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Coffee Pulp Biomass Utilization on Coffee Production and Its Impact on Energy Saving, CO_2 Emission Reduction, and Economic Value Added to Promote Green Lean Practice in Agriculture Production

Devi Maulida Rahmah [1,2,*], Efri Mardawati [1,2], Roni Kastaman [1], Totok Pujianto [1] and Rahmat Pramulya [3]

[1] Department of Agricultural Industrial Technology, Faculty of Agricultural Industrial Technology, Universitas Padjadjaran, Bandung 40132, Indonesia
[2] Research Collaboration Center for Biomass and Biorefinery between BRIN and Universitas Padjadjaran, Jatinangor 40600, Indonesia
[3] Faculty of Agriculture, University of Teuku Umar, Meulaboh 23681, Indonesia
* Correspondence: devi.maulida.rahmah@unpad.ac.id

Abstract: The global market's sustainability demand for coffee as a result of environmental concerns has influenced coffee producers to practice green coffee production. The efforts to improve the environmental performance of coffee production should also consider the other sustainability aspects: energy and economics. Using a green fertilizer from agricultural biomass can lower carbon dioxide (CO_2) emissions since the cultivation process, which is directly impacted by fertilizer use, has been identified as an environmental damage hotspot for coffee production. This study aims to determine the impact of coffee pulp biomass utilization on coffee production in terms of energy savings, CO_2 emission reduction, and economic value added. The methodologies used were environmental Life Cycle Assessment, energy requirement analysis, life cycle costing, and eco-efficiency analysis. The study findings showed that using coffee pulp biomass in coffee cultivation impacted the energy savings, environmental damage reduction, and increased economic value added. Applying coffee pulp biomass can potentially reduce 39–87% of cumulative energy demand, 49.69–72% of CO_2 emissions, and 6–26% of the economic value-added increase. Moreover, coffee pulp utilization as a fertilizer is recommended to be applied broadly to promote sustainable coffee production according to its beneficial impact. This study provided that scientific information farmers need to apply green fertilizers in coffee production.

Keywords: coffee pulp biomass; coffee production; carbon footprint; energy saving; economic value added

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1. Introduction

The natural depletion and scarcity of resources that are caused by extensive agriculture production has encouraged global awareness of sustainability. The rapid increase in food demand has impacted the gradual expansion of the agricultural production sector. It has become evident that agriculture production needs to emphasize resource efficiency and utilization, solve environmental issues, and develop a green circular economy toward sustainable production and consumption. Therefore, Sustainable Development Goals (SDGs) are related to the sustainability of nature and resources for future generations [1]. Agriculture production requires improvements in the production operations to meet sustainability requirements. Consequently, the agriculture actors need to identify and manage the procedures that enhance resource efficiency and promote the benefit to the overall sustainability [1].

Coffee is one of the agricultural commodities traded on the global market, with more than 7 million tons of green beans consumed globally per year. Coffee consumption has increased annually, with a percentage increase of 2.47% in 2017, 3.44% in 2018, and 0.78% in 2019. The demand for coffee is expected to continuously increase during the forthcoming year [2]. The high consumption of coffee yields a significant amount of waste and could potentially cause environmental damage. According to studies, agricultural production on a farm level has contributed significantly to greenhouse gas (GHG) emissions [3,4]. Specifically, coffee cultivation is a hotspot of emissions in the coffee supply chain, with a 32–78% contribution to the total carbon footprint [3,4]. Moreover, fertilizer also contributes significantly to emitting CO_2 during cultivation [4–6]. Therefore, the employment of a green fertilizer during coffee cultivation should be considered for future sustainable coffee production.

Conventional coffee production by Indonesian farmers involves the usage of a substantial amount of a chemical fertilizer along with manure [5]. The alternative of practicing green coffee production at the farmer level should be explored in accordance with the sustainability requirements of global coffee consumption [7]. Coffee pulp biomass, a byproduct of coffee production, is one of the potential fertilizers that can be applied as an alternative fertilizer. The high demand for coffee has impacted the enormous waste generated during the process, such as coffee cultivation residue, pulp, parchment, water waste, and ground coffee waste. Coffee pulp biomass is a waste generated by post-harvest processing in the pulping process. Moreover, cherry bean processing results in approximately 40–65% of the coffee pulp biomass. The potential coffee pulp biomass is estimated to be 1,367,280 tons per year, according to the average Indonesian coffee cherry bean production [2].

Some coffee farmers in Aceh, Indonesia, utilize coffee pulp biomass as a fertilizer for coffee production. They use coffee pulp as a primary and additional fertilizer, along with a chemical fertilizer. Traditionally, Indonesian coffee farmers have used chemical fertilizer, manure, and compost as fertilizer during coffee production [5]. However, a previous study revealed that chemical fertilizer is the chief contributor to environmental damage in coffee production [5]. Moreover, manure accessibility is a major problem when applying the organic system gradually. Therefore, using coffee pulp biomass in coffee production promotes the green fertilizer application and develops a green circular economy in coffee production, as indicated by the waste resulting from its process of being used as the essential input in coffee production at the farm level [8]. The utilization of the coffee pulp biomass as a fertilizer during coffee production can potentially resolve two issues: (1) reduce the potential CO_2 emissions resulting from fertilizer use, and (2) solve the waste problem by implementing green waste management.

In recent years, several studies have investigated the environmental impacts of coffee production and consumption areas [9–12]. A specific study for coffee production in Indonesia was performed according to the fertilizer application by comparing chemical fertilizer and manure use in the cultivation process [5,12]. However, no literature specifically evaluates the comprehensive assessment of coffee pulp utilization as a fertilizer. Since the farmer can provide an abundance of coffee pulp after the post-harvest process, the utilization of coffee pulp is potentially being applied massively. The scientific literature is essential as evidence to encourage all coffee stakeholders to apply coffee pulp biomass as a fertilizer. Therefore, investigating the comprehensive sustainability aspect of coffee pulp biomass utilization as a fertilizer would provide valuable information for all coffee stakeholders: farmers, governments, and consumers. To evaluate the sustainability of coffee pulp biomass utilization, assessing the environmental, economic, and social aspects will provide a comprehensive evaluation of the sustainability status [13]. Therefore, further analysis connected to the SDGs related to the energy issue in agriculture production becomes essential [14]. The previous study in sustainability also included an energy analysis as an aspect of sustainability [15–18].

The life cycle approach is a holistic method for evaluating sustainability, specifically for environmental, economic, and social impact evaluation. In recent years, Life Cycle Assessment (LCA) has been widely used in many fields, such as energy and conservation [19], waste management [20], bioenergy and biorefinery production [21,22], business [23], medical [24], and social [25]. Many Life Cycle Assessment (LCA) studies also work on food and agriculture production [26–33].

The LCA study was conducted using single, multiple, or jointly integrated evaluations, based on which aspect would be evaluated. A few LCA studies on agriculture have comprehensively evaluated multiple sustainability assessments: energy, environment assessment, economy, and social [14]. The current study on sustainability also seeks to jointly integrate the performance of a system and product by identifying the cross-relations between the economic and ecological issues associated with environmental impact, known as the eco-efficiency index [34–36]. However, none of them are actively engaged in the application of biomass from coffee or in assessing its influence on all aspects of comprehensive sustainability.

Since no literature exists on comprehensive sustainability investigations of coffee pulp utilization as a substitute fertilizer in the coffee cultivation process in Indonesia, this study aims to investigate coffee biomass utilization in coffee production and its impact on the carbon footprint, energy savings, and economic performance by using an integrated Life Cycle Assessment approach. This study provides scientific evidence of the green fertilizer utilization from coffee pulp and its beneficial impact on the three comprehensive sustainability aspects: energy, environment, and economics. The application of green fertilizer from the biomass will promote green agriculture practices and circular economics in coffee production from the lower-level coffee actors. Figure 1 presents the framework of this study.

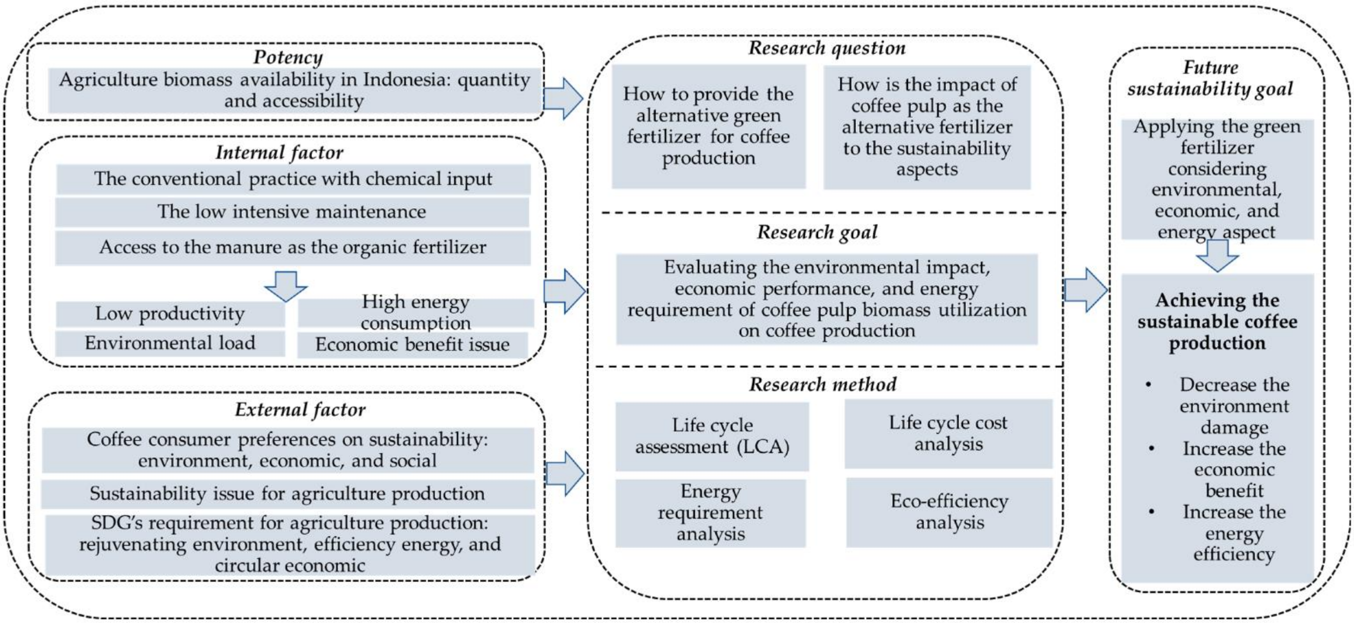

Figure 1. The research framework of the study.

