sustainability

MDPI

Article

A Life Cycle Assessment of Organic and Chemical Fertilizers for Coffee Production to Evaluate Sustainability toward the Energy–Environment–Economic Nexus in Indonesia

Devi Maulida Rahmah [1,2], Agusta Samodra Putra [3,4], Riaru Ishizaki [4], Ryozo Noguchi [4,5,*] and Tofael Ahamed [4]

1 Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba 305-8572, Japan; devi.maulida.rahmah@unpad.ac.id
2 Faculty of Agricultural Industrial Technology, Universitas Padjadjaran, Sumedang 45363, Indonesia
3 Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, South Tangerang 15341, Indonesia; chemguzta@gmail.com
4 Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba 305-8572, Japan; rirkun@gmail.com (R.I.); tofael.ahamed.gp@u.tsukuba.ac.jp (T.A.)
5 Laboratory of Agricultural Systems Engineering, Division of Environmental Science and Technology, Faculty/Graduate School of Agriculture, Kyoto University, Kyoto 606-8502, Japan
* Correspondence: noguchi.ryozo.gm@u.tsukuba.ac.jp; Tel.: +81-2985-37298

Abstract: Coffee is an important agricultural commodity that is branded according to its environmental criteria in the global market. Therefore, Indonesia's coffee production system needs to be investigated to meet the demand for eco-labeling, which has become a consumer preference. This study aims to assess the comprehensive sustainability evaluation of coffee production nurtured by an organic fertilizing system (*OFS*), chemical-organic fertilizing system (*COFS*), and chemical fertilizing system (*CFS*) that focuses on the energy–environment–economic nexus. A life cycle assessment (LCA), life cycle cost analysis (LCC), and energy analysis were performed as methods to evaluate the environmental impact, economic performance, and energy requirement analysis. The results indicated that the *OFS* had superior performance in two sustainability aspects: resulting in the lowest environmental damage and generating the highest economic benefit. Simultaneously, *COFS* shows the highest sustainability performance as it consumes the least energy. In contrast, *CFS* indicated the lowest sustainability performance in all aspects: highest environmental impact, lowest economic benefit, and highest energy consumption. Therefore, *OFS* is strongly recommended to be applied broadly, considering its environmental and economic superiority. Consequently, massive *OFS* application was followed by higher energy consumption. Alternatively, *COFS* can be considered for application due to its higher energy performance, even though it can potentially result in higher environmental damage and lower economic benefit. However, the government should explicitly provide some effort for the broad application of *OFS* in financial and assistance support since the shifting process needs more time to adapt.

Keywords: sustainability assessment; environmental impact; economic performance; energy analysis; coffee cultivation; organic fertilizer; chemical fertilizer

Citation: Rahmah, D.M.; Putra, A.S.; Ishizaki, R.; Noguchi, R.; Ahamed, T. A Life Cycle Assessment of Organic and Chemical Fertilizers for Coffee Production to Evaluate Sustainability toward the Energy–Environment–Economic Nexus in Indonesia. *Sustainability* **2022**, *14*, 3912. https://doi.org/10.3390/su14073912

Academic Editors: Riccardo Testa, Giuseppina Migliore, Giorgio Schifani and József Tóth

Received: 24 February 2022
Accepted: 23 March 2022
Published: 25 March 2022

1. Introduction

1.1. Sustainability Issue in the Global Market Demand

The global demand for agricultural commodities has increased with rapid population growth and economic development [1]. This demand has promoted intensive agricultural practices and the development of the agriculture industry. Simultaneously, intensive agriculture substantially depletes the natural resources and causes environmental damage [2–7]. From the global market perspective, environmental issues have become popular, and sustainability guarantees product competitiveness. Due to the increased environmental awareness campaign, the high consumer preferences stimulate business pressure on sustainability concerns [8]. Sustainability issues also challenge production activities: protecting and rejuvenating the environment, promoting and recycling economically, and saving and efficiently utilizing energy [9].

The three sustainability challenges in production activity correspond to the sustainable development goals (SDGs). The SDGs are the way to achieve peace and prosperity for both humans and the earth that are expressed by 17 goals by the United Nations [10]. Eight SDGs are related to agriculture production: zero hunger, economic growth, clean water sanitation, affordable and clean energy, responsible consumption and production, climate action, life below water, and life on land. The SDGs study also reported that SDGs play a central role in producing clean and affordable energy for preserving life both in the sea and on land [11]. Following the SDGs, agricultural production activity should practice methods, processes, and technologies during production activity to protect humans, nature, and resources for the use of future generations [11]. Thus, assessing and promoting the sustainability of agricultural production in environmental, economic, and energy aspects are essential.

