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LIFE CYCLE ASSESSMENT OF COFFEE ROASTING PROCESS BASED ON TWO DIFFERENT ENERGY SOURCES ON A SMALLHOLDER COFFEE FARM IN JEMBER

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Abstract

This study compares two scenarios for alternative energy supply options for the coffee roasting process. The scenarios are: Solar Panel-Biogas (SB), and Local Grid Electric-LPG (LL). To define the product for evaluation, the level of roasting was chosen as Medium Roasted (Code R55). These two alternative energy supplies are compared based on Global Warming Potential (GWP). The types of coffee chosen were Arabica, and Robusta with the wet and dry processing selected, and data obtained experimentally. As the biogas is supplied as a byproduct of coffee production, Life Cycle Assessment (LCA) was applied with the ReCiPe 2016 Midpoint level method to calculate the GWP. The key novelty of this study is that it describes the GWP that emerges from each of the three roast curve stages based on a total roast duration of 10 minutes. This covers the three phases in roasting coffee: the dehydration phase (0-4 min), the Maillard phase (4-8 min), and the pyrolysis-development phase (8-10 min). The results indicate that the emission impact of the dehydration stage is higher than the other two stages, due to the required heat to reduce the water content over a short time. In general, the turning point was highly important, as the water content of the coffee was decreasing, especially for coffee beans that have different densities, the heating power to reach this point is critical. The higher the density, the greater the required heating power. Then, in the phase of the Maillard reaction, the heating power requirement will decrease as the colour change develops. Scenario SB was (as anticipated) the lower GWP, and this study demonstrates the benefit of integrated Sustainable Coffee Production (SCP) as an Industrial Ecology (IE) solution.

Keywords: Biogas, Coffee profile, Coffee roasting, Density, Industrial ecology.

1. Introduction

The impact of climate change has been witnessed all around the world. However, many of the effects are being most critically felt in countries of the global south, including most countries where coffee is grown. Coffee is the second most-traded commodity in the world after petroleum products, and Indonesia is the fourth largest coffee-producing country, whose economy generates a large amount of foreign exchange from coffee exports [1, 2]. Coffee-producing countries have faced the effects of climate change for decades such as fluctuations in temperature, rainfall, humidity, soil nutrients, sunlight, and aeration which affect coffee plants. [3].

Coffee production in Indonesia is divided into two main types of products, Arabica and Robusta, which are spread across smallholder plantations (95.37% of production) in Java, Sumatra, and Sulawesi [4]. Robusta is generally grown in South Sumatra, Lampung, and East Java, while Arabica is grown in Aceh, North Sumatra, South Sulawesi, Bali, and Flores. Coffee processing does not require specialised certification. Still, the importance of the expertise gained through a certificate in coffee processing can improve the quality of premium products to become specialty coffee, which will bring higher prices [5]. Generally, coffee processing is divided into wet and dry processing [6-8]. Figure 1 describes the wet and dry coffee processing processes, both of which are divided into on-farm and off-farm categories. Primary products (On-Farm) can be sold directly to coffee processors, while secondary products (Off-Farm) are segmented by smallholders, and Small-Medium Enterprise (SMEs).

While coffee production can be impacted by climate change, it is also important for the sector to consider how it can improve its performance environmentally. Mitigation of emissions from all processes in the coffee processing chain using alternative energy should be a priority as a contribution to mitigating the impacts that threaten the industry. Utilizing wastewater from coffee processing into biogas is a step towards Sustainable Coffee Production (SCP) [9]. Robusta products are commercial products, so they are handled on the plantation [10], with the specific processing methods being important for the impact on sustainability. Almost all Robusta processing is carried out using the dry process, which currently benefits farmers most [11]. Coffee processing produces around 0.42 kg CO_{2eq} per kg of cherry emissions from transportation and 0.08 kg CO_{2eq} per kg of Coffee roasted from LPG Sources and Local Grid electricity [12].