2. Materials and Methods

The study was conducted in Aceh Tengah district, Aceh Province, Indonesia. This area, where coffee is cultivated in the mountainous region, is regarded as one of Indonesia's most prominent coffee production centers. Figure 2 indicated the research location.

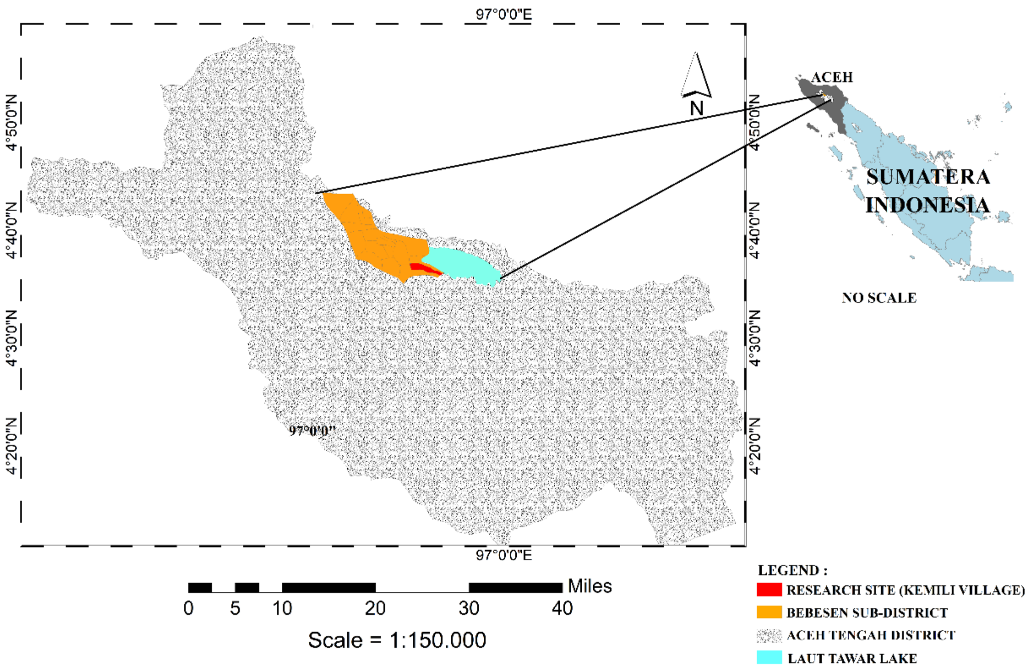

Figure 2. Area overview with a zoomed-in area showing the research location.

The present study evaluated all three aspects related to the sustainability, i.e., the energy, environment, and economy, of coffee pulp biomass utilization on coffee production from the upstream to downstream. Further analysis that jointly evaluated the environmental and economic impacts was also performed by assessing the eco-efficiency index. Figure 3 shows a schematic representation that exhibits the research stages.

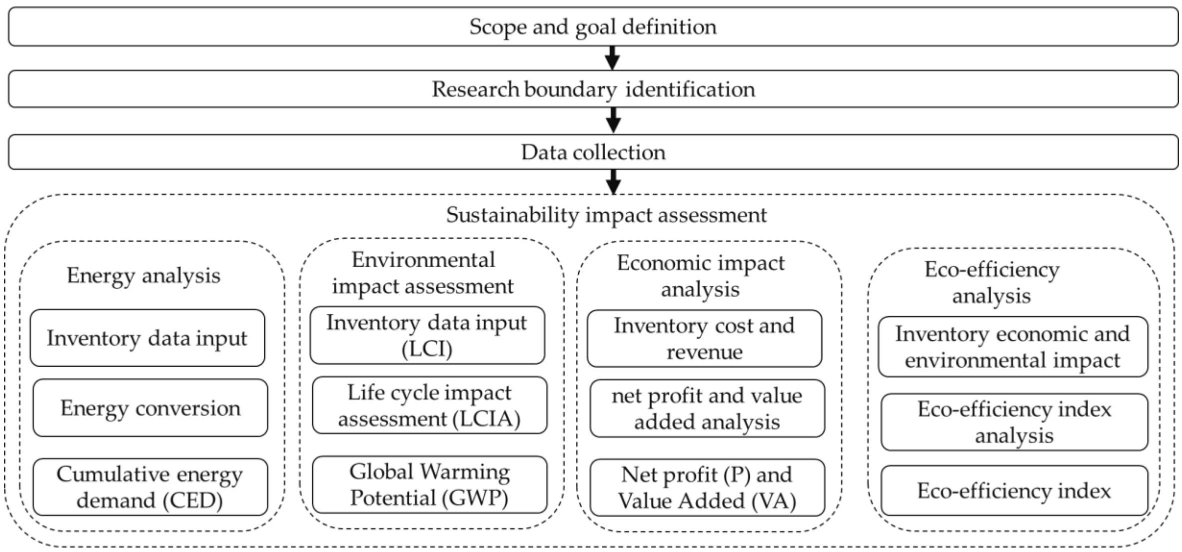

Figure 3. Schematic representation of the research stages.

The first stage was to identify the scope and goal of the Life Cycle Assessment (LCA) study. The goal of this study was to comprehensively evaluate the sustainability aspects—energy, environment, economy—and the eco-efficiency of coffee pulp biomass utilization as a fertilizer in coffee production.

The second stage was research boundary identification. This study examined the analysis from the cradle to gate: from the cultivation until the coffee post-harvest process. In the cultivation, all activities related to the nursery, land preparation, planting, maintenance, harvesting, and replanting were considered. In the post-harvest processing, all production processes from cherry bean preparation, pulping, drying, and packaging were included.

The third stage was data collection, which was carried out among 60 coffee farmers in Aceh Tengah. The data were collected using a questionnaire, deep interviews, and field observation. This study involved 15 farmers who have been practicing conventional non-organic farming (CM), 15 farmers using conventional organic farming (OM), 20 farmers using non-Organic Coffee pulp (CPB), and 10 farmers using inorganic coffee pulp (OPB). The questionnaire is provided in Table A1.

The last stage was the sustainability analysis. This study had four sustainability aspects: energy, environment, economics, and eco-efficiency. This study used the cumulative energy demand (CED) as the indicator for the energy aspect; Global Warming Potential (GWP) as the environmental impact indicator; value added (VA) as the economic indicator; and the eco-efficiency index as the integrated economic–environmental indicator.

2.1. The Research Boundary and Scenarios

2.1.1. The Research Boundary

Research boundary identification is an important stage after the goal and scope of the LCA research definition. The boundary system of this study followed Figure 4.

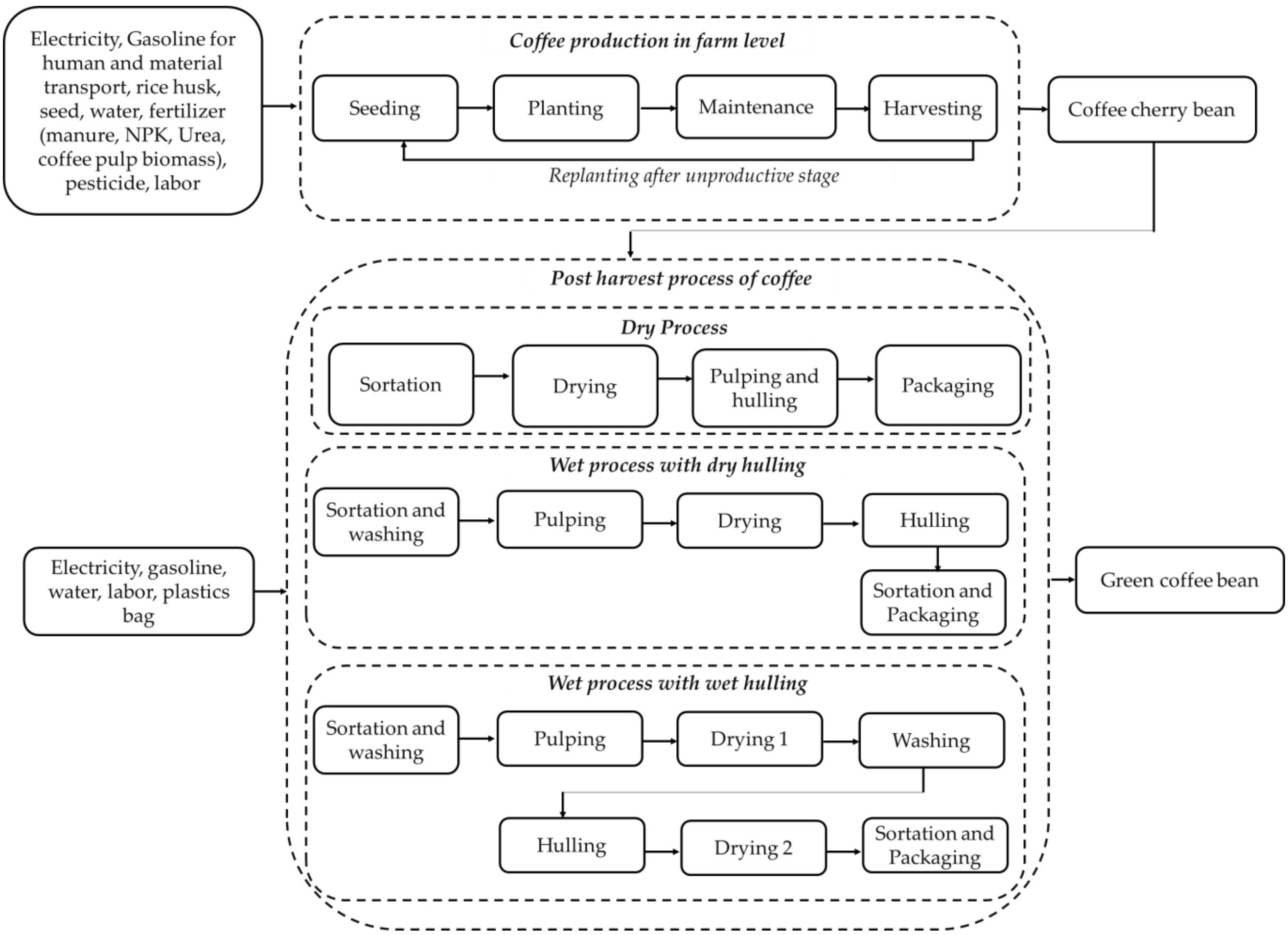

Figure 4. The boundary system for this study.