1.2. Coffee Production in Indonesia and its Sustainability Issue

According to the International Coffee Organization, the world coffee demand followed an upward trend, with an average increase of 1.4% per year from 2017 to 2020 [12]. Indonesia contributes 7.42% to world coffee demand and is the fourth most significant contributor, with an average annual production of 683.64 million kg y^{-1}. This shows that Indonesia is a potential global coffee producer. Therefore, the coffee industry in Indonesia should consider sustainability concerns for natural responsibility and when competing with the global market. Indonesia's coffee is produced by three different sectors: smallholder communities (95.45%), government companies (2.21%), and private companies (2.44%) [13]. Coffee plantations in Indonesia are predominantly managed by smallholders who apply conventional methods with massive amounts of chemical fertilizer, and only a few practiced organic systems. Massive amounts of fertilizers, pesticides, human labor, electricity, gasoline, and other materials were used during the coffee production process at the farm level. Simultaneously, the environmental damage is predicted to be severely impacted by the conventional practice of coffee production. The study also reported that production activity at the farm level is predicted to be a hotspot for GHG emissions in the coffee supply chain [14]. Shifting into more green coffee cultivation will significantly decrease the environmental damage impacted by coffee production activity. The organic cultivation system that avoids chemical substances represents the green cultivation in progress which is currently broadly practiced in agricultural production [15].

However, some studies have been conducted on coffee in recent years: the environmental study of coffee at different levels of fertilizer input and shade trees in Nicaragua and Costa Rica [14]; the identification of the carbon footprint of coffee beverages in Japan, which evaluated the carbon footprint of the coffee serving technology [16]; the study of shade tree application and its impact on the environment [17]; a cycle of participatory study in Organic coffee [18]; and the study of the environmental profile of green bean coffee in Brazil [19]. However, a specific study on coffee in Indonesia related to fertilizer management during the production of Robusta coffee without evaluating the sustainability profile has been investigated [20]. A study also reported that the coffee industry in Indonesia still provides limited financial benefits to smallholder farmers [21].

Referring to the study reports on coffee, some issues concerning coffee production in Indonesia are highlighted. First, studies on the area of coffee cultivation calculated in multiyear cultivation were limited. As coffee is a multiyear crop, it is essential to calculate the multiyear input-output system during cultivation to obtain a more precise emission result. Second, there is a lack of comprehensive information about the sustainability of coffee production in Indonesia based on fertilizer treatments. Lastly, previous studies only investigate the environmental impacts of coffee cultivation and disregard the economic and energy perspectives.

1.3. Sustainability Measurement

A comprehensive sustainability evaluation on the environment, economy, and energy aspects can be conducted using the life cycle assessment (LCA) approach [22]. In environmental evaluation, LCA specifically estimates the environmental damage over the entire life cycle of a process or product [7]. Some environmental indicators linked to the sustainability performance using an LCA approach, such as carbon footprint which is currently represented by carbon dioxide emissions [2,23,24], acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) [25,26].

However, economics is one crucial aspect in SDGs which is classified in economic growth development goals in SDGs [10]. Agriculture production activity should include economic sustainability to ensure sustainable production in the future. In coffee production, economic benefits for farmers becomes a concern of the ICO. A recent study conducted by the ICO reported that coffee farmers in selected countries are operating at a loss and that coffee growing is becoming less profitable over time [27]. Additionally, farmers are likely to consider implementing a strategy with a positive economic result. Therefore, economic performance evaluation is essential for coffee production activity. The life cycle cost (LCC) assesses all costs associated with a product's life cycle in economic performance. The LCC can detect the direct and indirect cost factors and estimate improvements in the planned product changes [22,28–30]. The production cost, revenue, and profit were identified during the LCC analysis. Cost and profit were used as indicators of economic performance to determine the relative success of a farm operation in terms of its ability to meet short-term financial obligations [31].

In the energy aspect, promoting affordable and clean energy is one of the goals of SDGs. In modern production, activity was also challenged to achieve energy-saving and efficient utilization. Considering the energy goal of SDGs and energy direction of modern production, analysis of the energy aspect in coffee production is essential. According to energy analysis, the energy requirement is the basis to evaluate the efficient use of energy aspects that become principal requirements of sustainable agriculture [32]. Therefore, measuring the energy requirement can also indicate the sustainability status.

Considering SDGs for agricultural production and the current sustainability issue for coffee in global demand, it is necessary to consider three sustainability aspects comprehensively–environmental impact, economic benefits, and energy–to enhance the sustainability of coffee production. However, the comprehensive evaluation of the environmental, economic, and energy situation at the farm-level potentially has a significant impact on the effective improvement since reported as the hotspot to environmental damage during agriculture production.

1.4. Research Objective

The objective of this study was to comprehensively evaluate the sustainability assessment considering the environmental impact, economic performance, and energy requirements of coffee production nurtured by different fertilizer applications within a multiyear production period. The energy–environment–economic evaluation of coffee production can provide valuable information for all stakeholders to achieve the three sustainable production goals: rejuvenating the environment, promoting economics, and saving and effectively utilizing energy. Additionally, this study can scientifically fill the research gap in coffee production management in Indonesia. Further research is required to encourage farmers to develop a more environmentally and economically viable coffee production system. Moreover, such efforts can also provide considerable insight into the government's decision-making process to support coffee farmers applying the green coffee production method.

