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Life Cycle Assessment (LCA) Analysis Of Robusta Coffee Factory

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ABSTRACT
A coffee processing system must be evaluated using a life cycle assessment approach to understand its environmental impacts arising from its entire production process. This study aims to evaluate the environmental impacts associated with the production of robusta coffee at UD. Cipta Lestari, located in Pujungan Village, Tabanan Regency, Bali. The assessment was carried out using the Life Cycle Assessment (LCA) approach, a systematic method for evaluating the environmental impacts throughout the entire life cycle of a product, from raw material acquisition to final output. This research employed a descriptive quantitative approach, following the ISO 14044:2006 standard for LCA implementation. Additionally, greenhouse gas (GHG) emissions were calculated based on guidelines provided by the Intergovernmental Panel on Climate Change (IPCC) 2006. The results indicate that processing 1,000 kg of robusta coffee cherries yields approximately 516.5 kg of ground coffee. The total energy required for the processing was 1,476.8 megajoules (MJ) per ton of coffee cherries. Energy consumption analysis revealed that the production process accounted for 74.13% of total energy use, transportation activities 23.43%, and packaging 2.44%. Furthermore, the total GHG emissions from robusta coffee processing were estimated at 111.38 kg CO_2eq/ ton of fresh coffee cherries, or approximately 0.22 kg CO_2eq/ kilogram of ground coffee. These findings serve as a foundation for developing strategies to reduce environmental impacts and promote sustainable production practices.

1. INTRODUCTION

The coffee plantation sector is one of the key contributors to Indonesia's foreign exchange earnings. In 2019, the total area of coffee plantations in Indonesia reached approximately 1.27 million hectares, with an annual production of 729,074 tons (Ditjenbun, 2020). Currently, Indonesia ranks as the fourth-largest coffee exporter in the world, holding around 11% of the global market share (Raharjo, 2012). Coffee processing activities in Indonesia have experienced significant growth, particularly in downstream sectors, as evidenced by the increasing number of coffee processing businesses, coffee shops, cafés, and coffee stalls (AIKE, 2017). This indicates that the coffee processing activities plays a significant economic role; however, its environmental implications remain insufficiently quantified, particularly at the small scale industry level.

Every stage in the coffee processing system contributes to environmental impacts, including acute and chronic aquatic ecotoxicity, human toxicity, and eutrophication. These impacts can be systematically evaluated using the Life Cycle Assessment (LCA) approach, which enables a comprehensive assessment from cradle to grave (Astuti et al., 2021; Choiron et al., 2023). However, recent studies indicate that LCA applications in the coffee sector still lack methodological consistency, particularly in defining system boundaries and impact categories, which limits comparability across different studies (Muchangos et al., 2025).

The disposal of organic waste from the processing industry into rivers and watercourses also triggers eutrophication in aquatic systems, depleting the oxygen essential for aquatic plants and wildlife (Blinová et al., 2017). These impacts arise across multiple stages of the coffee life cycle, highlighting the need for a systematic and standardized LCA framework. At each of these stages, including agricultural practices, processing, and distribution, substantial natural resources such as water, energy, and land are consumed. Additionally, each stage of coffee production generates solid, liquid, and gaseous waste, which has the potential to pollute the environment. Even at the consumption stage, single-use coffee packaging contributes to the growing plastic waste burden, which is difficult to degrade. In addition, agricultural inputs such as fertilizers and energy use have been identified as major contributors to environmental impacts in coffee production systems, particularly in terms of global warming potential and eutrophication (Rahmah et al., 2022).

Despite the growing number of studies on coffee production, limited research has been conducted on small- and medium-scale coffee processing industries in Indonesia, particularly in Bali. This creates a research gap in understanding localized environmental impacts and identifying improvement opportunities using a standardized LCA framework. Furthermore, variations in processing technologies have been shown to significantly influence environmental performance, particularly in energy consumption and emissions, highlighting the need for case-specific LCA studies (Irawan & McLellan, 2024).