All LCA impact analyses followed the boundary system for the calculations. The two stages of coffee production that were examined in this study were the cultivation in upstream and post-harvest processing in downstream. The cultivation process included all the stages of coffee production at the farm level: seeding and nursery, planting, multiple years of maintenance, and multiple years of harvest until the coffee tree required replanting. Moreover, considering all the stages of coffee cultivation, from seeding until replanting, would provide the actual conditions that would affect the validity of the calculation in the life cycle study [5]. In the coffee post-harvest process stage, this study included all production processes, from the cherry bean preparation to the green coffee bean production.

2.1.2. The Research Scenario

In the cultivation stage, four scenarios were performed according to the fertilizer application, namely:

(1) Chemical Manure (CM): This scenario is commonly used by farmers in Indonesia and involves the use of a combination of chemical fertilizer (NPK) and manure as the organic fertilizer.
(2) Organic Manure (OM): This scenario is performed by applying the manure as the primary fertilizer input during the cultivation. A previous study reported that access to large amounts of manure is challenging [5]. The farmers must frequently travel long distances to provide a lot of manure for their coffee cultivation. Therefore, only a few coffee farmers are practicing using organic manure with a single application on their farm.
(3) Chemical Coffee pulp (CPB): This scenario is performed by applying chemical fertilizer combined with the coffee pulp as an organic fertilizer. The amount of coffee pulp per tree is 2–4 kg per application.
(4) Organic Coffee pulp (OPB): This scenario uses the coffee pulp as a fertilizer. The farmer directly applies the coffee pulp after the pulp is resulted as the co-product of green coffee beans production. In the single use of a coffee pulp application (OPB), an amount of about 4–8 kg of coffee pulp is applied per coffee tree in the farm, which is higher than in CPB. Since the availability and accessibility of coffee pulp are not difficult for farmers, the application of coffee pulp can be widely applied.

Figure 5 presents the coffee pulp application on the farm.

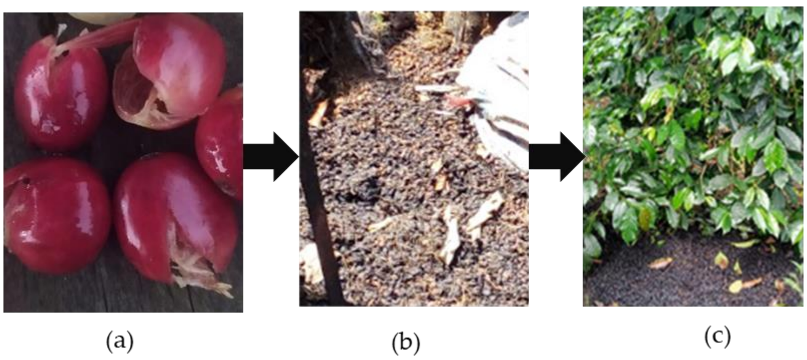

Figure 5. Coffee pulp biomass application. (**a**) Fresh coffee pulp as the co-product from the pulping process; (**b**) coffee pulp after a two-week waiting period before applying to the field; (**c**) coffee pulp application in a coffee plantation.

In the post-harvest process, the cherry bean that results after harvesting is processed into a green coffee bean. Three scenarios were evaluated in this study, namely:

(1) Dry Process: this is also known as the natural process. The coffee cherry bean is directly dried after the sortation process. The pulping is performed after the dried coffee has lost 10–12% of its moisture content. In the natural process, the water consumption during the process is lower than the other process.
(2) Wet Process with Dry Hulling: the coffee cherry bean is directly pulped after sortation. The coffee is dried after pulping until the moisture content is between 10% and 12%. Then, the dried coffee bean is hulled in dry conditions.

(3) Wet Process with Wet Hulling: the coffee is pulped in wet conditions, and then the coffee bean is dried until the moisture content is between 25% and 35%. Later, the coffee is hulled in wet conditions. After the hulling process, coffee is dried in the second stage until coffee moisture content is 10–12%.

This study performed the analysis in a partial and integrated scenario at the upstream and downstream levels. In partial, the analysis is conducted in each scenario during the cultivation and post-harvest process. While the integrated scenario analysis is performed by combining each scenario at cultivation with each scenario at the post-harvest process. About 12 of integrated scenarios were performed: Chemical Manure (CM)–Dry Process; Chemical Manure (CM)–Wet Process with Wet Hulling; Chemical Manure (CM)–Wet Process with Dry Hulling; Organic Manure (OM)–Dry Process; Organic Manure (OM)–Wet Process with Wet Hulling; Organic Manure (OM)–Wet Process with Dry Hulling; Chemical Coffee pulp (CPB)–Dry Process; Chemical Coffee pulp (CPB)–Wet Process with Wet Hulling; Chemical Coffee pulp (CPB)–Wet Process with Dry Hulling; Organic Coffee pulp (OPB)–Dry Process; Organic Coffee pulp (OPB)–Wet Process with Wet Hulling; and Organic Coffee pulp (OPB)–Wet Process with Dry Hulling.

2.1.3. The Functional Unit

This study used 1 hectare of coffee cultivation for the inventory data regarding the cultivation process throughout the data collection. During the post-harvest process, the data was collected using 1 ton of processed coffee cherry beans. The functional unit was utilized to collect the data while considering the availability and accessibility data. It is easy for farmers to provide data based on the cultivation area and their processing activity. Subsequently, the data availability and accessibility were assured. The data were converted after the calculation and corrected using the same functional unit, which is 1 kg of green coffee beans, as the final functional unit.

2.2. The Calculation of Indicators

The environmental impact assessment, energy analysis, economic performance, and eco-efficiency are the four key procedures used in this study. In general, the life cycle approach was employed in this study, and the inventory data for further calculations was performed prior to the conduct of the four analyses. Furthermore, the complex process makes finding accurate life cycle inventory (LCI) data challenging [37]. Therefore, it is crucial to define the boundary for all processes. Our study suggests that the LCI follows a boundary system that considers all coffee production, both in the upstream and downstream. The LCI in the upstream counted all the inputs from the cradle to the gate and from seedlings until replanting. Whereas the LCI in the downstream considered the process from the gate to gate, from the first sortation and preparation until the packaging. This study provided LCI in two processes: LCI for life cycle coffee cultivation and LCI for post-harvest processing, as presented in Tables A2 and A3.

2.2.1. The Cumulative Energy Demand Analysis (CED)

The cumulative energy demand (CED) represents the total input of energy during the process. The CED is calculated from the total energy used in all stages of coffee production: the cultivation and post-harvest processing stages. The sum of the total consumption of each input, such as fertilizer, pesticide, herbicide, gasoline, rice husks, and human labor, multiplied by the energy conversion factor [5,17], was used to calculate the total cumulative energy demand (CED) in the cultivation process. The calculation is based on the following equations:

$$CED = Eg + Eel + Eh + Ef\ o,c + Ep + Ew + Ebh \quad (1)$$

$$Eg = g \times EGf \quad (2)$$

$$Eel = el \times EELf \quad (3)$$

$$Eh = h \times EHf \quad (4)$$

$$Ef\ o = o \times Ff\ o \quad (5)$$

$$Ef\ c = c \times Ff\ c \quad (6)$$

$$Ep = p \times EPf \quad (7)$$

$$Ew = w \times EWf \quad (8)$$

$$Erh = rh \times RHf \quad (9)$$

where *CED* is the total of energy requirement; *Eg* is the energy from gasoline (MJ); *Eel* is the energy from electricity (MJ); *Eh* is the energy from human labor (MJ); *Ef o, c* is the energy from fertilizer (MJ) (*o* for organic fertilizers and *c* for chemical fertilizers); *Ep* is the energy from pesticides (MJ); *Ew* is the energy from the water (MJ); *Erh* is the energy from rice husk (MJ kg^{-1}); *el* indicates the total electricity; *h* indicates the human labor; *o* indicates the total of the organic fertilizer; *c* indicates the total of the chemical fertilizers; *p* indicates the total pesticide; *w* indicates the total water; *rh* indicates the total rice husk; *EGf* is the gasoline energy factor (MJ L^{-1}); *EELf* is the electricity energy factor (MJ kWh^{-1}); *Ehf* is the human energy factor (MJ h^{-1}); *Ff o* is the organic fertilizer energy factor (MJ kg^{-1}); *Ff c* is the chemical fertilizer energy factor (MJ kg^{-1}); *Epf* is the pesticide energy factor (MJ kg^{-1}); *Ewf* is the water energy factor (MJ m^{-3}); and *RHf* is the rice husk energy factor (MJ kg^{-1}).