This paper consists of five sections. Section 1 is the Introduction; Section 2 is Materials and Methods; Section 3 is study Results; Section 4 is the Discussion; Section 5 is the Conclusion.

2. Materials and Methods

2.1. Research Location and Object Studied

This study was conducted on a farmer's plantation, managing a small-medium coffee industry. Simultaneously, the farmer also practiced intensive maintenance coffee production. The farmer practiced some coffee cultivation systems in 480 ha of chemical-organic fertilizing systems, 25 ha of organic fertilizing systems, and 5 ha of chemical fertilizer fertilizing systems in the central arabica coffee production area sub-district of Sindangkerta, which is located in the West-Bandung District. West Bandung District is located in the specific geographical position at 6°41′–7°19′ S and 107°22′–108°5′ E with 130,577.40 ha of total area. This area is popular as the producer of many agricultural commodities due to the high soil fertility level. This area has the potential to adequately access the hydrological system for agriculture since the main watershed traverses. This region contains evergreen and moist-deciduous forest types. The climate in this location is hot and humid, with the rainfall continuously around four months in a year [33]. Specifically, the Sindangkerta sub-district is more popular with its coffee production and has become one of the coffee production centers in West Java that has produced coffee for domestic and international coffee consumption for more than two decades. The detailed information is presented in the following figure (Figure 1).

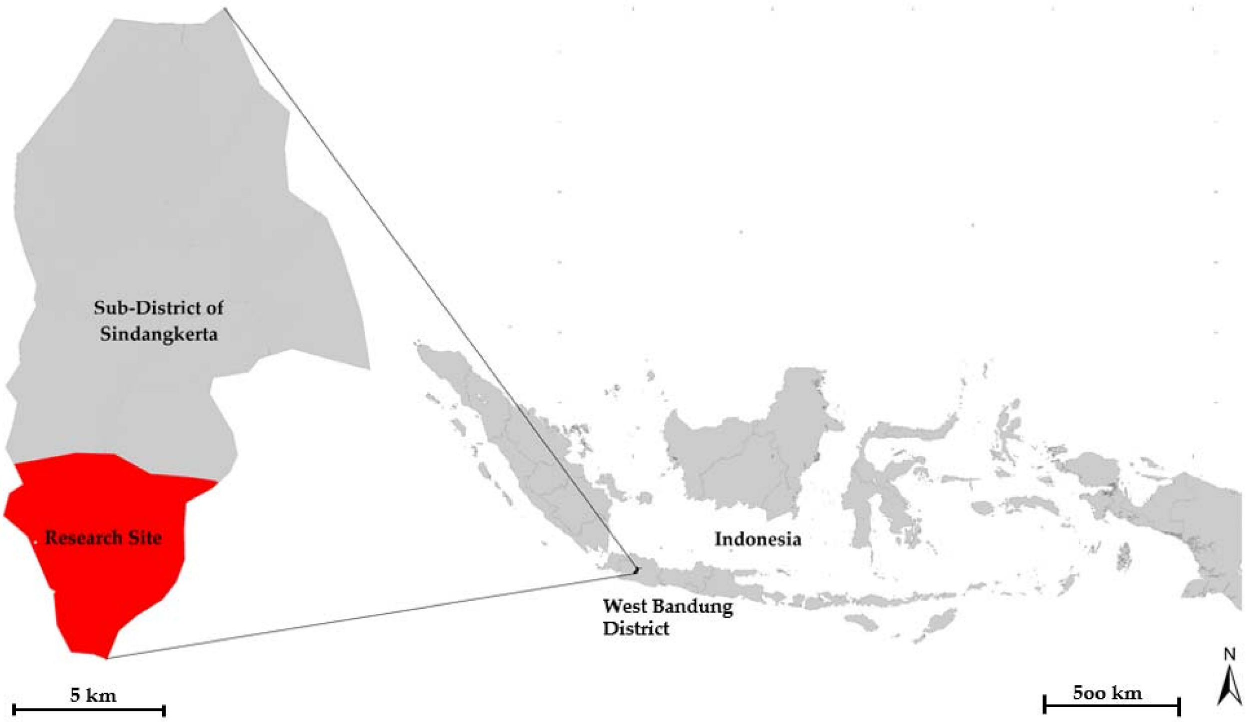

Figure 1. Surveyed coffee plantation area in the sub-district of Sindangkerta, Bandung Barat District, West-Java, Indonesia.

In this study, all coffee cultivation was planted in agroforestry areas. Nowadays, coffee has become more prevalent in agroforestry areas, whereas a few farmers have temporarily planted coffee in open field areas in Indonesia. Table 1 presented detailed geographical information of coffee cultivation studied.