Coffee roasting is part of the off-farm processes; all smallholders can roast coffee by buying Green Beans (GB) from suppliers, determining the roast profile, and aiming to develop the best aroma, colour, and taste [13]. The roasting method can be fast, medium, or slow roast [14]. Moreover, all stages in the coffee process contribute to Global Warming Potential (GWP), with most coffee processing using fossil fuel sources. Replacing LPG with biogas is one potential method for mitigation of the emissions produced in the coffee roasting stages. For example, the coffee process by smallholders in Jember contributed emissions of around 1.2 kg CO_{2eq} per kg Coffee Powder (CP) with scenario fossil fuels and biogas this was reduced to 0.42 kg CO_{2eq} per kg CP [9].

In this study, LCA is used to calculate the potential emissions from coffee roasting, with the use of energy sources such as solar panels and the local electric grid compared. A previous study has demonstrated solar panels and local grid electricity leading to 0.318 CO_{2eq}, 0.744 CO_{2eq} per kg CR [15]. The scenario of biomass as energy in the coffee processing process in Mexico was previously shown to produce lower emissions than fossil energy [16]. Economically, CR has been shown to provide a beneficial impact compared to GB products in the Robusta Bromo Mountain coffee farmer group [17], but the importance of selective processing during the production process and considering the use of alternative energy as a supporting energy source needs further investigation from direct economic, environmental and potential marketing perspectives. Smallholders in coffee processing are essential to sustainable coffee production [18]; through collaboration with smallholders, the industry will be strong and sustainable with quality GB [19].

In the case of coffee, it is important to define the functional unit for evaluation. Roasters use the colour profile to indicate various levels of roast. In this case, the roast colour profile tested is based on codes #95 very light, and #25 very dark [20]. As roasting progresses, changes can be seen physically occurring with time and changes in temperature during the roasting process, with coffee from a water weight content of 12% to around 5% [21] The changing colour during coffee roasting also has a relation with the coffee taste [20]. There has not been any previous detailed explanation of the emissions arising at each stage of the roasting process. The novelty of this research is to explain the potential emissions from the coffee roasting process explicitly by dividing it into three roasting stages: first, the dehydration stage; second, the Maillard reaction stage; and third, the development stage. A coffee roasting curve was formed at each stage, which became a reference for smallholders to determine the roast profile.

In this study, we discuss the potential emissions generated by the roasting stage of coffee with Arabica and Robusta from two different types of processing. Potential emissions reduction analysis has been undertaken with LCA, using SimaPro software and the ReCipe 2016 method. Two different energy sources, solar panels-biogas, and local grid electric-LPG are used for comparison.

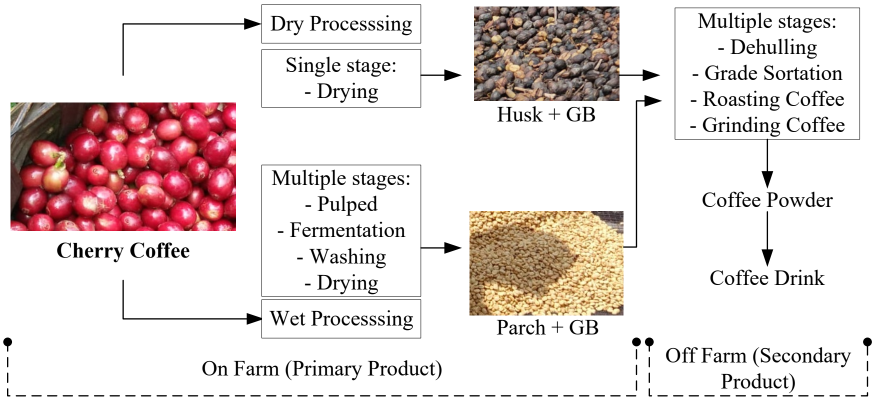

Fig. 1. Coffee processing and on-off farm categories.

2. Materials and Methods

This study used raw dry coffee materials, Arabica, and Robusta, from the Processing Group at the Indonesian Coffee and Cocoa Research Institute (ICCRI). The coffee roasting was done at a company in Jember Regency, East Java. LCA is used for the analysis of Global Warming Potential (GWP) [22, 23] in SimaPro V9.3, with the ReCipe 2016 midpoint level method as an impact assessment [18, 24]. The Eco-Invent database was used to calculate the GWP of production using Local electricity - LPG (LL), and Solar Panels-Biogas (SB). Consumption of LPG and electricity was measured experimentally. Figure 2 shows the flowsheet of coffee roasting assessment boundaries. Data were collected during August and September 2022, using direct observation and experimentation at the Gusto Coffee Company, Jember, East Java-Indonesia.