One of the coffee enterprises in Bali, Indonesia, is UD. Cipta Lestari. UD. Cipta Lestari processes robusta coffee and is located in Pujungan Village, Tabanan Regency, an area renowned for its fertile coffee farming potential. The excellence of UD. Cipta Lestari in producing high-quality robusta coffee has made it one of the significant coffee producers contributing to the local economy of Tabanan Regency, Bali. In addition to meeting domestic market demand, UD. Cipta Lestari's coffee products have penetrated international markets. The partnerships established with foreign companies for marketing coffee products further strengthen UD. Cipta Lestari's position as a key player in the coffee industry. This success has not only had a positive impact on the local economy but also created employment opportunities, introduced Bali coffee to the global market, and promoted the diversity and potential of Indonesia's local products.

Behind the success of UD. Cipta Lestari in robusta coffee production lies a significant potential to enhance sustainability and operational efficiency through Life Cycle Assessment (LCA). Life Cycle Assessment (LCA) is an approach used to assess the environmental impact of a processing system from its initial stage to its final stage, encompassing the entire life cycle from the raw materials used (cradle) to the disposal of the product after use (grave) (Hanafi et al., 2021). This approach allows for a more comprehensive and quantitative evaluation of environmental impacts by considering each stage in the product's life cycle. Without LCA, UD. Cipta Lestari may not have been able to identify areas with potential for improvement in resource management and reducing negative environmental impacts.

Several coffee processing system have assessed the life cycle of their operations. Examples include coffee processing operations in Beloe Klasik Lampung (Adiwinata et al., 2021a), CV. Gunung Betung in Bandar Lampung (Adiwinata et al., 2021b), coffee agroindustries in Klungkung, Jember (Novita et al., 2023), and coffee and cocoa production in Sumedang (Rahmah et al., 2024). Conducting a life cycle assessment at UD. Cipta Lestari is important because it will encourage the development of a green industry community, particularly in coffee production.

2. METHOD

The goal of this study is to evaluate the environmental impacts associated with robusta coffee production at UD. Cipta Lestari using a Life Cycle Assessment approach. The functional unit used in this study is 1 kg of ground coffee ready for consumption. The system boundary is defined as cradle-to-gate, covering raw material extraction, cultivation, harvesting, processing, and packaging stages. Primary data were collected from field observations and interviews, while secondary data were obtained from databases and literature.

Research Location

The research was conducted at UD. Cipta Lestari, Pujungan Village, Pupuan District, Tabanan Regency, Bali (Figure 1). The study was carried out over a period of 1 month, covering the process from the input of materials to the final coffee product.

Figure 1. Research Location of UD Cipta Lestari, Pujungan Village, Pupuan District, Tabanan Regency, Bali

Data Collection and Analysis

The types of data used in this study are primary and secondary data. Primary data was obtained from surveys conducted at the research site, while secondary data was sourced from research articles relevant to the research topic. Quantitative descriptive analysis was employed to describe the research data.

The application of LCA in agro-industrial systems provides a systematic framework to evaluate environmental impacts across the entire life cycle (Schmidt Rivera et al., 2020). The life cycle assessment (LCA) was evaluated based on two activities: coffee bean collection and coffee production. The LCA identification was examined through the input and output processes of each activity. The LCA method was implemented following the guidelines outlined in the ISO 14044:2006 Framework.

Energy usage in the coffee production process includes the consumption of gasoline, diesel, gas, and electricity. Greenhouse gas (GHG) emissions were calculated based on the guidelines from the Intergovernmental Panel on Climate Change (IPCC, 2006). The emission calculation uses the following formula:

$$Emission = QF \ x \ NK \ x \ FE \text{..............(1)}$$

Where:
QF = Fuel consumption (gasoline, diesel, gas)
NK = Net calorific value
FE = Emission factor