Table 1. General information of the three coffee fertilizing systems.

Particulars	Unit	Fertilizing System		
		Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
			Geographical information	
Elevation	MSAL *		1200–1300	
Slope	Degree		0–45	
Land area	ha	25	480	5

* MASL is meters above sea level.

According to this study objective, the sustainability assessment will compare the three cultivation systems based on their fertilizer applications. Farmers in Indonesia practice some plantation management systems according to their fertilizer application: organic fertilizing system (*OFS*), chemical-organic fertilizing system (*COFS*), and chemical fertilizing system (*CFS*). *OFS* is still applied in small areas, whereas the *COFS* is extensively applied in Indonesia. However, higher productivity has encouraged farmers to apply the *COFS* continuously. This condition is under some literature and experience in producing other agricultural commodities that suggest that chemical and organic fertilizers can improve production capacity [6], regardless of environmental and economic considerations.

Currently, organic coffee is produced by practicing *OFS* on the farm level to fulfill the demands of specialty coffee export and environmental protection. Farmers used poultry manure, compost, and liquid fertilizer as the main fertilizers in the *OFS*. In *COFS*, organic and chemical fertilizers were combined during the plantation activities. In *COFS* and *CFS*, farmers used NPK as a chemical fertilizer. However, *CFS* is not mainly applied to coffee plantations because of its low productivity. Moreover, the excessive use of chemical fertilizers in the long term reportedly contributes to land degradation and nutrient pollution [34]. Therefore, it seems good progress since the chemical fertilizing system provides severe environmental damage.

2.2. Work Procedure

This study is conducted in four stages. The first stage is the goal and scope definition. In this stage, the objective and the boundary system are also defined. The second stage is data collection and inventory analysis. The data is collected in the research object refers to the boundary system. The third stage is sustainability analysis which evaluates three aspects: environmental impact assessment, economic performance analysis, and energy requirement analysis. The environmental impact analysis of multiyear coffee cherry bean production is performed using the life cycle assessment (LCA) methodology according to ISO 14040:2006. LCA is defined by ISO 14040 as the compilation and evaluation of the input, output, and potential environment of a product system throughout a life cycle [35,36]. Simultaneously, this study performed the life cycle cost method to evaluate the economic performance; and energy requirement analysis is used to evaluate the energy aspect. After conducting the primary analysis in stage 3, result interpretation will be at the end of this study procedure work. Figure 2 expresses the detailed work procedure of this study.

2.2.1. Goal and Scope Definition

The boundary system includes all stages of coffee plantation with multiyear production until replanting as presented in Figure 3. All necessary input-output was calculated following the research scope and boundary in a 1 ha coffee plantation. This study set four and five years as the pre-productive and productive stages, respectively. The pre-productive stage is the period before the coffee tree produces the coffee cherry beans, whereas the productive stage is when the coffee tree yields the coffee cherry bean. Coffee is categorized as an annually harvested plant with a three-month harvesting period per year. The harvesting started from the fourth year after planting and could be harvested until the ninth year of cultivation. The following figure expresses the boundary system of this study.

