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Eco-Efficiency Level Analysis at Various Scales of Robusta Coffee Production of Argopuro Mountain, Jember, Indonesia, Based on Life Cycle Assessment

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Abstract

Ground coffee is one of the high value added downstream coffee products that can be developed to increase the income of coffee processors. However, there are concerns about the increasing environmental impact of the downstream process into ground coffee, so it is necessary to evaluate the impact from environmental and economic aspects. The Argopuro Robusta coffee processing business in Jember Regency is trying to be developed towards downstream products to increase the income of coffee farmers. Of course the negative impact on the environment must be considered. The aim of this research are first, to determine the environmental impacts that occur in the Robusta ground coffee production process; second, to determine the level of eco-efficiency of the Robusta ground coffee production process; and third, knowing how to compare the environmental impact and level of eco-efficiency at various scales of ground coffee production. The method used is life cycle assessment (LCA) with a scope from caring for coffee plants to delivering coffee products to consumers. The impact measured is for every one hectare of harvest. The research sample is a Argopuro Robusta coffee processing unit that produces green beans and ground coffee. The higher the scale of ground coffee production, the higher the CO_2 equivalent (eq) emissions. However, the added value is also getting higher. Eco-efficiency calculations show that if the coffee harvest (6 tons fresh coffee cherries ha^{-1}) is converted all into ground coffee, it produces emissions of 1086 kg CO_2 eq and a profit of USD 11,300 with an eco-efficiency index value of 97.37% and is included in the classified as affordable and sustainable. This value does not differ if the ground coffee conversion scale is 15% as current condition or 50%. This indicates that the conversion of ground coffee to maximum scale in Robusta coffee processing businesses is still considered environmentally sustainable.

Keywords: Eco-efficiency, Robusta coffee, life cycle assessment, ground coffee

INTRODUCTION

Downstreaming of agricultural commodities is the process of converting fresh materials into processed products using both simple and advanced technology. Downstreaming is intended to increase the added value of agricultural commodities and is a strategic effort to increase business income on both large and small scales (Elizabeth & Anugrah, 2020). Yusmeidi (2020) states that the downstream program is an additional technology activity that changes the form of a primary product into a new product to increase added value. Downstreaming is one of the supporting activities in Indonesia's agricultural development strategy. Product downstream is one of the main targets of the national medium term development plan for 2020-2024 (Perpres, 2020), the industry is currently required to process semi-finished products into finished products. However, there are concerns that the downstream processing stages will cause environmental impacts resulting in climate change. The current industrial development paradigm needs to minimize environmental impacts that occur during the production process. This aligns with one of the sustainable development goals (Bappenas, 2021) and objectives, namely handling climate change.

One potential agro-industry currently developing in Indonesia is coffee processing. Jember Regency, in East Java Province, is a center for Robusta coffee production, with a total production of 11,795 tons in 2022. The famous type of robusta coffee is Argopuro Robusta, which is found in the southern part of the Argopuro mountains (BPS Jatim, 2023). This coffee is cultivated and processed by local people who are members of coffee farmer groups. These groups have a downstream coffee processing unit (DCPU). This unit is what coffee farmers rely on to earn a decent income by selling processed coffee in the form of green beans and ground coffee. One of the DCPUs in Sukorambi District, namely Sumber Kembang, also does this. They process fresh cherries wetly using traditional tools to produce green beans and ground coffee. Sumber Kembang DCPU processes 2-3 tons of coffee fruit in one process with a total harvest of 6 tons of coffee fruit in one season. The coffee harvest season occurs in June–October of the year. The product composition on Sumber Kembang DPU are 85% in the form of green beans and 15% in the form of ground coffee from total production for one season, respectively, which is then sold to the cities of Surabaya, Jakarta, Yogyakarta, and Denpasar. Producing 1 kg of ground coffee requires approximately 4 kg of fresh cherries or 1.2 kg of green beans, this is supported by research by Novita *et al.* (2023). The price of green coffee is around USD 3.27 kg^{-1}, while ground coffee is sold for USD 7.85 kg^{-1}. Production cost for coffee beans is USD 0.74 kg^{-1} and for ground coffee is USD 1.40 kg^{-1}. It can be said that optimizing the increase in ground coffee production will help increase farmers' income.