The coffee pulp was assumed to be excluded from the CED calculation as it is a co-product of the coffee production process from cherry beans. Furthermore, we assume that during the cultivation process, it had already been taken into consideration in the energy calculation. The energy conversion factor is presented in Table A4 [38–49].

2.2.2. Environmental Impact Assessment

The LCA approach was employed to calculate the environmental impact. The LCA has been applied to assess the potential environmental impact associated with agriculture production [28]. This study analyses the global warming potential (GWP) as the primary environmental impact indicator. The GWP considers the emissions from material and energy input during the production activity along with the emission impact from N application in the field [12]. The following expressions were applied to calculate the total GWP impact of each scenario:

$$Total\ GWP = GWP_{el} + GWP_g + GWP_{f(o,c)} + GWP_p + GWP_{rh} + GWP_N \quad (10)$$

$$GWP_{el} = el \times EF_{el} \quad (11)$$

$$GWP_g = g \times EF_g \quad (12)$$

$$GWP_o = o \times EF_o \quad (13)$$

$$GWP_c = c \times EF_c \quad (14)$$

$$GWP_p = p \times EF_p \quad (15)$$

$$GWP_{rh} = rh \times EF_{rh} \quad (16)$$

where GWP_{el} is the CO_2 emission from electricity (kg $CO_{2\text{-eq}}$); GWP_g is the CO_2 emission from gasoline for transportation (kg $CO_{2\text{-eq}}$); $GWP_{f(o)}$ is the CO_2 emission from organic fertilizer production (kg $CO_{2\text{-eq}}$); $GWP_{f(c)}$ is the CO_2 emission from chemical fertilizer production (kg. $CO_{2\text{-eq}}$); GWP_p is the CO_2 emission from pesticide production (kg $CO_{2\text{-eq}}$); GWP_{rh} is the CO_2 emission from rice husks (kg $CO_{2\text{-eq}}$); and GWP_N indicates the emission from N applications in the field, including direct and indirect emissions resulting from N additions, deposition, and leaching [12,50]; *el* indicates the total electricity (kWh); *o* indicates the total of the organic fertilizer (kg); *c* indicates the total of the chemical fertilizer (kg); *p* indicates the total pesticide (L); *w* indicates the total water (L); *rh* indicates the total rice husk (kg); EF_{el} indicates the electricity emission factor (kg. $CO_{2\text{-eq}}$/kWh); EF_g is the gasoline emission factor (kg $CO_{2\text{-eq}}$/L); EF_o is the organic fertilizer emission factor (kg $CO_{2\text{-eq}}$/kg); EF_c is the chemical fertilizer emission factor (kg $CO_{2\text{-eq}}$/kg); EF_p is the pesticide emission factor (kg $CO_{2\text{-eq}}$/L); EF_{rh} is the rice husk fertilizer emission factor (kg $CO_{2\text{-eq}}$/kg). For calculating the direct and indirect emissions resulting from N additions, deposition, and leaching (N_2O), we followed the 2019 Refinement to IPCC Guidelines for National GHG Inventories. The calculation used the IPCC tier 1 default value of 1% for N inputs from all fertilizer applications.

2.2.3. Economic Performance Analysis

The economic performance consists of two analyses: life cycle cost and value-added analysis.

- Life cycle cost (LCC) analysis

The present study considered the life cycle of coffee during an LCC analysis from the cradle to gate. The LCC involves all economic aspects in the lifespan of products. It counted all the variable costs, such as the cost of material, labor, packaging, and transportation, according to the goal and boundary. The goal and boundaries of an LCC are similar to those of an LCA [51]. This study excludes the capital costs, such as land, in the calculation. The LCC of coffee production can be estimated using the following equations:

$$LCC_{GCB} = C_{cu} + C_{pr} - S \tag{17}$$

$$C_{cu,pr} = C_{MA} + C_{hl} + C_{TD} + C_{PA} \tag{18}$$

where C_{cu} represents the costs during the cultivation process; C_{pr} is the cost for post-harvest processing; and S represents savings-related revenue from end-of-life waste management. Following the usual LCC practice, the capital goods costs are not considered [35,51]. The costs for the cultivation process (C_{cu}) involve the material costs, such as seed, fertilizer, pesticide, and herbicide; the labor costs (C_{hl}); the transportation and distribution costs (C_{TD}) that consider the cost to transport and distribute the material to the field; and the packaging costs (C_{PA}) that considers the cost to package the product after it is harvested. The cost of post-harvest processing (C_{cr}) considers the cost of material (electricity, gasoline); the cost of transportation and distribution (C_{TD}) that considers the cost to transport and distribute the product after harvesting from the field to the factor; and the cost of packaging (C_{PA}). The study of LCC used 1 kg of green coffee beans as the functional unit during the calculation. However, the additional LCC is also provided, such as LCC producing 1 kg of coffee cherry beans and LCC managing 1 hectare of coffee cultivation. The calculation assumes there is no cost to obtain the coffee pulp as it is categorized as a waste from coffee production [12]. The cost to transport the coffee pulp includes the transportation cost.

- Value-added analysis (VA)

The value-added (VA) analysis is defined as the net profit that is calculated by the revenue (R) minus the costs of the life cycle of the product (LCC_{CGB}), reflecting the increase in economic value due to the production of the final goods [35]. In this study, the VA was estimated by considering the cycle cost incurred from the cradle to gate by using the following equation:

$$VA = R - LCC_{CGB} \tag{19}$$

2.2.4. The Eco-Efficiency Analysis

The eco-efficiency index can be used to provide a ratio between the environmental and economic performance [35]. The eco-efficiency can be calculated from two different perspectives: (1) the focus on the economic value perspective and (2) the focus on the environmental improvement perspective [34]. This study focuses on an environmental perspective, which evaluates the environmental intensity of a product or service due to the economic activity [35]. The eco-efficiency will be calculated using the following equation:

$$Eco - efficiency = \frac{EI}{EP} \quad (20)$$

where *EI* is the environmental impact expressed by the global warming potential impact and *EP* is the economic performance expressed by the net profit of the coffee cultivation.

3. Results

This study examined the CED, environmental impact assessment, economic performance, and eco-efficiency analysis of the coffee pulp biomass used in coffee production. Analysis was carried out on three upstream scenarios and four downstream scenarios.

3.1. The Cumulative Energy Demand (CED) of Coffee Production

3.1.1. The Cumulative Energy Demand in Coffee Cultivation

The CED is calculated using all the materials and energy inputs during coffee production. The productivity per hectare impacted the CED for 1 kg of product (coffee cherry beans). A lower CED follows the higher productivity per 1 hectare coffee cultivation for 1 kg of coffee cherry beans. According to this study, the average coffee production per hectare for a Chemical Manure system (CM) was 2.9×10^3 kg ha^{-1}, 2.59×10^3 kg ha^{-1} for an Organic Manure system (OM), 3.851×10^3 kg ha^{-1} for a Chemical Coffee pulp biomass system (CPB), and 2.8×10^3 kg ha^{-1} for Organic Coffee pulp biomass system (OPB). Table 1 presents the CED for coffee production at the farm level.

Table 1. Cumulative energy demand for coffee production at the farm level.

Category	Unit	Cumulative Energy Demand (CED)			
		Chemical Manure (CM)	Organic Manure (OM)	Chemical Coffee Pulp Biomass (CPB)	Organic Coffee Pulp Biomass (OPB)
Per hectare	MJ ha^{-1}	142,395.60	118,907.92	86,463.19	14,321.39
Per kilogram of coffee cherry beans	MJ kg^{-1}	55.12	56.18	22.42	5.55
Per kilogram coffee green beans (6.6. kg cherry)	MJ kg^{-1}	363.79	370.78	147.97	36.63

The utilization of coffee pulp biomass, either as the primary fertilizer or as an additional fertilizer, successfully decreased the CED in 1 hectare of coffee production. The use of the coffee pulp biomass in a conventional system (CPB) resulted in a 38.27% reduction of the CED. However, the coffee biomass utilization in an organic system resulted in an 87.95% reduction in CED. Our study was conducted on coffee farmers performing a low-level coffee production maintenance. A previous study in West Java, Indonesia, demonstrated that the most intensive maintenance required energy of 304,510 MJ·ha^{-1} for the non-organic system and 222,340 MJ·ha^{-1} for the Organic Manure system during managing 1 hectare coffee cultivation [5]. Furthermore, compared to the coffee study in West Java, our study had a lower CED when managing a 1 hectare coffee production. Hence, performing a higher level of maintenance for coffee production required a higher energy input while managing 1 hectare coffee cultivation. Moreover, the CED for a 1 kg coffee cherry bean production was lower than in this study, which is caused by the higher yield of coffee produced by the high-level coffee maintenance system rather than by the lower-middle level maintenance.

The result indicated a significant difference in CED by practicing coffee pulp biomass in the OPB. The OPB consumed 5.5 MJ·kg^{-1} of energy during 1 kg of coffee production. Furthermore, compared to the study performed in the high-level maintenance of coffee production that required 7.92 MJ kg^{-1} of CED [5], the utilization of coffee pulp biomass in OPB still produced the lower CED. Therefore, substituting the fertilizer with the coffee pulp biomass can potentially decrease the CED during the coffee production at the farm level. This result confirms a previous study that found that the fertilizer consumed a significant proportion of energy at the farm level for the agriculture production [15,52]. Moreover, the present study also reveals that using manure as the organic fertilizer in CM and OM significantly contributed to the CED, with an average contribution of 38% in the CM and 93% in OM. A recent study on coffee production in Indonesia found a similar result, indicating that the manure provided the highest contribution to the CED [5].