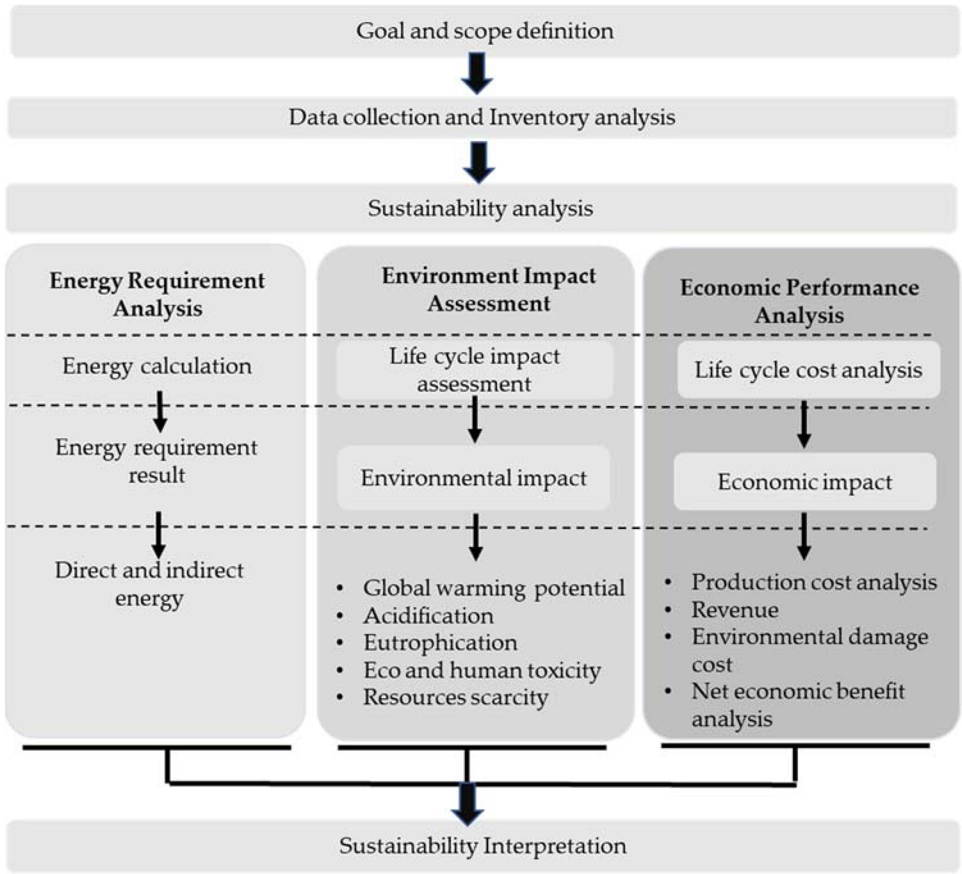

Figure 2. Research stage.

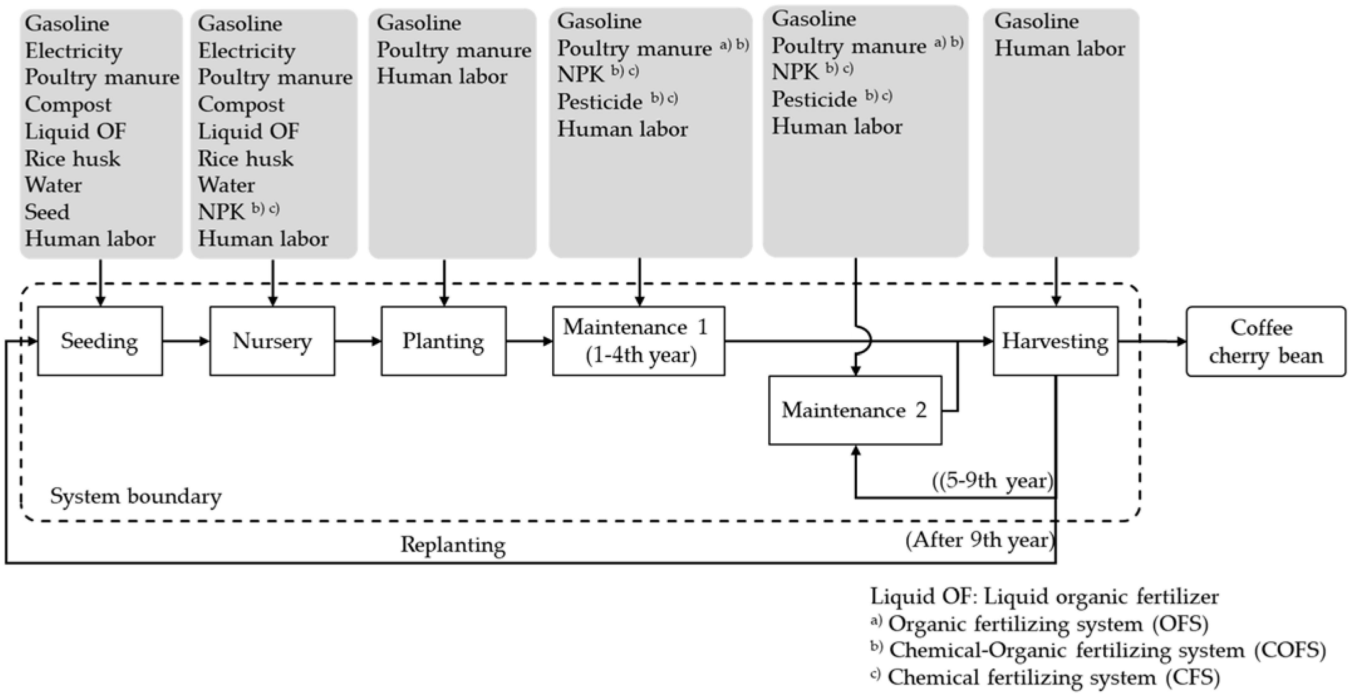

Figure 3. System boundary of the three coffee fertilizing systems.

2.2.2. Data Collection and Life Cycle Inventory Analysis (LCI)

The data was collected by field observation, in-depth interview, and questionnaire based on the coffee farmers with the research scope and boundary. The life cycle inventory (LCI) is an essential phase in the LCA that processes data collected from the farmer. The LCI was conducted based on the material and energy requirements during coffee production. A 1 ha coffee plantation is used as the functional unit during the inventory analysis. Table 2 presented the inventory analysis result of 1 ha coffee cultivation system.

Table 2. Inventory data of the input and output by fertilizing system.