Robusta coffee processing generally consists of dry, wet, and semi-wet processing. Wet coffee processing requires 7-9 m^3 of water per ton of coffee cherries during peeling and is estimated at 5-6 m^3 per ton of parchment coffee beans during washing (Mulato *et al.*, 2006). Using too much water will produce by-products in the form of wastewater and solid waste from the coffee production process and result in pollution of water bodies. Also, using fossil fuels (biodiesel and gasoline) during coffee processing such as washing, grinding, roasting, and transportation can increase air pollution and have the potential for global warming due to GHG emissions released. Several studies showed that the total GHG emissions generated in the coffee processing process amounted to 1.30 kg CO_2 eq kg^{-1} of ground coffee (Adiwinata *et al.*, 2021) and 0.49 kg CO_2 eq kg^{-1} of ground coffee (Novita *et al.*, 2023).

This research aims to determine the environmental impact that occurs during the production process of ground Robusta coffee and its level of eco-efficiency and to find out the extent of comparison of environmental impacts caused by various scale production of ground coffee and its level of eco-efficiency as an effort to increase farmers' income and value of the product sold.

MATERIALS AND METHODS

This research was conducted through three stages, including the environmental impact assessment stage with the LCA approach, the environmental efficiency calculation stage, and the interpretation stage. Environmental impact assessment and eco-efficiency calculations were conducted under three conditions, namely (1) 85% green beans production and 15% ground coffee production (current condition), (2) 50% green bean production and 50% ground coffee production as the first additional scenario (1st scenario), and (3) 100% ground coffee production optimization as the second additional scenario (2nd scenario) with the assumption that all inputs and outputs are considered stable. The research was conducted from July to October 2023.

The sample for this research is from Sumber Kembang DCPU. The data collected includes all data required for LCA analysis. The scope of activities is starting from coffee plant care, transportation of fresh cherries from the land to the DCPU, wet coffee processing using full wash method, waste water and emissions produced during processing, and product delivery to consumers. Data on water needs, fuel, and product selling prices are also carefully identified. This research also uses secondary data such as energy conversion factors and emission factors that obtained from the National Green-house Gas Inventory Implementation Guidelines (Boer *et al.,* 2012) and Intergovernmental Panel on Climate Change (IPCC), and information of output input material during the ground coffee production process to support LCA analysis. Three sampling repetitions were used to get the average value of prices, fuel use, and wastewater. Calculation of emissions only from mobile and stationary sources does not include emissions from fertilizer use and wastewater.

Environmental Impact Assessment

The first stage of this research was to conduct an environmental impact assessment. Environmental impact assessment is carried out using Life Cycle Assessment (LCA) method. LCA is a method used to evaluate the environmental impact at each phase of a product's existence, from raw material extraction, material processing, manufacturing, and distribution to its use and disposal (Muralikrishna & Manickam, 2017).

Goal and Scope

This stage begins with determining the objectives and scope of the study. The objectives of environmental impact assessment in this study are to determine the environmental impacts caused during the production of full-wash ground Robusta coffee and environmental costs that must be incurred to reduce these impacts in each scenario. The scope of the environmental impact assessment is the full wash Robusta ground coffee production system, starting from land maintenance, which includes fertilization and weeding, farm-to-factory transportation, production processes, and product distribution (cradle to gate).

Life Cycle Inventory (LCI)

The next step is inventory analysis, which identifies each input and output in full-washed robusta ground coffee production. This step includes calculating the emissions generated by each energy use in the form of both fuel and electricity. This research does not measure the environmental impact caused by fertilizers and wastewater. The calculation of GHG emissions from fuel use in stationary uses Tier 1 equation as follows (Boer *et al.*, 2012).

$$E = AD \times EF \quad (1)$$

Where E is emission (kg CO_2; kg CH_4; and kg N_2O), AD is activity data (electricity: Kwh; liquefied petroleom gas (LPG); diesel fuel;

and pertalite fuel: TJ) and EF is emission factor (kg CO_2/AD; kg CH_4/AD; and kg N_2O/AD).