3.1.2. The Cumulative Energy Demand (CED) of the Coffee Post-Harvest Process

The CED is performed in three types of coffee post-harvest processes, i.e., the Dry Process, the Wet Process with Wet Hulling, and the Wet Process with Dry Hulling. Figure 6 shows the cumulative energy demand to produce 1 kg of green coffee beans in the post-harvest process.

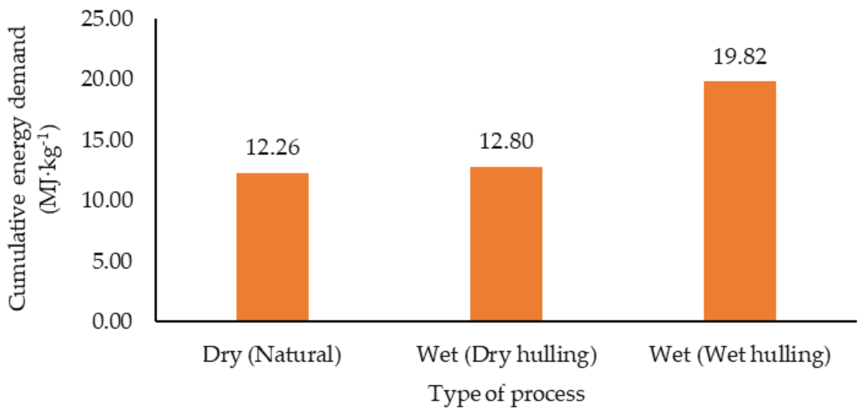

Figure 6. Cumulative energy demand (CED) of a 1 kg green coffee bean production.

Referring to the CED calculation for 1 ton of coffee cherry beans, the CED for a 1 kg green bean production is calculated by multiplying the CED for 1 ton of cherry beans processed by the total number of green beans that resulted from 1 ton of cherry beans processed [A5]. According to this study, 1 ton of processed coffee cherry beans will generate 150 kg of green coffee beans. Therefore, the CED to produce 1 kg of green coffee beans is 12 MJ kg^{-1} for the Dry Process, 12.8 MJ kg^{-1} for the Wet Process with Dry Hulling, and 19.82 MJ kg^{-1} for the Wet Process with Wet Hulling. According to the previous research, the CED for 1 kg of green coffee beans with a wet process needs 24.22–33.37 MJ [10]. While in the dry method, processing 1 kg of green coffee beans consumed the least energy (12.26 MJ kg^{-1}) than the other coffee processes.

3.1.3. The Cumulative Energy Demand of the Coffee Life Cycle

Figure 7 shows the CED for coffee production from the cradle to gate to produce 1 kg of green coffee beans.

The combination of the OM cultivation system with all coffee post-harvest processing consumed more energy than other coffee cultivation systems, as indicated by the CED of 394.4 MJ kg^{-1} of green coffee beans. Furthermore, according to a previous study, the fertilizer has been identified as the hotspot of energy consumption during agriculture production [15,53]. Additionally, the utilization of coffee pulp in the OPB with the Dry Process downstream exhibited the highest performance compared to all combinations from upstream to downstream, as shown by the lowest CED. The lower CED contributes to the decrease in CED in the cultivation stage. Moreover, substituting manure with coffee pulp as a fertilizer significantly contributed to the reduction of the CED.

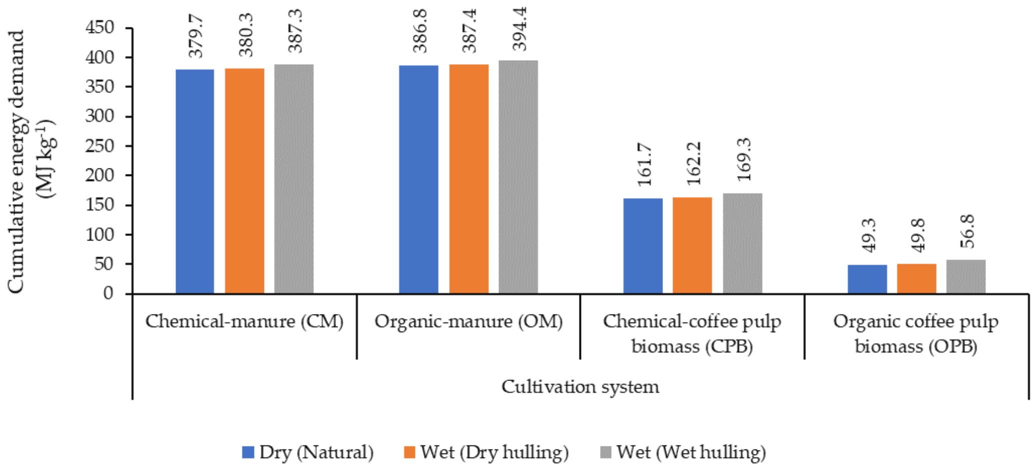

Figure 7. Cumulative energy demand of the life cycle of 1 kg of coffee green bean production from cradle to gate.

3.2. Environmental Impact of Coffee Biomass Utilization

Table 2 presents the environmental impact of coffee production with four scenarios in the cultivation process and three scenarios in the post-harvest process.

Table 2. Resumé of GWP impact in coffee production.

Stages	Categories		Unit	Scenario			
				Chemical Manure (CM)	**Organic Manure (OM)**	**Chemical Coffee Pulp (CPB)**	**Organic Coffee Pulp (OPB)**
Cultivation	Per hectare		kg $CO_{2\text{-eq}}$ ha^{-1}	6906	2705	4725	1627
	Per kg of cherry beans		kg $CO_{2\text{-eq}}$ kg^{-1}	0.24	0.096	0.058	0.03
	Per 6.6 kg of cherry beans to produce 1 kg of green beans		kg $CO_{2\text{-eq}}$ kg^{-1}	1.584	0.6336	0.3828	0.198
Post-harvest process	Categories		Unit	Dry Process	Wet Process with Wet Hulling	Wet Process with Dry Hulling	
	Per ton of cherry beans		kg $CO_{2\text{-eq}}$ t^{-1}	10.2	36	36.45	
	Per kg of green coffee beans		kg $CO_{2\text{-eq}}$ kg^{-1}	0.068	0.24	0.243	
Cumulative	Categories	Scenario	unit	Dry Process	Wet Process with Wet Hulling	Wet Process with Dry Hulling	
	Per 1 kg of green coffee beans	CM	kg $CO_{2\text{-eq}}$ kg^{-1}	1.652	1.824	1.827	
		OM	kg $CO_{2\text{-eq}}$ kg^{-1}	0.7016	0.8736	0.8766	
		CPB	kg $CO_{2\text{-eq}}$ kg^{-1}	0.4508	0.6228	0.6258	
		OPB	kg $CO_{2\text{-eq}}$ kg^{-1}	0.266	0.438	0.441	

3.2.1. The Global Warming Potential in the Coffee Cultivation Stage

This study assessed an environmental impact assessment, specifically on the Global Warming Potential impact in four types of coffee cultivation: Organic Manure (OM), Chemical Manure (CM), Organic Coffee pulp biomass (OPB), and Chemical CPB. The use of coffee pulp in both the organic and non-organic systems emitted a lower emission compared with organic (OM) and non-organic (CM), which used manure as a fertilizer during the management of 1 hectare of coffee cultivation (Table 2). Inversely, CM emitted the highest emission during managing a 1 hectare coffee plantation with 6909 $CO_{2\text{-eq}}$ ha^{-1} of GWP impact. Using coffee pulp in the Chemical Coffee pulp system (CPB) could decrease the GWP impact with a 31.58% potential reduction compared with the Chemical Manure system (CM). Moreover, coffee pulp use in the OPB will reduce 39.85% of the GWP impact compared to Organic Manure (OM).

Table 2 also presents the CO_2 emission impact for 1 kg of coffee cherry beans and cherry beans input to produce 1 kg of green coffee beans. This study used 6.6 kg of cherry beans to produce 1 kg of green coffee beans. The result indicates that 1 kg of green coffee beans has a potential CO_2 emission impact of 1.3 kg $CO_{2\text{-eq}}$ kg^{-1} for CM, 0.2772 kg $CO_{2\text{-eq}}$ kg^{-1} for OM, 0.32 kg $CO_{2\text{-eq}}$ kg^{-1} for CPB, and 0.08 kg $CO_{2\text{-eq}}$ kg^{-1} for OPB; with a potential decrease of 75.83% for the CPB application compared with CM, and 68.75% for OM compared with CM.

According to a previous study on coffee, the organic system emitted CO_2 during the production of 1 kg of coffee cherry beans, with the impact being 0.27 kg $CO_{2\text{-eq}}$ kg^{-1} [15], and 0.12–0. 52 kg $CO_{2\text{-eq}}$ kg^{-1} [12]. The previous study has the highest impact that might be caused by the moderate-intensive fertilizer application, while in this study, it was categorized as the low maintenance application. The coffee cultivation productivity in the previous study was also higher, with the average coffee production of 7.0–9.9 ton ha^{-1} y^{-1} in chemical organic and 4.8–6.6 ton ha^{-1} y^{-1} in organic practice [12]. However, the average coffee production in this study was only 2.9–3.8 ton ha^{-1} y^{-1} in chemical organic and 2.53–2.59 ton ha^{-1} y^{-1} in the organic system. According to this, the level of maintenance will be followed by higher production and its potential emissions.

The result showed that substituting the fertilizer with a green fertilizer can reduce the GWP impact. It indicated that the fertilizer is a potential emission hotspot in coffee production. Furthermore, a previous study had also reported that the fertilizer made a significant contribution to CO_2 emissions and other environmental impacts [5,15,53]. Therefore, by considering the potential GWP reduction and its productivity, coffee pulp is recommended.