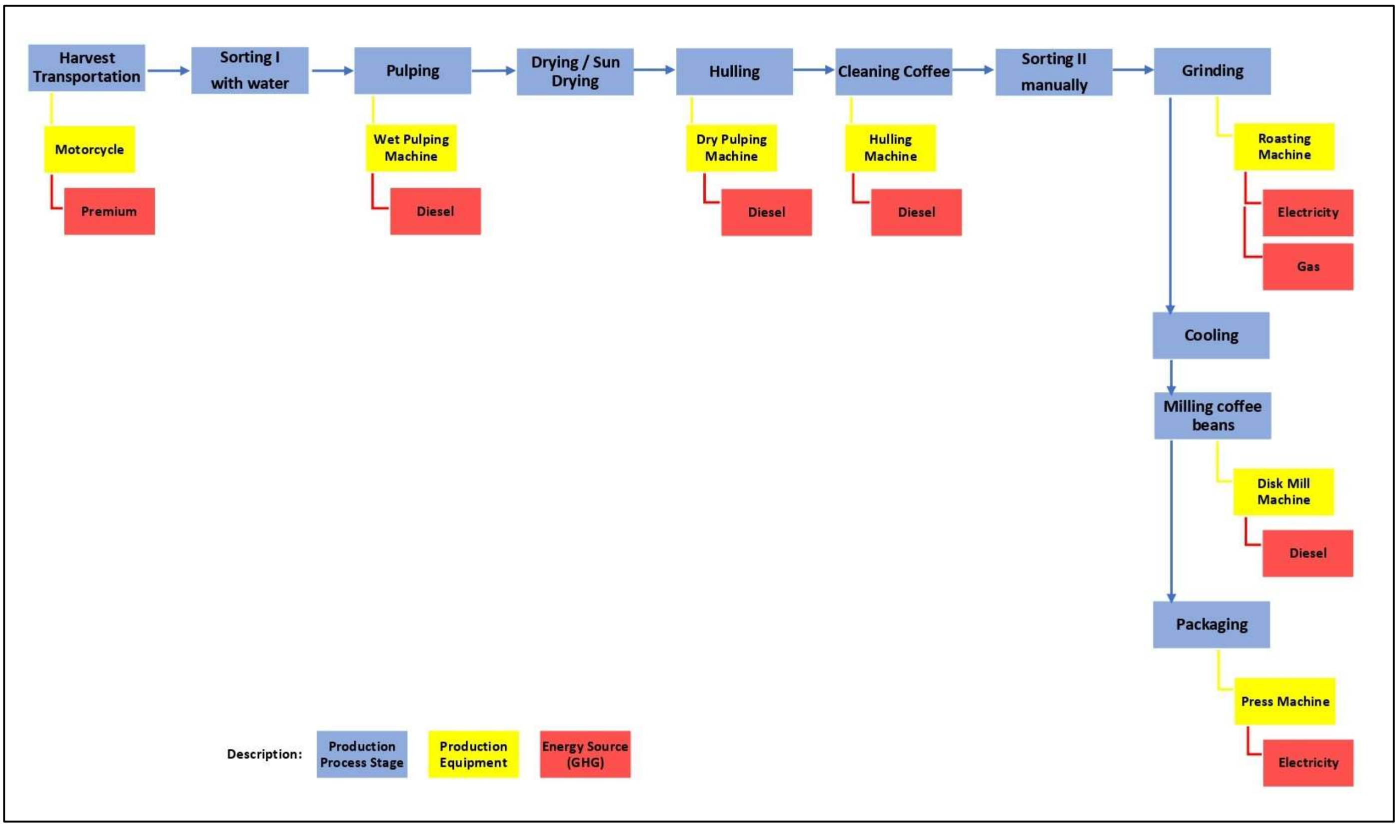

Figure 2. Life Cycle Assessment Process at UD. Cipta Lestari
(Source: Analysis, 2025)

3. RESULTS AND DISCUSSION

Based on the research conducted on the robusta coffee processing activities at UD. Cipta Lestari, the input and output analysis of the production process, processing from 1,000 kg, resulted in 516.5 kg. The coffee production experienced a reduction of 48.35% from red cherry picking to ready-to-consume coffee. When compared to research conducted at other locations, the reduction in wet coffee production at Beloe Klasik Lampung reached 79.93% (Adiwinata et al., 2021a), and the reduction in dry coffee production was 77.15% (Adiwinata et al., 2021b). The difference in production reduction is about 27.80-31.58%. This variation could be attributed to the quality of the coffee beans and the geographical conditions of the area.

In addition to coffee powder, the coffee processing system also generates waste, consisting of 332.5 kg of solid waste, 2,000 liters of liquid waste, and 151 liters of water content along with other volatile compounds that are evaporated (Table 1). Waste reduction measures are an important initiative to mitigate the waste discharged into the environment. Waste treatment should apply the recycling principle, as the solid waste produced can be used to create organic fertilizer (Buhani et al., 2024). This fertilizer can then be reused by farmers to meet plant nutritional needs and reduce the use of chemical fertilizers. In addition, coffee processing generates significant amounts of organic waste, particularly spent coffee grounds and pulp residues, which can contribute to environmental pollution if not properly managed. These waste streams have been identified as key contributors to environmental burdens in coffee production systems (Rajabi Hamedani et al., 2022).