Input and Output		Unit	Fertilizing System		
			Organic (*OFS*)	**Chemical-Organic (*COFS*)**	**Chemical (*CFS*)**
			Quantity		
Input					
Seeding	Gasoline	L ha^{-1}	2	2	2
	Electricity	kWh ha^{-1}	0.03	0.03	0.03
	Poultry manure	kg ha^{-1}	100	100	100
	Compost	kg ha^{-1}	100	100	100
	Liquid organic fertilizer	L ha^{-1}	8	8	8
	Rice husk	kg ha^{-1}	100	100	100
	Water	L ha^{-1}	420	420	420
	Seed	kg ha^{-1}	2	2	2
	Human labor	h ha^{-1}	116	116	116
Nursery	Gasoline	L ha^{-1}	5	5	5
	Electricity	kWh ha^{-1}	11.25	11.25	11.25
	Poultry manure	kg ha^{-1}	2400	2400	2400
	Compost	kg ha^{-1}	1200	1200	1200
	Liquid organic fertilizer	L ha^{-1}	96	96	96
	Rice husk	kg ha^{-1}	1200	1200	1200
	Water	L ha^{-1}	48,000	48,000	48,000
	NPK Nitrogen	kg ha^{-1}	-	0.93	1.83
	NPK Phosphorus	kg ha^{-1}	-	0.93	1.83
	NPK Potassium	kg ha^{-1}	-	0.93	1.83
	Human labor	h ha^{-1}	320	320	320
Planting	Gasoline	L ha^{-1}	42	42	42
	Poultry manure	kg ha^{-1}	2500	2500	2500
	Human labor	h ha^{-1}	480	480	480
Maintenance 1 [1] (Pre-productive)	Gasoline	L ha^{-1}	26	20	12
	Poultry manure	kg ha^{-1}	40,000	24,000	-
	NPK Nitrogen	kg ha^{-1}	-	180	266.43
	NPK Phosphorus	kg ha^{-1}	-	180	266.43
	NPK Potassium	kg ha^{-1}	-	180	266.43
	Pesticide	L ha^{-1}	-	3	12
	Human labor	h ha^{-1}	320	192	128
Maintenance 2 [2] (Productive)	Gasoline	L ha^{-1}	78	60	36
	Poultry manure	kg ha^{-1}	137,400	60,000	-
	NPK Nitrogen	kg ha^{-1}	-	750	981
	NPK Phosphorus	kg ha^{-1}	-	750	981
	NPK Potassium	kg ha^{-1}	-	750	981
	Pesticide	L ha^{-1}	-	5	24
	Human labor	h ha^{-1}	960	576	384

Table 2. *Cont.*

Input and Output		Unit	Fertilizing System		
			Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
			Quantity		
Harvesting [3]	Gasoline	L ha^{-1}	288	288	288
	Human labor	h ha^{-1}	4400	5000	2200
Output	Coffee cherry bean	kg ha^{-1}	44,000	50,000	22,000

[1] Maintenance 1 is the maintenance activity in the pre-productive stage; [2] Maintenance 2 is that in the productive stage; and [3] Harvesting indicates the input and output for six years of harvesting.

The inputs for coffee production included gasoline, electricity, fertilizer (poultry manure, compost, liquid organic fertilizer, and NPK), pesticides, rice husks, water, seeds, and labor. Gasoline is used in vehicles to transport labor and materials to the field. Electricity is required for watering during the seeding and nursery stages. Two types of fertilizers were used in this study: organic and non-organic. Compost, poultry manure, and liquid organic fertilizers were used as organic fertilizers, and NPK was used as a chemical fertilizer. Pesticides are conditionally used to control pest attacks. Chemical pesticides are applied in CFSs and COFSs, whereas organic pesticides are used in the *OFS*. The seed is an essential material in the first stage of plantation. Organic seeds were used in all the coffee fertilizing systems. A 1 ha coffee plantation needs 2 kg of organic seed. As the additional material, rice husk is provided as the growth medium during the seeding and nursery stages. Another vital activity during seeding and nursery is watering. The level of water used during seeding and nursery maintenance is different in each stage. As typical of conventional agricultural practice, all the physical activities in plantations are conducted by human labor. Therefore, human labor is an essential input presented by the total labor working hours during coffee production activities. As the output, the total coffee cherry production is generated by six years of harvesting. The following table expresses the inventory analysis results of the input-output system.

2.2.3. Sustainability Analysis

Energy Requirement Analysis

The total energy is calculated as the sum of energy required by each material and energy input during coffee production in energy requirement analysis. The energy of each input system was obtained by multiplying the input consumption (Table 2) and its energy conversion factor (Table 3). This study used the energy conversion factors from scientific literature, as presented in the following table.

Table 3. Energy conversion factor.

