimation GWP from solid waste composting.

| Technology alternatives | Enclosed composting | Open composting |
|---|---|---|
| Emission factor for $CH_4$[30] | 5-46 kg $CO_2$-eq/ton wet waste | 0.8-169 kg $CO_2$-eq/ton wet waste |
| Emission factor for $N_2O$ [30] | 0.3-35 kg $CO_2$-eq/ton wet waste | 57-165 kg $CO_2$-eq/ton wet waste |
| Amount of solid waste (ton) | 99 | 99 |
| $CH_4$ emission (kg $CO_2$-eq) for upper limit | 4554 | 16731 |
| $N_2O$ emission (kg $CO_2$-eq) for upper limit | 3465 | 16335 |
| GWP (kg $CO_2$-eq) | 8019 | 33066 |

**Table 7.** GHG emissions proposed for improvement of production processes.

| Activities | Input | Emission factors | |
|---|---|---|---|
| | | Method 1 | Method 2 |
| Transportation | Biodiesel | 322.14 | 317.783 |
| Distillation | Natural gas | 12679.67 | 9862.862 |
| Water pump | Electricity | 0 | 97.43 |
| Enclosed is composting for solid waste | Solid waste | 8019.00 | 8019.00 |
| Other electricity use | Electricity | 92.393 | 6.1 |
| Liquid waste | Liquid waste | 2510.13 | 2377.43 |
| **Total** | | 23623.33 | 20680.60 |
| **Percentage of emission reduction** | | 81.41% | 80.61% |

## 4. Conclusions

There are two methods of citronella oil production process studied, namely the first method using one boiler for one kettle and the second method using one boiler for three kettles. Method 1 has a greater potential for global warming and acidification than method 2. This is because the energy use of method 1 is greater than that of method 2. Meanwhile, environmental impact reduction is possibly conducted by increasing the combustion efficiency of the distillation process or replacing wood biomass fuel with natural gas. Solid waste that is usually burned can also be used as products with added value, such as organic fertilizer, animal feed, briquettes, and biogas. This research is limited by its focus on Aceh. We encourage further studies in other regions with different conditions to investigate how traditional practices in Aceh can be modified or integrated with modern technologies, thereby broadening the applicability of the findings. Further research is then recommended to consider environmental impacts and financial analysis of other energy replacements and solid and liquid waste treatment.

### Authors' contribution

The authors contributed to the conceptualization, methodology, and analysis of the research presented in this article. Trisna was responsible for the study design, the data analysis, and initial manuscript drafting. Muhammad Zakaria contributed to the data collection, data analysis, interpretation of results, and manuscript revision. Mochamad Ari Saptari helped refine the final manuscript. All authors reviewed and approved the final manuscript before submission.

### Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article. The authors have not received any financial support for the research, authorship, and/or publication of this article. The authors have no financial or personal relationships with other people or organizations that could inappropriately influence or bias the content of the work.

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### Data availability

All data supporting the findings of this study are available from the corresponding author upon reasonable request. Raw data and analysis documentation can be provided to interested parties seeking to replicate or verify the results, subject to verification procedures and relevant ethical approval. No data are stored in public repositories due to confidentiality considerations.

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