The calculation of air pollutant load on mobile sources can be calculated using the formula in Permen LH (2010) by using the vehicle kilometers traveled (VKT) based emission factor or the average vehicle trip length per year.

$Ea = VKT_{b,c} \times FE_{a,b,c} \times 10\text{-}3$ .... (2)

Where Ea is the pollutant load for pollutant a (kg year^{-1}); $VKT_{b,c}$ is the total annual travel length of category b motor vehicles using type c fuel (km year^{-1}); $FE_{a,b,c}$ is the amount of pollutant a emitted for each kilometer traveled by category b motor vehicles using type c fuel (g km^{-1}) or also called emission factor; a is the type of pollutant (1-6 for CO, NO_2, HC, PM10, SO_2,CO_2); b is the category of motor vehicle; c is the type of fuel (1-2 for gasoline and diesel).

Figure 1 shows the flow of inputs (fertilizer, ground coffee, and water) and outputs (wastewater, emissions, and solid waste) of full-wash Robusta ground coffee production under current condition which means that 15% of green beans are processed into ground coffee.

Life Cycle Impact Assessment (*LCIA*)

The calculation at this stage uses the Eco Cost 2023 method approach with the help of openLCA 2.0 software. Some studies that have similarities with this method include Windrianto *et al.* (2016), Purwaningsih *et al.* (2021a), and Susanto & Putranto, (2022). The steps taken at this stage consisted of:

1. Characterization is a stage to classify LCI results into several categories by multiplying the characterization factor and LCI results. The Eco Cost 2023 method will group the LCI results into 13 categories, including acidification, baseline water stress, climate change, ecotoxicity freshwater, eutrophication, human toxicity-cancer, human toxicitynon cancer, land use (biodiversity change), landfill, metals scarcity, particulate matter, photochemical ozone formation, use fossil-based plastic and fossil-based transport fuels, and use uranium.
2. Normalization and Weighting. Normalization is calculated by dividing the characterization results by the normalization value. Then, the weighting is calculated by multiplying the normalization result by the weighting factor.
3. Single score is the total value showing which activities contribute most to environ-mental impacts. The single score results are eco-costs or environmental costs, which are needed for further calculations. The unit used is the Euro currency, which is then converted into USD according to the current conversion rate. The results of LCIA will be an indicator of eco-costs used to determine the eco-efficiency index and eco-efficiency ratio (Purwaningsih *et al*., 2021a).

Eco-efficiency Calculation

The determination of eco-efficiency starts from calculating the net value of a product (Purwaningsih *et al.*, 2021). Net value of a single product can be found by reducing the selling price of the product by production cost (Purwaningsih *et al.,* 2021a). For net value on multiple products, as in this study, the equation based on the previous equation is shown as follows.

Net value =

Total revenue-Total cost of goods sold-Total expenses................................ (3)

Net value for multiple products can be found by subtracting the total revenue generated from the sale of green beans and ground coffee by selling at the cost of goods sold, which includes operational costs and labor