Input System		Unit	Energy Conversion Factor (MJ Unit^{-1})	References
	Gasoline	L	34.2	[37]
	Electricity	kWh	11.93	[38]
	Human labor	h	1.96	[39,40]
	Pesticide	L	278	[40]
NPK	Nitrogen	kg	64.4	[41]
	Phosphorus	kg	12.44	[42,43]
	Potassium	kg	11.15	[42,43]
	Compost	kg	6	[44]
	Poultry manure	kg	1.32	[45–47]
	Water	L	1	[43,45]
	Liquid organic fertilizer	L	1.32	[45–47]
	Rice husk	kg	14.6	[48]

Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment is the main stage for assessing the environmental impact. The LCA analysis of coffee cherry bean production performed LCA methodology according to ISO 14040:2006. According to ISO 1440:2006, LCA analysis evaluates the potential environmental impact throughout a product's life cycle [36,49]. The present study adopted the LCA methodology developed by the ReCiPe 2016 v.1.0.4 midpoint method with a hierarchy version created by RIVM, Radboud University, Norwegian University of Science and Technology, and PRé Consultant [49]. The calculation was performed using Simapro v.9.1.1.1® software with the Ecoinvent 3.7.1 database. The environmental impact on this present study considered eleven impact categories: the global warming potential (GWP), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FEc), marine ecotoxicity (MEc), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HnCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). The environmental impact of each fertilizing system was calculated using the following equation:

$$EI\ (OFS,\ COFS,\ CFS) = \sum_{k=1}^{n} (EF_{\mathrm{k}} \times material\ or\ energy\ input_{\ \mathrm{k}} \tag{1}$$

The environmental impact indicators for each coffee plantation are expressed as EI (*OFS*, *COFS*, *CFS*). Where *OFS*, *COFS* and *CFS* indicate the organic fertilizing system, chemical-organic fertilizing system, and chemical fertilizing system, respectively. The sum of all emission inputs is calculated in all environmental indicators The emission per input was obtained by multiplying each emission factor (*EF*) by the material or energy input *(n*). The *EF* indicates the emission impact per unit input. Some studies either used EF from the literature or conducted preliminary calculations. This study conducted a preliminary calculation using SimaPro to obtain the EF and environmental impact results.

Life Cycle Cost Analysis (LCC)

The life cycle costing (LCC) study aimed to fully account for the financial costs of the environmental aspects and impacts of the life cycle [22,48]. The LCC is calculated considering all the input-output inventory costs and the environmental impact costs of the LCA. The LCA input cost is represented by all the expenses required to provide the materials and energy during the plantation. The cost of each specific input was calculated by multiplying the total input used by the standard cost of its input. The environmental impact cost is represented by the CO_2 emission cost, which is calculated as the total CO_2 emissions multiplied by the CO_2 emission tax. This study only calculates the CO_2 emission cost as the primary environmental impact cost considering Indonesia's condition, which is still preparing to implement the CO_2 tax in its environmental policy. The CO_2 emission tax refers to the standard carbon tax for developing countries as the standard carbon tax for Indonesia is still unavailable. According to the OECD Taxing Energy Use (TEU) Database, Indonesia recommends using a moderate emission tax standard emission [50]. As our study considers multiyear production costs, this calculation also assumes the discount rate for the small-to medium-scale sector. Therefore, the following equation is used for the LCC calculation:

$$Total\ life\ cycle\ cost\ (TLCC) = Production\ cost + Emission\ cost \tag{2}$$

$$Production\ cost = Fixed\ cost + Variable\ cost \tag{3}$$

$$Emmision\ cost = Total\ production \times Emission\ tax \tag{4}$$

The total life cycle cost (*TLCC*) is the total cost of the life cycle of coffee, which fully accounts for all the production and emission costs. The production cost indicates all expenses during the coffee production life cycle, which consists of a fixed cost and variable cost. A fixed cost is the initial investment cost, such as the machinery, tools, and rent for the cultivation land. The variable cost included all materials, labor, transportation, distribution, and environmental impact costs during the project's life cycle. The emission cost is the impact of the environmental damage cost. The total production indicates the total coffee cherry bean production. This study considers the multi-year costs following the research boundary.

The economic benefit was also investigated by a subsequent economic analysis using the following equation:

$$Net\ profit = Revenue - TLCC \tag{5}$$

$$Revenue = Total\ production \times selling\ price\ per\ kg \tag{6}$$

Net profit represents the potential profit generated by the farmer which is calculated by the revenue subtracted with the *TLCC*. All currency values are converted into USD from IDR using 14,409 IDR USD^{-1} [51].

2.2.4. Sustainability Interpretation

This stage explains a descriptive interpretation of the study results that compared the sustainability analysis: energy requirement, environmental impact, and economic performance on the three coffee fertilizing systems. By comparing all results, better performance in energy, environmental, and economic aspects will be provided.

3. Result

This section describes the results of the present study: energy requirement analysis, environmental impact assessment, and life cycle cost analysis of coffee production.