In this process, circular economy principles are implemented to enhance resource efficiency (Joshua & Endah, 2020; Pazmiño et al., 2024; Pongsiriyakul et al., 2024; Wijaya et al., 2024). This not only reduces the volume of waste that ends up in landfills but also optimizes the use of natural resources more efficiently while reducing carbon emissions (Wiratama & Wijaya, 2024). The valorisation of coffee waste into energy, compost, or bio-based materials has been widely recognized as an effective strategy to reduce environmental impacts and improve resource efficiency in agro-industrial systems (Schmidt Rivera et al., 2020). The application of this principle will become increasingly important to support environmentally friendly agriculture and reduce the negative impacts of unsustainable farming practices. Organic coffee farming can also reduce the energy consumption used in the coffee processing system (Hasan et al., 2024). Alternative waste management strategies, including composting and material recovery, have been identified as environmentally preferable options compared to conventional disposal methods (Forcina et al., 2023).

The energy requirement at UD. Cipta Lestari for a capacity of 1,000 kg is 1,476.8 MJ/ton. The energy sources used are premium gasoline, diesel, LPG, and electricity. The process stages and detailed energy requirements are shown in Table 2. The results clearly indicate that the processing stage represents the main environmental hotspot in the coffee processing system, particularly due to intensive energy consumption during roasting, milling, and hulling processes.

This finding is consistent with previous industrial-scale LCA studies, which highlight that post-harvest and processing stages contribute significantly to overall environmental burdens (Kor Simsek & Icier, 2026).

Table 1. Input and Output of Robusta Coffee Processing at UD. Cipta Lestari

Process		Input		Output			
					Waste		
		Materials (kg)	Water (L)	Products (kg)	Solid Waste (kg)	Liquid Waste (L)	Vaporized Waste (L)
Harvesting red coffee cherries	Red Coffee Cherries	1000	-	-	-	-	-
Sorting I with water	Selected Red Coffee Cherries	1000	2000	985	15	2000	-
Pulping	Selected Coffee Fruit	985	-	815	170	-	-
Drying / Sun drying	Dried Coffee Cherries	815	-	724	-	-	91
Hulling	Coffee Beans (unprocessed)	724	-	611	113	-	-
Cleaning Coffee	Clean Coffee Beans	611	-	605	6	-	-
Sorting II manually	Premium Coffee Beans	605	-	577	28	-	-
Roasting	Ripe Coffee Beans	577	-	521	-	-	56
Cooling	Ripe Coffee Beans (processed)	521	-	520	-	-	1
Milling coffee beans	Coffee Powder	520	-	517	-	-	3
Packaging	Packaged Coffee	517	-	516,5	0.5	-	-
Total				**516,5**	**332.5**	**2000**	**151**

Source: Analysis, 2025

Table 2. Energy Requirements for Robusta Coffee Processing (Capacity 1,000 kg/day)

Process	Emission Sources (MJ)								Total (MJ)	Percentage (%)
	Premium (L)	Diesel (L)	Gas (kg)	Electricity (kwh)	Premium (MJ)	Diesel (MJ)	Gas (MJ)	Electricity (MJ)		
Harvesting red coffee cherries	10	-	-	-	346	-	-	-	346	23.43
Sorting I with water	-	-	-	-	-	-	-	-	-	0.00
Pulping	-	5	-	-	-	179	-	-	179	12.12
Drying / Sun drying	-	-	-	-	-	-	-	-	0	0.00
Hulling	-	5	-	-	-	179	-	-	179	12.12
Cleaning Coffee	-	2	-	-	-	71.6	-	-	71.6	4.85
Sorting II manually	-	-	-	-	-	-	-	-	0	0.00
Roasting	-	-	9	25	-	-	432	90	522	35.35
Cooling	-	-	-	-	-	-	-	-	0	0.00
Milling coffee beans	-	4	-	-	-	143.2	-	-	143.2	9.70
Packaging	-	-	-	10	-	-	-	36	36	2.44
Total	**10**	**16**	**9**	**35**	**346**	**572.8**	**432**	**126**	**1,476.8**	**100**