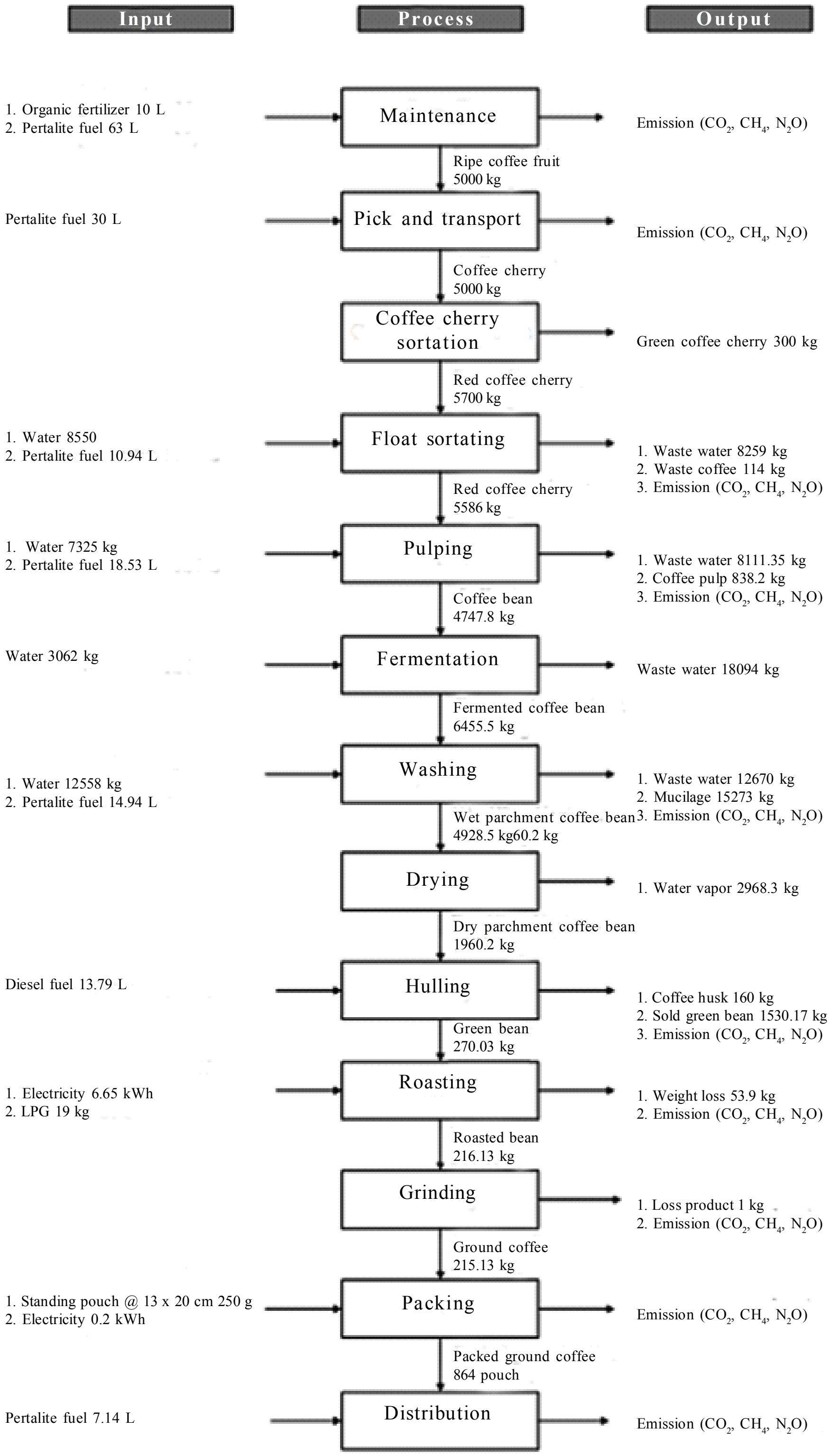

Figure 1. Full-wash Robusta coffee production process flow under the condition that 15% of green beans are processed into ground coffee

wages, and then deducting overhead costs such as taxes, marketing costs, and maintenance costs. Net value is needed to calculate the eco-efficiency index (EEI).

Eco-efficiency index is used to determine whether a product can be said to be affordable (financially affordable) and sustainable (environmentally friendly) (Susanto & Putranto, 2022) with the following equation.

$$EEI = \frac{Net\ velue}{Eco\ cost} \quad (4)$$

Eco-cost in the above equation is obtained from the single score at the LCIA stage. The single score value is obtained from the open LCA 2.0 software calculation. Then, the eco-efficiency index results are classified based on three criteria, namely affordable and sustainable (EEI>1), affordable but not sustainable (EEI = 0-1), not affordable and not sustainable (EEI < 0).