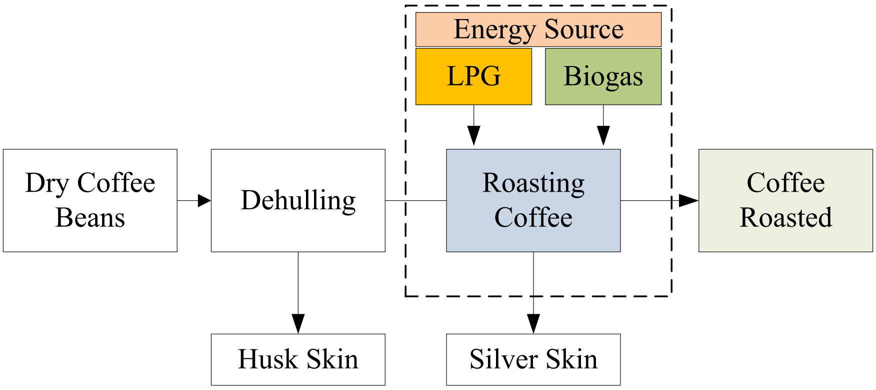

Fig. 2. The scope of the study is presented in the dash-line.

2.1. Scope

The functional unit defined for this study is one kilogram of coffee roasted at a medium level (*Agtron* 55). This study uses a roasting application and monitoring to display graphs during the process, including temperature, time, and gas consumption as shown in Fig. 3. The monitoring system is connected via a USB cable to a microcontroller coffee roaster machine. Drum speed control ranges from 60 to 75 rpm as a variable for control motor rotation, airflow control for heat power, and heat losses; it also detects bean temperature and drum temperature in real-time, and the gas pressure indicator is read during the roasting process gas pressure is converted to gas consumption in this monitoring system. The monitoring system readings are presented as a roasting curve and can be saved in the form of images and exported to Excel files. At the same time, observations record the amount of electricity demand using a digital power meter during the roasting process as shown Fig. 4. We completed the analysis by comparing the GWP of the two energy sources and separating it into the three contributing stages of the coffee roasting process; Dehydration, Maillard, and Pyrolysis [25].

The real-time monitoring system records temperature increases or decreases and time during the roasting process. These temperature changes help to identify the changing processes in roasting the coffee. These three stages can be read through the monitoring system, divided into time ranges from 0 to 4 minutes, 4 to 8 minutes, and 8 to 10 minutes. Data is stored as a reference for the roastery for the roasting stage with the same type of coffee beans. This study used coffee roaster samples, in a roaster machine with a capacity of 200 g. Table 1 shows the specific tools utilized. These tools were connected to software for the monitoring system on temperature, time, and gas pressure. Solar panels are used during the dehulling and roasting processes, with four monocrystalline-type panels and 100A batteries (Table 2). However, this study does not detail the GWP impact due to the dehulling process, because it is focused on the three stages of the roasting process, which should eventually be able to determine the relative impact of alternative roast levels, taste profiles, and beans. Figure 4 shows a roaster machine, solar panels, and *AC-DC* power meters.

Fig. 3. The company's coffee roaster machine application.

Fig. 4. Solar panel (left), coffee roaster machine (middle),
AC power meter (black, right), DC power meter (white, right).

Table 1. Roaster machine specifications.

No.	Materials	Parameters
1	Drum Stainless 304	125 mm; tick 2 mm, L 120 mm
2	Tray Stainless 304	L × W × H: 220 × 65 × 40 mm
3	Body Stainless 304	2 mm thick, L × W × H: 380 × 270 × 270 mm
4	Gas Indicator	0 - 100 millibar
5	Temperature	Digital Beans, Monitoring Connections
6	Capacity	100-200 g per batch
Specification		**Power (Watt)**
7	Motor Drum	15
8	Air Flow Fan	10
9	Cooling Fan	10
Total power (watt)		35

*Data taken from observation roaster machine

Table 2. Installation specifications.