3.2.2. The Global Warming Potential in the Coffee Post-Harvest Process

The quality of the post-harvest process affects the quality of the coffee. The post-harvest activity turns the coffee cherry bean into the coffee green bean. The private coffee industry and the small and medium-sized coffee farmer business groups mainly practice the post-harvest process. In this study, the post-harvest process was conducted by the small and medium-sized coffee farmer business groups. Generally, there are two types of methods: dry and wet. This study evaluated three different types of coffee post-harvest processes: the Dry Process, the Wet Process with Dry Hulling, and the Wet Process with Wet Hulling.

Table 2 indicates that the Dry Process emitted a lower CO_2 emission during 1 kg of coffee green bean production, with 0.068 kg $CO_{2\text{-eq}}$. Inversely, the higher CO_2 emission is emitted by the Wet Process with Wet Hulling, which emitted 0.43 kg $CO_{2\text{-eq}}$. The green coffee bean processed by dry and wet hulling is mainly produced for export purposes. Therefore, farmers conducted some processes according to their market destination. The following table details the emission contribution factor in all coffee post-harvest processes.

According to Table 3, the most significant contributing factor to CO_2 emissions in all post-harvest processes is gasoline, with 63–74% of the contribution used as the power source in machinery during the pulping and hulling processes. The second-highest contributor is electricity, which contributes to 25–36% of CO_2 emissions and is used as the power source to provide water for washing activities.

Table 3. Emission contributor factors.

Process	Unit	Total CO_2 Emission	Contribution Factor		
			Gasoline	Packaging Bag	Electricity
Wet (Wet hulling)	kg CO_2 eq	0.2428	0.1531	0.0002	0.0895
	%		63.0597	0.0896	36.8507
Wet (Dry hulling)	kg CO_2 eq	0.2395	0.1531	0.0007	0.0857
	%		63.9279	0.2947	35.7773
Dry Process	kg CO_2 eq	0.0686	0.0510	0.0002	0.0173
	%		74.4388	0.3174	25.2438

3.2.3. Global Warming Potential in the Coffee Life Cycle

Table 2 shows the combination processes in upstream (cultivation process) and downstream (post-harvest processing) that emitted the lowest emission is by practicing OPB combined with all scenarios in the coffee post-harvest process, with 0.26–0.441 kg $CO_{2\text{-eq}}$ of potential emissions for 1 kg of green coffee bean production with the potential reduction of 49–62% compared with the OM. On the other hand, the higher impact of the GWP is contributed by the Chemical Manure system (CM) applications, along with all downstream combination processes in that emit 1.62–1.82 kg $CO_{2\text{-eq}}$ per 1 kg of green coffee bean production. Applying the CPB to CM has a potential reduction of 63.7–72%. This study proved that using Organic Coffee pulp is significantly affected by the decrease in GWP during 1 kg of green coffee bean production. The previous study also reveals the lowest CO_2 emission affected by the organic systems [12].

3.3. Economic Performance

3.3.1. Economic Performance in Coffee Cultivation

Life cycle cost and net value-added evaluations as the economic performance indicators analyses were carried out in the cultivation stage. The LCC is calculated by considering all cultivation expenses, from seedlings to replanting. Whereas the value added is a result of the net profit generated by the cultivation process. The summary of the economic performance analysis in the cultivation process is shown in Table 4.

Table 4. The environmental performance of coffee production in the cultivation stage.

Economic Performance Indicators	Categories	Unit	Cultivation Systems			
			Chemical Manure (CM)	Organic Manure (OM)	Chemical Coffee Pulp (CPB)	Organic Coffee Pulp (OPB)
Life Cycle Cost	Per hectare coffee production	USD	3955.48	2175.03	3543.23	2857.18
	Per kg cherry bean	USD	0.17	0.1	0.04	0.05
	Per kg green coffee bean	USD	1.11	0.64	0.29	0.35
Revenue	Per hectare	USD	11,117	12,016	38,427	29,124
Value Added	Per hectare coffee production	USD	7161	9841	34,884	26,267
	Per kg coffee cherry bean	USD	0.31	0.44	0.43	0.48
	Per kg coffee green bean	USD	2.02	2.91	2.84	3.2

According to the LLC result during the cultivation stage, the chemical fertilizer used in managing a 1 hectare coffee cultivation system both on the CM and CPB needs to be more expensive than the organic system both in OM and OPB. The LCC for managing 1 hectare of coffee cultivation is the basis for calculating the LCC for 1 kg of coffee cherry beans as the final product of the cultivation process. Therefore, the LCC for 1 kg of coffee cherry beans depends on its productivity during cultivation. This research used the average production from the coffee farmers in this study area. Following the study result, using the coffee pulp biomass during the cultivation process in OPB and CPB had a lower cost than CM and OM. The LCC analysis for the whole cherry bean used to produce 1 kg of green coffee beans also indicates that using the coffee pulp in CPB and OPB can significantly reduce the cost. A 1 kg coffee green bean production in the upstream needs 0.35 USD and 0.29 USD by performing OPB and CPB. At the same time, the CM and OM coffee cultivation systems requires 1.11 USD and 0.64 USD to provide the total coffee cherry beans as the input to produce 1 kg of green coffee beans. The margin of LCC was also contributed by the reduction cost for fertilizer. Whereas this study did not involve the coffee pulp during the LCC calculation, according to previous research, the coffee pulp has no economic value since it is resulted as the waste from coffee production [12].

In the value-added aspect, both the Chemical Coffee pulp (CPB) system and the Organic Coffee pulp biomass (OPB) system generated a higher value added than the CM and OM systems. The VA is commonly contributed by the lower LCC and higher revenue per hectare of coffee cultivation in the OPB and CPB (Table 4).

3.3.2. Economic Performance in the Coffee Post-Harvest Process

In the downstream, the LCC calculated all costs from gate to the gate: from the sortation stage until packaging. Table 5 presents the LCC during 1 kg of green coffee bean production in the downstream.

Table 5. Economic performance for 1 kg of green production in the post-harvest process.

Economic Performance Indicator	Category	Unit	Post-Harvest Process		
			Dry (Natural)	Wet (with Dry Hulling)	Wet (with Wet Hulling)
Life Cycle Cost	Organic (OM, OPB)	USD kg^{-1}	3.93	3.71	3.76
	Non-Organic (CM, CPB)	USD kg^{-1}	4.35	4.13	4.18
Value added	Organic (OM, OPB)	USD kg^{-1}	1.97	2.19	2.14
	Non-Organic (CM, CPB)	USD kg^{-1}	1.13	1.35	1.3

The LCC during the post-harvest processing for 1 kg of green coffee beans was lower when using the organic coffee cherry bean as the raw material produced by the OM and OPB than when using the non-organic coffee cherry beans from the CM and CPB. The high cost is contributed by the use of the raw material, coffee cherry beans, with an 80–86% contribution to the total cost. The human labor cost is the second highest contribution, with an 18% contribution. During the coffee post-harvest processing, the Wet Process with Wet Hulling combined with the organic coffee cherry bean as the raw material input for the process is potentially more value added for the farmer, with the potential VA of 2.19 USD kg^{-1} for the organic Wet Process with Wet Hulling and 1.35 USD kg^{-1} of VA for the non-organic Wet Process with Wet Hulling. According to these results, the organic green beans in all post-harvest processes generate a higher profit for the coffee processing industry. Currently, most farmers practice the CM in their coffee production. The higher yield attracted farmers to apply this method. However, the VA analysis results indicated that after considering all aspects of the calculation, the organic system in OM and OPB still provides a higher economic benefit impact. The higher economic impact was also contributed by the higher selling price of organic coffee in the market.

3.3.3. Economic Performance in Life Cycle Coffee Production Chain

The VA in the life cycle of coffee from upstream to downstream is important to be identified. Figure 8 shows the combination of the Organic Coffee pulp (OPB) during the cultivation stage, and the Wet Process with Wet Hulling during the post-harvest stage produced the highest value that contributed to all the upstream and downstream processes.

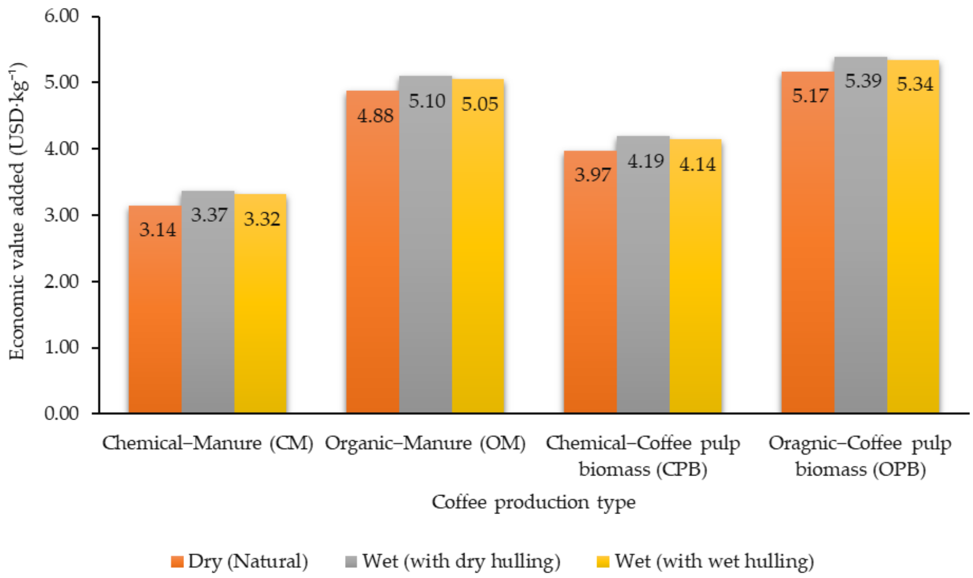

Figure 8. Value added in the life cycle of 1 kg of coffee green beans.