Source: Primary data analysis and assumptions (IPCC, 2006)
Premium = 34.6 MJ/Liter, Diesel = 35.8 MJ/Liter, LPG = 48 MJ/kg, Electricity = 3.6 MJ/kWh

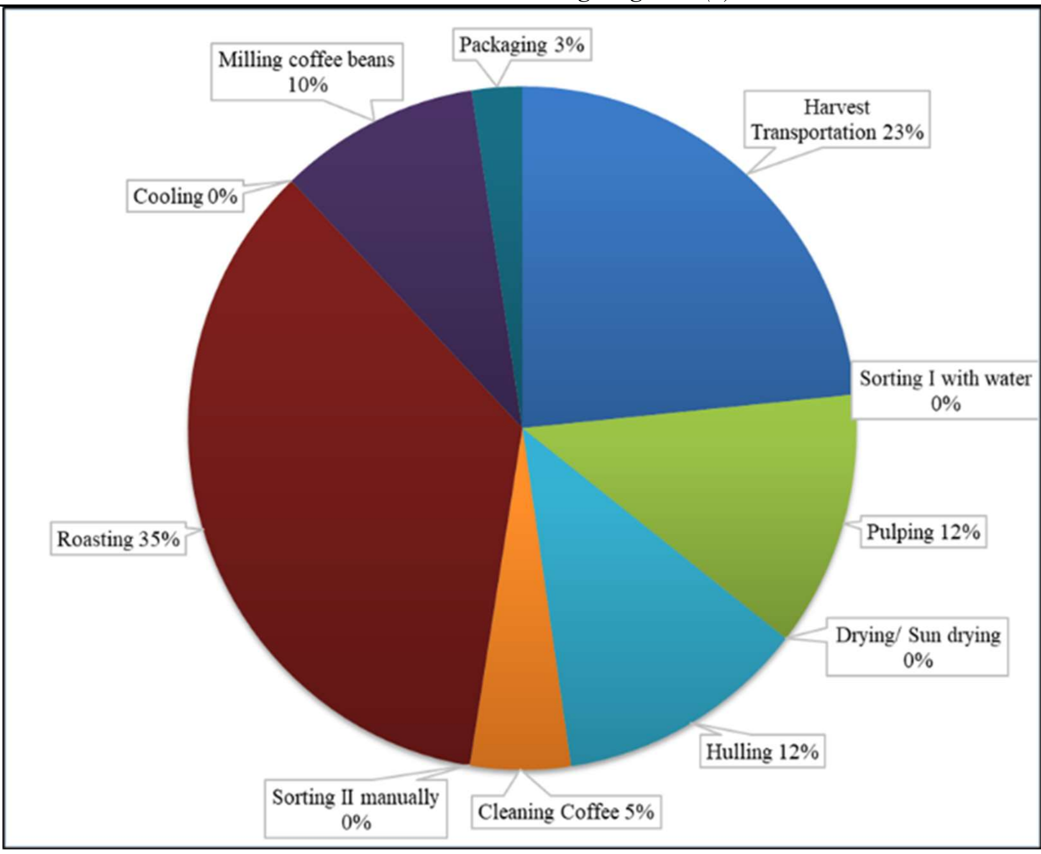

Figure 3. Percentage of Energy Requirements for Robusta Coffee Processing (Capacity 1,000 kg/day)

The coffee processing activities at UD. Cipta Lestari are divided into transportation, production, and packaging activities. The percentage comparison of these activities shows that production requires the highest energy consumption, accounting for 74.13%, followed by transportation at 23.43%, and packaging at 2.44%. The dominance of energy consumption in the production stage is primarily driven by the use of fossil-based fuels such as diesel and LPG, which not only increase energy demand but also contribute significantly to greenhouse gas emissions (Irawan & McLellan, 2024).

When examining the use of primary and secondary energy, differences are also evident. The primary energy, sourced from the combustion of fossil fuels, accounts for 62.22%, while secondary energy, derived from the indirect combustion of fuels, accounts for 37.78%. The energy requirements for each processing activity can be seen in Figure 3.