No.	Type Panel	Monocrystalline	Energy DC	DC to AC
1	Maximum Power (Pmax)	100 W	-	-
2	Maximum Power Current (Imax)	5.62 A	-	-
3	Maximum Power Voltage (Vmax)	17.8 VDC	-	-
4	Open Circuit Voltage (V)	21.8 VDC	-	-
5	Battery (Gel)	-	100 Ah, 12 V	-
6	Inverter Cosine Wave	-	-	1000 W
7	Power Meter Indicator	-	-	100 A

*Data were taken installation

2.2. Inventory

The coffee roasting mass balance inventory is presented in Table 3. Roasting milestone parameters were measured respectively; raw material, bulk density in GB, bulk density in CR, apparent swelling, turning point, first crack, and second crack. Next, the emissions factor was applied to calculate the LCA [26]. The amount of energy and electricity consumption is explained in Table 4. Observation of gas consumption with a flow meter and pressure, for each phase of the roasting process, from minutes 0-4 (dehydrate), 4-8 (Maillard), and 8-10 (develop). The gas consumption was recorded on the monitoring system using a gas pressure indicator and gas flow meter indicator for gas flow measurement. Gas consumption is based on the three stages of the roasting process. The gas cylinder is placed on the scale and connected to the monitor system. The initial to final gas weight at each stage is recorded and described in Table 4. The LCA input data for the LL Scenario selected low voltage electricity Indonesia (ID), with electricity voltage transformation from medium to low voltage, Cut-off-S was selected as the database for electrical energy input. Low voltage electricity ID, photovoltaic, 3kWp slanted-roof installation, and Cut-off-S was used for the SB Scenario.

Table 3. Roasting parameters.

No.	1	2	3	4
Roast type	R55	R55	R55	R55
Coffee	A FW	A Nat	R FW	R Nat
Moisture, %	12% ± 0.5	12% ± 0.5	12% ± 0.5	12% ± 0.5
Beans mass, g	100	100	100	100
Roast mass, g	86.6	86.2	87.7	86.7
Bulk density in beans, g/ml	0.714	0.64	0.73	0.684
Bulk density in roasting, g/ml	0.421	0.383	0.391	0.398
Apparent swelling, %	46.87	44.04	63.74	49
Charge Temp, °C	180	180	180	180
Turning point temp, °C	92 ± 1	92 ± 1	92 ± 1	94 ± 1
First Crack temp, °C	**194 ± 1**	**196 ± 1**	**194 ± 1**	**193 ± 1**
Second Crack temp, °C	**205 ± 1**	**205 ± 1**	**205 ± 1**	**204 ± 1**
End Temp, °C	**210 ± 1**	**210 ± 1**	**210 ± 1**	**209 ± 1**

*Data were measured

Table 4. Fuel consumption parameters.

No.	Roast type	Coffee	Gas Consumption LPG, g				Electric Consumption, kWh
			Pre heat 0-5 min	Dehydration 0-4 min	Maillard 4-8 min	Develop 8-10 min	
1	R55	A FW	4	6	2.3	1.2	0.02
2	R55	A Nat	4	6.3	1.5	1.4	0.02
3	R55	R FW	4	4.5	2.3	2	0.02

4	R55	R Nat	4	3.5	3.4	2.5	0.02

*Data were measured

3. Result and Discussions

This study used a 100 g GB coffee sample. The input temperature is fixed the same; 180° C. This temperature is used as a reference when inputting GB at the start of roasting [27]. Furthermore, the water content was set at 12% uniformly based on National Standard Indonesia for coffee dried. However, each GB has a different density depending on the variety of beans and the meter above sea level of the plantation. This results in a difference in temperature for each sample at the turning point, where for a moment, the temperature of the coffee beans is lowest and then starts to rise. In the coffee roasting process, the beans change colour and size, which is affected by high temperatures; these changes occur between 160° C - 300° C [28]. The initial turning point temperature of coffee beans can vary due to processing and physical characteristics of GB such as size and variety of raw material. Table 4 describes the electricity consumption as a total of 0.2 kWh, with an estimate of 0.08 kWh between dehydration and Maillard, and 0.04 kWh for the development phase.