The overall economic value added for the four alternative processes in the upstream and three alternative processes downstream revealed that the use of coffee pulp biomass provided a higher economic value added in all combinations with the post-harvest processing, both in the OPB and CPB. From a post-harvest processing perspective, the most beneficial process is the wet process combined with the wet hulling process. Therefore, combining the coffee pulp biomass utilization with the wet process, specifically in the wet hulling process, potentially generated the highest value added during 1 kg of coffee green bean production.

The value-added result indicates some scenarios generate a higher value added for the coffee producer. The first scenario is the partial production of coffee between the upstream and downstream processes. Presently, coffee farmers and the coffee industry commonly practice this scenario. This mechanism provided benefits for some actors: (1) the benefit for the farmer at the upstream level and (2) the benefit for actors in the coffee processing industry. The results indicate that the farmers generate a higher benefit than the coffee processing industry at the same coffee green bean production level. Furthermore, the farmers obtained a higher economic value added by applying both on OPB and CPB in the cultivation process. About 3.2 USD·kg^{-1} of economic value added will be generated by applying the organic coffee pulp biomass (OPB), and 2.84 USD kg^{-1} of value added by applying chemical-coffee pulp biomass. Comparing OPB with OM and CPB with CM, the utilization of coffee pulp biomass in the upstream provided a higher economic benefit for the farmers. At the downstream level, organic coffee green bean production with the wet process and wet hulling provided a higher benefit to the coffee processing industry with a potential value added of 2.19 USD kg^{-1} of coffee green bean production. Overall, the organic green bean process in all post-harvest processing provides a higher value added than the non-organic green bean process.

Moreover, the integrated coffee process from upstream to downstream is an alternative for farmers or the coffee processing industry. Several farmers and the coffee industry have practiced this system and supplied coffee cherry beans as the raw material for the coffee post-harvest process from their cultivation and processed coffee green beans. According to the value-added chain of coffee production, the integrated coffee processing obtained a higher value added than the partial management of the upstream and downstream in coffee production. Combining the Organic Coffee pulp biomass in the upstream with the Wet Process with Wet Hulling in the downstream provided the highest value added, with a potential benefit of 5.39 USD kg^{-1}, compared with the partial coffee production, which provided only 2.19–3.2 USD kg^{-1} for actors at the farm level, and 2.14 USD kg^{-1} for actors at the downstream level. This research finds economic evidence to promote green coffee production by utilizing the coffee pulp biomass that provides benefits for actors in the coffee supply chain.

3.4. Eco-Efficiency Analysis

This study used an environmental perspective during eco-efficiency analysis that a lower eco-efficiency indicated a lower environmental impact emitted for the same economic benefit obtained. A lower eco-efficiency indicates a lower environmental damage for the same unit of economic benefit [34]. Therefore, the coffee production scenario with the lower eco-efficiency index is recommended, as it provides a low of GWP impact per unit of generated economic benefit. Table 6 shows the eco-efficiency index of coffee production from the upstream to downstream.

Table 6. The eco-efficiency index in coffee production in the upstream to downstream.

Post-Harvest Processing	Unit	Cultivation System			
		Chemical Manure (CM)	Organic Manure (OM)	Chemical Coffee Pulp Biomass (CPB)	Organic Coffee Pulp Biomass (OPB)
Dry (natural)	kg $CO_{2\,eq}$.USD^{-1}	1.462	0.356	0.399	0.135
Wet (with dry hulling)	kg $CO_{2\,eq}$.USD^{-1}	1.353	0.400	0.464	0.201
Wet (with wet hulling)	kg $CO_{2\,eq}$.USD^{-1}	1.462	0.408	0.509	0.204

Table 6 presents the comparison of the four types of coffee cultivation combined with the three types of post-harvest processes for coffee. According to the eco-efficiency index, coffee pulp both on the OPB and CPB consistently provide a lower eco-efficiency index. It indicates that per unit of economic benefit resulting from practicing OPB and CPB will lower the GWP impact. The higher VA and the lower GWP caused the lower eco-efficiency index during practicing the coffee pulp in the CPB and OPB. This study indicates that in an economic-environment aspect, coffee pulp also showed a beneficial impact.

4. Discussion

4.1. Coffee Pulp Biomass Utilization Impact on Energy Saving, CO_2 Emission Reduction, and Economic Benefit Increases at the Farm Level

The use of coffee pulp in an organic system (OPB) required energy at 14,321.39 MJ ha^{-1} with 86,462.19 MJ ha^{-1} for the non-organic system (CPB). Furthermore, compared to other research in coffee that uses regular fertilizers (chemical fertilizer, compost, and manure), managing 1 hectare of coffee cultivation with a higher intensive maintenance in Indonesia required the most energy at 304,510 MJ ha^{-1} for a non-organic system and 222,340 MJ ha^{-1} for an organic system [5]. Similarly, other studies on coffee in different countries have reported that the organic system requires 16,576 MJ ha^{-1} of energy, while the non-organic system needs 43,513 MJ ha^{-1} of energy [15]. According to the three different studies on coffee, using coffee pulp in an organic system shows a lower energy requirement. However, when comparing non-Organic Coffee pulp in Indonesia to conventional non-Organic Coffee pulp in other countries, a higher CED is still required [15]. According to a previous study report on coffee production in Indonesia, the higher CED in coffee cultivation in Indonesia was caused by the higher manure application since the manure was identified as an energy hotspot in coffee production [5]. Moreover, by using coffee pulp during the management of 1 hectare of coffee cultivation, we can potentially reduce the energy use in organic systems and in non-organic systems in the same region with a potential CED reduction of 39–87%. This reduction is primarily due to a reduction in manure use. The use of coffee pulp in the upstream combined with the post-harvest process during 1 kg of green coffee bean production also showed a potential energy reduction (Table A6). According to the total of green coffee bean production in Indonesia in 2020, the use of coffee pulp biomass on CPB can potentially decrease the energy consumption at 152.6 × 10^6 GJ, and 235.9152.6 × 10^6 GJ of potential energy saving by applying coffee pulp on the OPB system.

In the environmental aspect, the utilization of the coffee pulp biomass in the organic system (OPB) combined with all coffee processes in the downstream provides a potential reduction of 49.69–62% of GWP impact. At the same time, the coffee pulp utilization in the CPB also provided a potential decrease in the GWP impact compared with CM, with the potential GWP decrease of 63–72%. Both the OPB and CPB, during the calculation of GWP emission from direct and indirect N_2O emission (volatilization, runoff, and leaching), still consider manure and coffee pulp utilization [12]. According to this, the significant potential decrease in coffee pulp biomass utilization both in the CPB and OPB were contributed by the GWP emissions from materials and energy during the production input, where the GWP from the production input calculation did not involve manure and coffee pulp. Therefore, OPB and CPB is recommended. Currently, the farmer is challenged by the limited availability of manure when practicing conventional organic farming, as it is obtained from a long distance from the coffee cultivation location. Moreover, by using coffee pulp that results from coffee processing activities in the upstream process, the availability is guaranteed with lower-distance transportation. The emissions caused by transportation activities can be continuously reduced.

In the economic performance aspect, the use of coffee pulp biomass could potentially increase the economic value added. By using coffee pulp biomass on the CPB system, 1 kg of coffee green bean production provided 0.83 USD of the additional value added. However, applying OPB generated an additional value of 0.29 USD per kg of coffee green beans. Therefore, according to the average coffee green bean production from 1 hectare of coffee cultivation, the farmer will obtain a greater economic benefit, with an additional profit of 480.19 USD for the CPB system and 112.18 USD for the OPB system. Moreover, the results from this study indicated that the coffee pulp biomass can be recommended for applications since it provides benefits in all aspects of sustainability.

4.2. Coffee Pulp Biomass Utilization and the Potential Impact on CO_2 Emission Reduction during the Distribution to Global Market

The advantages of coffee pulp biomass utilization in all sustainability aspects, specifically in CED reduction, CO_2 emission reduction, and value-added increase in the upstream process, impacted all coffee life cycles until the coffee was consumed by domestic and global consumers. This study did not directly analyze the coffee distribution process in local and global markets. However, in the current Indonesian coffee exports, the green bean that is exported to the global market is produced by practicing CM and OM, which utilize chemical fertilizers and manure during coffee production. The use of intensive chemical fertilizers in agriculture results in environmental damage [15,35], thereby challenging coffee production. Furthermore, reducing its environmental impact should be conducted by exploring the alternative ways practiced in the upstream and downstream processes. The utilization of coffee pulp biomass as the primary and substitution fertilizer during coffee cultivation significantly decreased the CO_2 emissions. This decrease in CO_2 emissions during coffee production has impacted environmental damage globally, since coffee from Indonesia has contributed substantially to market demand.

4.3. Coffee Pulp Biomass Utilization and Its Relationship on Promoting a Green-Lean (GM) Production toward the Circular Economy

Coffee pulp biomass is the waste that results from the pulping process during the coffee post-harvest process. Applying coffee pulp as the fertilizer input for coffee cultivation indicated an application for the green and lean principles in agriculture production. The green lean principle is an extension of lean production, focusing on reducing waste. The green lean (GL) emphasizes the increase in environmental and economic efficiencies in the manufacturing process [53,54]. According to lean production and the green lean principle (GL), the utilization of coffee pulp is practiced to increase the energy efficiency and to reduce the environmental impact, while at the same time successfully reducing waste and increasing the economic value added. It was indicated that this method performed a green lean concept on coffee production. Moreover, a production process that successfully reduces environmental damage and saves energy encourages sustainability and a circular economy [55,56]. This study demonstrated that we could promote the sustainability of coffee production and develop a circular economy by using coffee pulp as the input for coffee production.