The emissions generated are largely a result of the use of fossil fuels, namely premium gasoline, diesel, and LPG. The relatively high contribution of emissions from the roasting process is associated with thermal energy requirements, which have been identified as one of the main contributors to global warming potential in coffee processing systems (Pazmiño et al., 2024). The production activity contributes 78.98 kg CO_2eq, transportation contributes 23.40 kg CO_2eq, and packaging contributes 9 kg CO_2eq. The greenhouse gas (GHG) emissions calculation for the coffee processing process at UD. Cipta Lestari can be seen in Table 3 and Table 4. These findings highlight the importance of improving energy efficiency and transitioning to cleaner energy sources as key strategies to reduce environmental impacts in small-scale coffee processing industries (Muchangos et al., 2025).

Table 3. Greenhouse Gas Emissions from Robusta Coffee Processing at UD. Cipta Lestari

Process	Emission GHG CO_2eq (Kg)			Total CO_2eq (Kg)	Percentage (%)
	CO_2	CH_4	N_2O		
Harvesting red coffee cherries	23.4	0.0005	0.0003	23.40	21.01
Sorting I with water	-	-	-	-	0.00
Pulping	13.4	0.0005	0.00025	13.40	12.03
Drying / Sun drying				0.00	0.00
Hulling	13.4	0.0005	0.00025	13.40	12.03
Cleaning Coffee	5.36	0.0002	0.0001	5.36	4.81
Sorting II manually	-	-	-	0.00	0.00
Roasting	36.09	0.00152	0.00518	36.10	32.41

Cooling	-	-	-	0.00	0.00
Milling coffee beans	10.72	0.0004	0.0002	10.72	9.63
Packaging	9	0.0005	0.002	9.00	8.08
Total	**111.37**	**0.00412**	**0.00828**	**111.38**	**100**

Source: Analysis, 2025

Table 4. Estimation of Greenhouse Gas Emissions from Robusta Coffee Processing at UD. Cipta Lestari (capacity 1,000 kg)

Process	Emission GHG CO_2eq (Kg)		
	Per Day	Per Month	Per Year
Harvesting red coffee cherries	23.40	702.02	8,424.29
Sorting I with water	0.00	0.00	0.00
Pulping	13.40	402.02	4,824.27
Drying / Sun drying	0.00	0.00	0.00
Hulling	13.40	402.02	4,824.27
Cleaning Coffee	5.36	160.81	1,929.71
Sorting II manually	0.00	0.00	0.00
Roasting	36.10	1,082.90	12,994.81
Cooling	0.00	0.00	0.00
Milling coffee beans	10.72	321.62	3,859.42
Packaging	9.00	270.08	3,240.90
Total	**111.38**	**3,341.47**	**40,097.66**

Source: Analysis, 2025

The total GHG emissions are dominated by CO_2, with CH_4 and N_2O gases also contributing to the impact. The GHG emissions from robusta coffee processing at UD. Cipta Lestari amount to 111.38 kg CO_2eq/ton of red coffee cherries or 0.22 kg CO_2eq/kg of coffee powder. The GHG emission value at UD. Cipta Lestari is considered good when compared to the lower threshold value set by the Ministry of Industry in Ministerial Regulation No. 54 of 2020, which is 3.75 tons CO_2eq/ton of product (Kementerian Perindustrian, 2020). Assuming the monthly productivity of UD. Cipta Lestari, the emissions would amount to 3,341.47 kg CO_2eq per month, and 40,097 kg CO_2eq per year.

Overall, the findings of this study confirm that energy consumption and processing activities are the main contributors to environmental impacts in coffee processing systems. Therefore, improving energy efficiency, optimizing processing technologies, and implementing sustainable waste management practices are essential strategies to enhance environmental performance, particularly in small-scale coffee industries.

4. CONCLUSION

Based on the results and discussion, it can be concluded that the robusta coffee processing system at UD. Cipta Lestari, from the input and output process of 1,000 kg of coffee beans, results in 516.5 kg of coffee powder. The energy requirement for processing is 1,476.8 MJ/ton. The percentage comparison of activities shows that production requires the highest energy consumption, at 74.13%, followed by transportation at 23.43%, and packaging at 2.44%. The GHG emissions from robusta coffee processing are 111.38 kg CO2eq/ton of red coffee cherries or 0.22 kg CO2eq/kg of coffee powder.

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