Figure 5 describes the turning point range between 2-3 minutes; if the turning point is at 3-5 minutes, the heat power is low. In 3-4 minutes, the temperature of the beans reaches 130°C-150°C, and the color changes due to the low GB moisture content (dehydration-drying phase). Furthermore, in the period between 4-8 minutes, the temperature will rise to the point where the coffee beans begin to show apparent swelling between 180°C-195°C (Maillard reaction phase); the “first crack” is heard in this phase. Finally, in the 8th-10th minutes of the development phase, the temperature rises between 195℃-230℃, and the final profile is formed. In this phase, there is a second “crack” sound. It is important to monitor the target coffee color because, at this stage, the determination of coffee caramelization and flavor is achieved.

The results of the analysis show that the contribution of emissions from the development phase is lower than the Maillard and dehydration phases. This is due to a decrease in gas consumption during this phase.

Figure 6 compares the two LL and SB scenarios for the FW Arabica roasting, the contribution of GWP per one kg CR of LL energy sources at the dehydration stage were 0.299 kg CO_{2eq}, Maillard 0.166 kg CO_{2eq}, and development 0.084 kg CO_{2eq}. For the LL scenario, the use of Local Electricity and LPG contribute GWP 30% and 8%. When compared with the SB scenarios for the FW Arabica, dehydration was only 0.025 kg CO_{2eq}, Maillard 0.021 CO_{2eq}, and development 0.019 kg CO_{2eq}, these scenarios are lower than the LL scenarios. The use of biogas is a preferable option that can utilize liquid and solid waste converted into energy towards SCP [29].

The main contributor to energy and emissions for coffee roasting in the SB scenario is the biogas, between 73%-74% of the total, with a GWP contribution of 0.2 kg CO_{2eq} - 0.22 kg CO_{2eq} per kilogram CR. In the LL scenario, the GWP of the LPG system contributes 0.063 kg CO_{2eq} - 0.068 kg CO_{2eq} per kg CR. As seen in Fig. 7(b), the scenario of SB contributing to GWP is dominated by dehydration, Maillard, and development at 0.0247 kg CO_{2eq}, 0.0197 kg CO_{2eq}, and 0.018 kg CO_{2eq}, respectively. Meanwhile, Fig. 7(a) shows GWP for 1 kg CR from the LL scenario is 0.27 kg CO_{2eq}, 0.1856 kg CO_{2eq}, and 0.0855 kg CO_{2eq} from the main phases respectively.

On the other hand, for robusta CR, Fig. 8 illustrates the GWP for the Robusta type FW processing. The GWP contributor is higher in the dehydration phase than in the other two steps. Figure 9 includes the same type of coffee but using natural processing. In this study, robusta has a higher density than arabica. Coffee with different densities may require additional power and heat and produce a different taste depending on the roast profile [30].

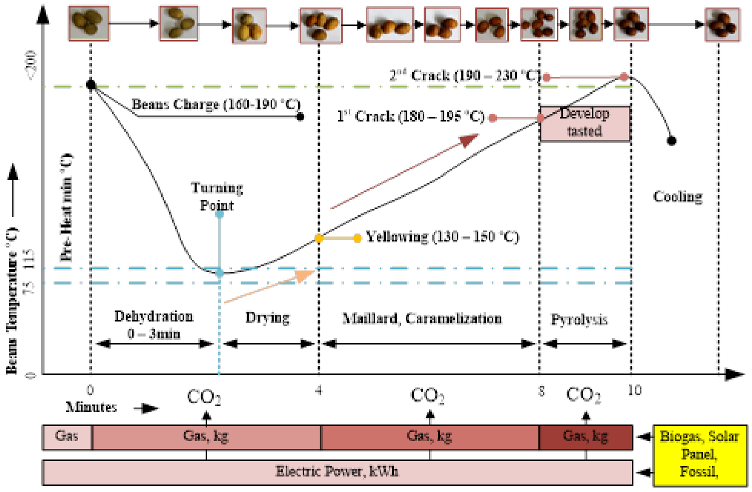

Fig. 5. Roasting milestone.