Next is to determine eco-efficiency value ratio as a reference for making products that have "maximum value" for the minimum environmental cost (environmental burden). (Susanto & Putranto, 2022) with the following equation.

$$EVR = \frac{Eco\ cost}{Net\ velue} \quad (5)$$

$$EER = (1-EVR) \times 100\% \quad (6)$$

EVR is the eco-cost value ratio as an indicator showing the-linking of economy (value) and ecology (eco-cost) of a product or a service. EER (energy efficiency ratio) is used as the final calculation of eco-efficiency, expressed in percentages. If the EER value is negative, the eco-cost or environmental burden is higher than the product value. If EER = 0, the eco-cost is equal to the product value, and if EER = 100%, then the product has no eco-cost, or it can be said that the product produced has no environmental burden. (Vogtlander, 2010).

Interpretation and Recommendation

This stage is to interpret the results of environmental impact assessment and eco-efficiency in the previous stage, see which conditions are in accordance with the concept of eco-efficiency, and become recommendations for agroindustry owners.

RESULTS AND DISCUSSION

Environmental Impact Assessment

Some studies that use LCA analysis as an approach to assess environmental impacts include Nisa *et al*. (2015), Windrianto *et al*. (2016), Purwaningsih *et al*. (2021b), and Susanto & Putranto (2022). First stage of LCA measurement is the environmental impact analysis stage. There are three stages carried out in environmental impact analysis. First, characterization of inventory results at the LCI stage and grouping them into categories based on the environmental impact of eco-costs 2023 method. Table 1 shows the results of environmental impacts based on calculations with open LCA 2.0 software.

The characterization results in the table above are potential impacts that may occur based on calculations using open LCA software, however actual conditions have yet to be measured. The table above shows that the climate change category has the highest results compared to other categories. This is due to the use of fuel (LPG, diesel, and gasoline) and electricity that emit greenhouse gas emissions that can cause climate change. Research from Purwaningsih *et al.* (2021a) and Hartini *et al.* (2021) also shows that the climate change category can have the highest result, especially processes that require materials electrical energy and petroleum materials. Ground coffee processing processes that produce greenhouse gas emissions

Table 1. Environmental impact of ground Robusta coffee production process

Impact category	Unit	Result		
		Current condition	First scenario	Second scenario
Climate change	kg CO_2 eq	481.91	730.43	1086.67
Acidification	mol H^+ eq	0.01	0.02	0.02
Particulate matter	kg PM 2.5 eq	0.06	0.08	0.12
Eutrophication	kg PO_4 eq	1.16	1.35	1.61
Eco-toxicity	CTUe	0.38	0.54	0.78
Human toxicity non cancer	CTUh	1.66×10^{-5}	2.37×10^{-5}	3.38×10^{-5}
Photochemical ozone formation	kg NVMOC eq	2.55	5.30	9.24
Water stress indicator	m^3 eq	14.13	14.13	14.13

include washing, pulping, hulling, grinding, and transportation. On the other hand, the GHG emission value at Sumber Kembang DCPU can be said to be good because it is still below the threshold set Permenindag (2020) which states that the maximum limit of instant coffee industry GHG emissions is 3,75 ton CO_2 eq ton^{-1} of product or 3,75 kg CO_2 eq kg^{-1} of product (Adiwinata *et al.*, 2021) while at Sumber Kembang DCPU it is 2.24 kg CO_2 eq kg^{-1} of ground coffee in the current condition, 1.02 kg CO_2 eq kg^{-1} of ground coffee in the first scenario, and 0.76 kg CO_2 eq kg^{-1} of ground coffee in the second scenario.

Next stage is normalization. In this research, normalization aims to homogenize units at the characterization stage. Value in normalization is the result of multiplying characterization value by normalization factor, where all impact category results use the same unit. Normalization results are shown in Table 2 and Table 3.