5. Conclusions

This study presented a comprehensive sustainability impact evaluation of coffee pulp biomass as a fertilizer for coffee production. Some essential findings are highlighted: (1) the use of coffee pulp as a fertilizer significantly decreased CO_2 emissions and CED, and increased its economic value. Moreover, the impact of the cultivation stage continuously affected the final product of coffee resulting from post-harvest processing. Therefore, the potential impact on the environmental load reduction during the green coffee bean production by applying the coffee pulp in the upstream will also contribute to the CO_2 reduction globally, since coffee from Indonesia significantly contributes to supplying the world's coffee demand. (2) The coffee pulp biomass utilization indirectly performed a green lean agriculture production that focuses on reducing waste and recycling the waste as the primary fertilizer input, to reduce the chemical input used during coffee production. (3) The integrated coffee production process from the upstream to downstream is recommended to be performed by coffee farmers or coffee stakeholders. This is indicated by the results on CED, CO_2 emissions, and value-added economic chains, which indicate that farmers, or coffee producers, potentially obtain a higher benefit from the economic aspect. However, in the environmental impact and energy aspects, there are no significant differences between practicing them partially or integrating them. The difference is caused only by the reduced transportation of coffee after harvesting to the coffee factory for further processing.

This study provides valuable scientific evidence related to the impact of coffee pulp utilization on energy, the environment, and economy comprehensively. Therefore, it can be a good consideration for all stakeholders to promote the widespread use of coffee biomass as a fertilizer during coffee cultivation. The specific action that can effectively affect the success of its implementation should be explored in a scientific way by combining it with the social aspect that considers all stakeholder situations. It is undoubtedly true that support and cooperation from all coffee stakeholders will contribute to its successful implementation.

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Abbreviations

CED	Cumulative energy demand
CM	Chemical manure cultivation system

CPB	Chemical coffee pulp cultivation system
C_{Cu}	Cost of cultivation process
$C_{cu.pr}$	Cost of cultivation or cost for post-harvest process
C_{hl}	Cost of human labor
C_{MA}	Cost of material input
C_{PA}	Cost of packaging
C_{pr}	Cost of post-harvest process
C_{TD}	Cost of transportation and distribution
E	Total energy requirement
Eel	Energy requirement for electricity
EELF	Energy factor for electricity
Efc	Energy requirement of chemical fertilizer
Efo	Energy requirement of organic fertilizer
EFel	Emission factor for electricity use
EFg	Emission factor for gasoline
EFo	Emission factor for organic fertilizer production
EFc	Emission factor of chemical fertilizer production
EFp	Emission factor for pesticide production
EFrh	Emission factor for rice husk
Eg	Energy requirement for gasoline
Egf	Energy factor of gasoline
Eh	Energy requirement for human labor
EHf	Energy factor of human labor
EI	Environmental impact
El	Electricity use
Erh	Energy requirement for rice husk
EP	Economic performance
Ep	Energy requirement for pesticide
EPf	Energy factor of pesticide
Ew	Energy requirement for water
Ffc	Energy factor of chemical fertilizer
Ffo	Energy factor of organic fertilizer
g	Gasoline consumption
GWP	Global warming potential
GWPel	Emission from electricity use
GWPg	Emission from gasoline use
GWP o	Emission prof organic fertilizer production
GWP c	Emission from chemical organic production
GWPp	Emission from pesticide production
GWPrh	Emission from rice husk
GWPn	Emission from N application to the field
h	Human labor
p	Pesticide utilization
w	Water consumption
WWf	Energy factor of water
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle costing
LCC_{GCB}	Life cycle cost of green coffee bean
LCI	Life cycle inventory
OM	Organic manure cultivation system
OPB	Organic coffee pulp cultivation system
rh	Rice husk utilization
TLCC	Total life cycle cost
SDGs	Sustainable development goals
VA	Value added
SDGs	Sustainable development goals

Appendix A

Table A1. Brief questionnaire for data collection.

Items	Questions	Answer
General information	Location Total cultivation area Production per hectare Period of life cycle of coffee tree	....
Resources use during the life cycle coffee cultivation and post-harvest processing	Time period for each stage and process Working days per stage Working hour per working day Labor involved Organic fertilizer application Chemical fertilizer application Pesticide, herbicide, fungicide application Frequency of fertilizer and pesticide application Additional fertilizer and material application Machine type used Gasoline/fuel consumption per process Machine capacity per process Water use per process	....
Resources during distribution and transportation	Retailer destination Distance Vehicle used Vehicle capacity load for per process Total product to be distributed to retailer	....
Economic evaluation	Selling price of 1 kg of coffee green beans Labor cost per day Fertilizer cost per kg Pesticide cost pe liter Gasoline cost per liter Domestic distribution cost Packaging cost	....

Table A2. Inventory analysis of managing a 1−hectare coffee plantation.

Cultivation Stages	Input–Output System	Unit	Chemical Manure (CM)			Organic Manure (OM)			Chemical Coffee Biomass (CPB)			Organic Coffee Biomass (OPB)		
			Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average
Seeding and Nursery	Electricity	kWh	0.012	11.280	0.350	0.009	0.023	0.013	0.086	0.086	0.086	0.086	0.086	0.086
	Labor transport	person·km	20	70	385.4	0.4	90	75.4	432	228	330	6	114	432
	Material transport	t·km	0.4	10.5	2.1	5.8	180	43.1	5	10.5	7.8	5	10.5	7.8
	Rice husk	kg	-	1300	103.7	-	150	36.5	-	-	-	-	-	-
	Seed	kg	2	2	2.1	2	2	2	2	3	2.5	2	2	2
	Water	L	150	48,420	1662	120	300	167.1	1100	1100	1100	1100	1100	1100
	Manure	kg	100	2625	328.4	120	6000	2584	200	1000	600	300	1200	750
	Coffee pulp	kg												
	Labor	h	114	720	385.4	12	420	167.6	432.0	228.0	330.0	100	432	215.3
Planting	Labor transport	person·km	168	4560	658.7	10	243	79.4	31.5	30.0	30.8	45	52.5	105
	Material transport	t·km	12.4	88	26.0	5.8	180	43.1	45	54	49.5	22	33	36.7
	Manure	kg	1000	20,000	4001	120	6000	2584	75	200	137.5	600	600	600
	NPK	kg	-	300	68.8	-	-	-	20	34	27	-	-	-
	Urea	kg	-	100	5.9	-	-	-	-	-	-	-	-	-
	Pesticide	L	6	7.5	6.6	-	-	-	-	-	-	-	-	-
	Coffee pulp	kg	-	-	-	-	-	-	990	220	605	900	2250	1575
	Labor	h	252	6840	990	48	1416	602.4	-	-	-	-	-	-
Maintenance	Labor transport	person·km	288	1200	541.5	144	5124	1737	400	460	430	564	840	2376
	Material transport	t·km	1622	27,984	6432	-	1280	277.8	144	207	175.5	46.6	104	228.8
	Manure	kg	7000	270,000	45,930	5000	320,000	69,859	37,800	47,250	42,525	2100	21,000	21,000
	NPK	kg	726.0	26,490	4299.2	-	-	-	1134	1134	1134	-	-	-
	Urea	kg	-	3000	362.6	-	-	-	-	-	-	-	-	-
	Pesticide	L	-	120	24.1	-	-	-	-	-	-	-	-	-
	Coffee pulp	kg	-	-	-	-	-	-	24,000	42,750	33,375	30,240	58,800	40,897
	Labor	h	900	6552	2194.2	107.5	959	480	140	161.0	150.5	142.0	634.0	327.7
Harvesting	Labor transport	person·km	864	6720	2658	432.0	4992	2058	4872	6496	5684	41,000	60,500	54,167
	Material transport	t·km	33	425	117.2	34.1	328	120.9	256	416	336	3272	6096	5299
	Labor	h	1296	10,080	4014	432.0	4992	2107	4872	6496	5684	1952.4	2881	2579
	Total production	kg	8250	100,150	27,638	8520	80,500	28,078	61,000	101,000	81,000	41,000	60,500	54,167
	Average harvesting	$Kg{\cdot}y^{-1}$	1065	9104.5	2917.7	1065	7318	2593	2904.8	4809.5	3857.1	1952.4	2881	2579

Table A3. Inventory data for 1 ton of cherry bean processing in the post-harvest process stage.

Input	Unit	Post-Harvest Process		
		Dry Process (Natural)	Wet Process (Dry Hulling)	Wet Process (Wet Hulling)
Human labor	h	354	237	261
Water	L	1000	1000	2000
Electricity	kWh	2.24	11.09	11.58
gasoline	L	3	9	9
Plastic bag	kg	0.3	0.3	0.3

Table A4. Energy conversion factors.

Input System		Unit	Energy Conversion Factor (MJ·Unit^{-1})	References
Gasoline		L	34.2	[38]
Electricity		kWh	11.93	[39]
Human labor		h	1.96	[40,41]
Pesticide		L	278	[41]
NPK	Nitrogen	kg	64.4	[42]
	Phosphorus	kg	12.44	[43,44]
	Potassium	kg	11.15	[43,44]
Compost		kg	6	[45]
Poultry manure		kg	1.32	[46–48]
Water		L	1	[44,48]
Rice husk		kg	14.6	[48]
Plastic bag		pc	0.508	[49]

Table A5. Cumulative energy demand for a 1 ton coffee cherry bean process.

Input Items	Unit	Conversion	Post-Harvest Process		
			Dry (Natural)	Wet (with dry Hulling)	Wet (with wet Hulling)
Human	h	1.96	693.8	464.5	511.6
Water	L	1	1000	1000	2000
Electricity	kWh	11.93	26.7	132.3	138.2
Gasoline	L	34.2	102.6	307.8	307.8
Plastic bag	kg	0.508	15.2	15.2	15.2

Table A6. Potential energy reduction per kilogram of green coffee beans.

Impact	Unit	Cultivation System	
		Non-Organic (CPB)	Organic (OPB)
Energy saving	MJ·kg^{-1}	218.04	337.54
CO_2 emission reduction	kg CO_2 eq·kg^{-1}	1.07	0.19
Value added increased	USD·kg^{-1}	0.83	0.29

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