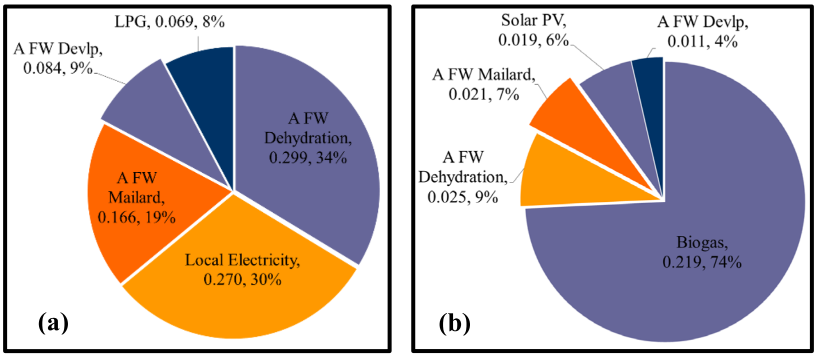

Fig. 6. (a) Carbon contribution of coffee roasting Arabica FW by LL energy source, (b) SB energy source.

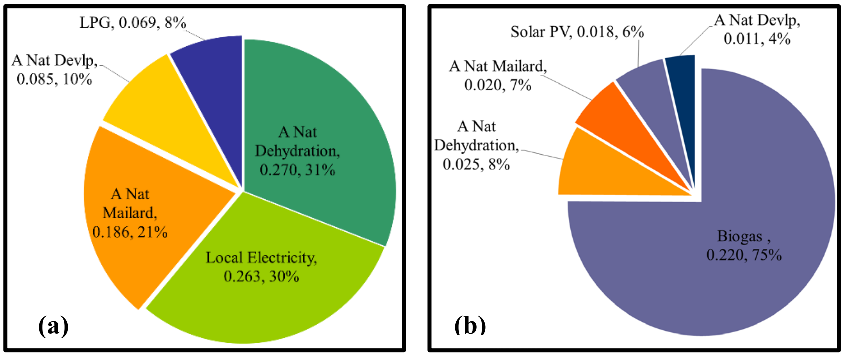

Fig. 7. (a) Carbon contribution coffee roasting Arabica natural by LL energy source, (b) SB energy source.

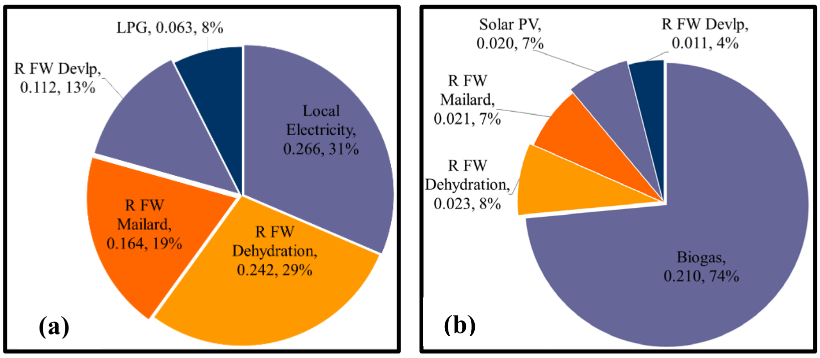

Fig. 8. (a) Carbon contribution coffee roasting R FW by LL energy source, (b) SB energy source.

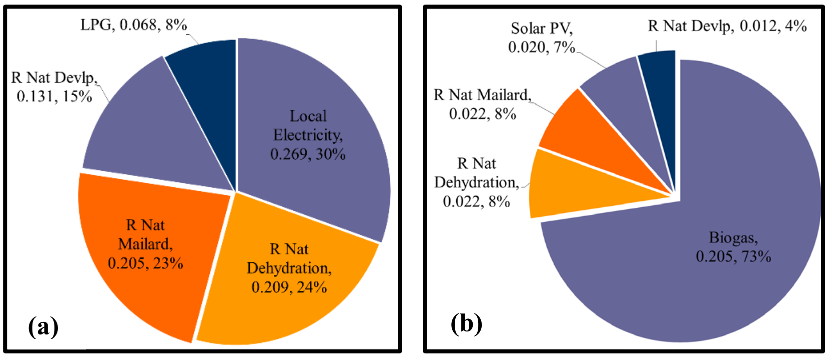

Fig. 9. (a) Carbon Contribution coffee roasting R Nat by LL energy source, (b) SB energy source.