The values listed in the table above are calculated based on standard euro costs according to research references Purwaningsih *et al.* (2021a), Hartini *et al.* (2021), and Susanto & Putranto (2022).

Based on results shown in Tables 2 in the current condition, 15% ground coffee production has the lowest eco-cost of USD 108.45, then the first scenario and second scenario have eco-costs of USD 161.93 and USD 238.59, respectively. It can be said that an increase in the amount of material to be processed will be in line with the increase in fuel requirements needed to drive production machinery so that environmental burdens or eco-costs will also increase.

Eco-efficiency Calculation

First step in calculating eco-efficiency is to determine net value with a cost-benefit analysis. Net value in multi-products is done by reducing total revenue with total production costs incurred in each condition. Table 3 shows total revenue that is earned in each condition with the assumption that all products, both green beans and ground coffee are fully sold. Total revenue is obtained from the sum of all green bean and ground coffee sales in each condition.

In the 15% ground coffee production (current condition), the total revenue was obtained from the sale of 1585.07 kg of green beans and 215.13 kg of ground coffee. In the 50% ground coffee production (first scenario), the total revenue was obtained from the sale of 990.11 kg of green beans and 716.38 kg of ground coffee. In the 100% ground coffee production (second scenario), the total revenue was obtained from sale of 1434.92 kg of ground coffee.

Next is to determine the EEI and EER values to determine the eco-efficiency criteria of the Robusta ground coffee production system.

Table 4 shows that each scenario has a very high eco-efficiency index (EEI), such

Table 2. Normalization based on open LCA 2.0 calculations

Impact category	Eco cost ($)		
	Current condition	First scenario	Second scenario
Climate change	64.02	97.03	144.35
Acidification	0.09	0.13	0.18
Eutrophication	2.40	3.34	4.68
Eco-toxicity	6.26	7.27	8.71
Particulate matter	0.001	0.002	0.003
Human toxicity non cancer	3.88	5.53	7.89
Summer smog	15.62	32.46	56.61
Water Stress Indicator	16.18	16.18	16.18
Total	108.45	161.93	238.59

Table 3. Total revenue of green bean and ground coffee sales for each scenario

Product	Current condition (USD)	First scenario (USD)	Second scenario (USD)
Green bean	5192.69	3243.60	-
Ground coffee	1694.15	5641.49	11300.00
Total revenue	6886.84	8885.09	11300.00
Net value	5229.07	6996.01	9079.34

Table 4. Table of eco-efficiency result

Indicator	Current condition	First scenario	Second scenario
Total revenue (USD)	6886.84	8885.09	11300.00
Cost production (USD)	1657.77	1889.08	2220.65
Net value (USD)	5229.07	6996.01	9079.34
Eco cost (USD)	85.50	108.45	161.93
EEI	48.21	43.20	38.05
EVR	0.02	0.02	0.03
EER (%)	97.93	97.69	97.37

as current condition with an EEI of 48.21. Then, EEI values in the first and second scenarios are 43.20 and 38.05, respectively, so that can be categorized as Robusta ground coffee products on the Argopuro mountain-side classified as affordable and sustainable products. Likewise, It can be seen that the highest EER value is in the current condition, with an EER value of 97.93%. Then, followed by EER value in the first scenario, which is 97.69%, and finally, the second scenario has an EER value of 97.37%. These results show that the comparison of environmental costs (eco-costs) is still far below the net value in all conditions, so it can be said that the contribution of the profit margin of each condition can still cover the environmental burden (eco-costs). This score compares favorably with an eco-efficiency analysis conducted on coffee processing in Vietnam, the study from Ho *et al.* (2018) showed that coffee plantations had an average eco-efficiency score of less than 50%, and coffee plantations with organic certificates had higher eco-efficiency scores.