Figure 10 describes each stage of coffee roasting with a total GWP for one kg of roasted coffee from both types of coffee with two energy sources; LL energy source from 0.85 kg CO_{2eq} to 0.89 kg CO_{2eq}; and SB 0.28 kg CO_{2eq} - 0.3 kg CO_{2eq}.

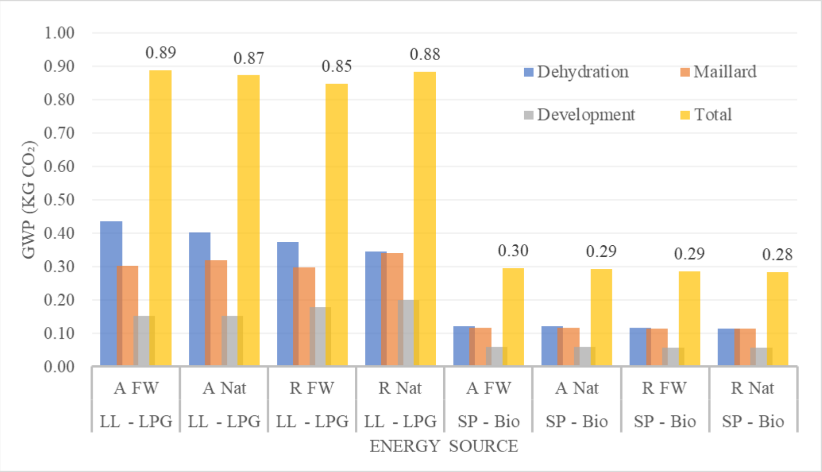

Fig. 10. GWP coffee roasting based on stages.

4. Conclusions

In the current study, the GWP contribution of one kg of roasted coffee under the LL scenario for Arabica and Robusta coffee with full wash and natural processing is undoubtedly higher than the SB scenarios. The potential for reduction in emissions is not just beneficial environmentally but could also provide a marketing advantage for coffee roasters. But to obtain the advantage of utilising biogas (specifically from coffee waste streams) it is important for the roasting to be done close to the coffee plantation. This is acceptable for domestic consumption, but much international coffee trade is currently at the green bean stage rather than roasted beans.

There are some limitations to this study. For example, there can be differences in each roasting process at the coffee roasting stage, especially on a home production scale. In this research, the roasting time is limited to 10 minutes, and the monitoring system on the roasting machine means that in household production with different capacities, gas and electricity consumption will be different. Non-uniform raw materials characteristics such as density, moisture content, and quality of raw materials, are challenges for coffee roasteries. A coffee roastery has a very important role in maintaining the consistency of roasted coffee products for sustainability in coffee production [31]. The use of renewable energy can be implemented using solar PV (SB-Scenario) which leads to lower GWP than Local electricity-LPG at the roasting stage from the dehydration phase. Research studies like this are possible as initiatives towards reducing environmental impacts in the off-farm sector as a mitigation strategy to overcome the effects of climate change. Future studies will aim to further classify the emissions associated with different levels of coffee roast, and different coffee bean types.

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Nomenclatures

CO_{2eq}	Chemical compound with the chemical formula CO_2

Abbreviations

AC-DC	Alternating current - direct current
A FW	Arabica full wash
Ah	Ampere hour
A Nat	Arabica natural
CR	Coffee roasted
FW	Full wash
GB	Green beans
GWP	Global warming potential
ICCRI	Indonesian coffee and cocoa research institute
ID	Indonesia
IE	Industrial ecology
Imax	Current maximum
JST	Japan science and technology agency
LCA	Life cycle assessment
LL	Local grid electric - LPG
L-W-H	Length - width - height
MSMSe	Medium small medium enterprise
Nat	Natural
Pmax	Power maximum
PV	Photovoltaic
R FW	Robusta full wash
R Nat	Robusta natural
R55	Roast colour code 55
SB	Solar panel - biogas
SCP	Sustainable coffee production
SMEs	Small medium enterprise
VDC	Volt direct current

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