Interpretation and Recommendation

Figure 2 is a graph showing the comparison between environmental impacts, especially in the climate change category which has the highest results, and eco-efficiency in each condition. Based on the graph, an increase in the amount of ground coffee processed will increase environmental burden because the need for fuel to drive production machines and clean water during the production process also increases. On the other

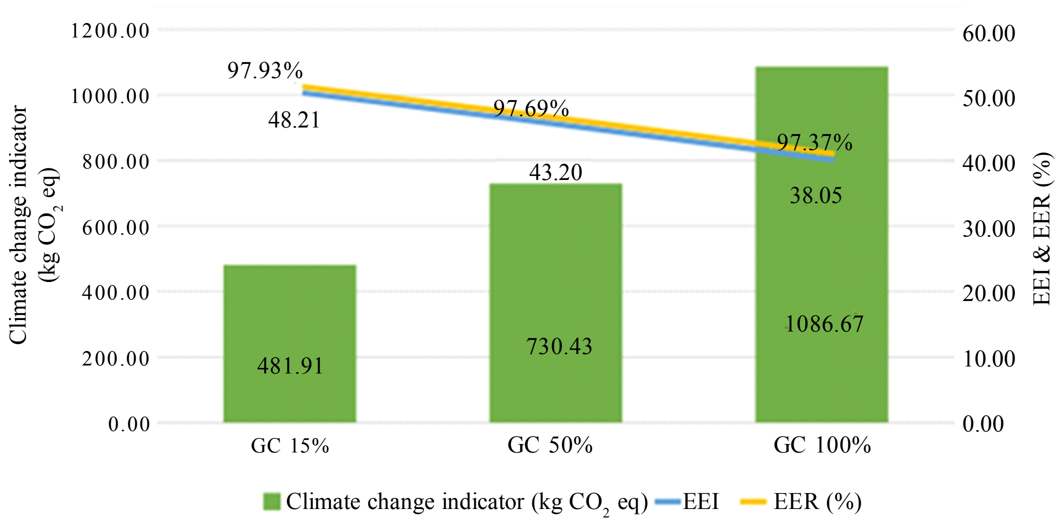

Figure 2. Comparison of environmental impact and eco-efficiency in processing 15, 50, 100% ground coffee (GC)

hand, the level of eco-efficiency will decrease as the amount of ground coffee processed increases, although it is still classified as affordable and sustainable. The results of environmental impacts in climate change category obtained are far adrift of several similar studies, such as coffee production process in Bengkulu Regency, which has a contribution of 109.43 kg CO_2 eq ha^{-1} (Hamdan *et al*., 2019) and in Bondowoso District which has a value of 102.53 kg CO_2 eq ha^{-1} (Harsono *et al*., 2021). This provides information that in this case study of ground Robusta coffee on the Argopuro mountain range, a high level of eco-efficiency does not necessarily represent a low environmental impact. Net value of the product can influence high eco-efficiency. As is known, the EER value is used as a reference to see whether a product can be said to be sustainable in environmental aspects and profitable in economic aspects. (Purwaningsih *et al*., 2021b). Based on the results of environmental impact and eco-efficiency assessment, Sumber Kembang DCPU can increase revenue by optimizing the production of downstream products in the form of ground coffee with the consideration that the ecoefficiency value in each scenario of increasing ground coffee production does not experience significant differences and is around 97% which indicates that the value is categorized as very high.

CONCLUSIONS

The environmental impact assessment in this study only calculates the environmental impact caused by emissions by using energy sources such as fuel (LPG, biodiesel, and gasoline) and electricity. It does not measure the environmental impact caused by fertilizers and wastewater. The results of the environmental impact analysis show that the climate change impact category has the highest value among other categories. At all levels of ground coffee production, it is still safe for the environment. It can be seen that the results of the analysis are still below the emission standards issued by the government for the instant coffee industry, so the encouragement of green beans downstream into ground coffee can be done optimally. This research can be pushed deeper by including the emission output from the process of adding fertilizers, liquid waste, and solid waste so that a more accurate picture of the eco-efficiency value is obtained.

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