3.1. Energy Requirement Analysis

The total energy requirement for managing 1 ha of coffee plantations was dominated by *OFS*, followed by *COFS* and *CFS*. The total energy consumption values in *OFS*, *COFS*, and *CFS* are 344.31 × 10^3, 304.51 × 10^3, and 222.34 × 10^3 MJ ha^{-1}, respectively (Table 4). The fertilizer usage requires the highest energy, wherein manure consumes the highest energy in the *OFS* and*COFS*, and NPK required the most energy in the *CFS*. Poultry manure consumed 240.77 × 10^3 and 117.48 × 10^3 MJ ha^{-1} in the *OFS* and *COFS*, respectively. In comparison, the energy consumption of NPK was 109.92 × 10^3 MJ ha^{-1} in *CFS*. As presented in Table A18, water was the dominant source of energy consumption after fertilizer use, consuming 48.42 × 10^3 MJ ha^{-1} in all the fertilizing systems. Regarding the energy requirement for labor, managing 1 ha of coffee plantations with the *COFS* requires the highest human labor energy at 18.15 × 10^3 MJ ha^{-1}. In contrast, the *OFS* requires lower energy for labor, at 17.23 × 10^3 MJ ha^{-1}. According to Table 4, the highest energy for labor is required for the harvesting activity, which is dominant in the *COFS* at 9.8 × 10^3 MJ ha^{-1}. Regarding the hotspot of energy requirements per stage of the coffee plantation as presented in Table A19, maintenance 2 was the dominant energy source in all coffee fertilizing systems. It consumed 185.92 × 10^3, 149.76 × 10^3, and 94.97 × 10^3 MJ ha^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. The following table presents the energy requirement for managing a 1 ha coffee plantation.

Figure 4 indicates that energy consumption for 1 kg of coffee is dominated by fertilizer application in all fertilizing systems. Specifically, manure consumed the highest energy in the *OFS* and *COFS*. In contrast, NPK predominantly used the energy in the *CFS*. According to Table A1, energy inputs for 1 kg of coffee cherry bean production in the *CFS*, *OFS*, and *COFS* were 10.35, 7.92, and 6.19 MJ kg^{-1}, respectively. The highest energy consumption was identified in all *CFS* inputs. In fertilizers, poultry manure is the highest contributor to energy consumption in the *OFS* and *COFS*. The manure application required 5.47 and 3.35 MJ kg^{-1} in the *OFS* and *COFS*, respectively. In comparison, NPK dominantly consumed energy in the *CFS* which consumed 4.996 MJ kg^{-1}. The second-largest contributor to energy consumption was water, which consumed 1.10, 0.97, and 2.20 MJ kg^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. The domination of energy from fertilizer usage in coffee cherry bean production is similar to the other study in which fertilizer dominated energy consumption in all coffee plantations [32,52]. The water application on managing of 1 ha coffee plantation is at the same level in all fertilizing systems. The differences in energy use related to the water consumption on 1 kg of coffee cherry beans production are caused by the different productivities of each coffee fertilizing system. The following figure presents the energy requirement for 1 kg coffee cherry bean production.

Table 4. Energy requirement for managing of 1 ha coffee plantation.

Stage of Plantation	Input System	Fertilizing System		
		Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
		Energy Requirement ($\times 10^3$ MJ ha^{-1})		
Seeding	Gasoline	0.068	0.068	0.068
	Electricity	0.0004	0.0004	0.0004
	Poultry manure	0.132	0.132	0.132
	Compost	0.6	0.6	0.6
	Liquid organic fertilizer	0.011	0.011	0.011
	Rice husk	1.46	1.46	1.46
	Water	0.42	0.42	0.42
	Seed	-	-	-
	Human labor	0.23	0.23	0.23
Nursery	Gasoline	0.17	0.17	0.17
	Electricity	0.13	0.13	0.13
	Poultry manure	3.17	3.17	3.17
	Compost	7.2	7.2	7.2
	Liquid organic fertilizer	0.13	0.13	0.13
	Rice husk	17.52	17.52	17.52
	Water	48	48	48
	NPK Nitrogen	-	0.06	0.12
	Phosphorus	-	0.012	0.023
	Potassium	-	0.01	0.02
	Human labor	0.63	0.63	0.63
Planting	Gasoline	1.44	1.44	1.44
	Poultry manure	3.3	3.3	3.3
	Human labor	0.94	0.94	0.94
Maintenance 1 [1]	Gasoline	0.89	0.68	0.41
	Poultry manure	52.8	31.68	-
	NPK Nitrogen	-	11.59	17.16
	Phosphorus	-	2.24	3.31
	Potassium	-	2	2.97
	Pesticide	-	0.83	3.34
	Human labor	0.63	0.38	0.25
Maintenance 2 [2]	Gasoline	2.67	2.05	1.23
	Poultry manure	181.37	79.2	-
	NPK Nitrogen	-	48.3	63.18
	Phosphorus	-	9.33	12.2
	Potassium	-	8.36	10.94
	Pesticide	-	1.39	6.67
	Human labor	1.88	1.13	0.75
Harvesting [3]	Gasoline	9.91	9.91	9.91
	Human labor	8.62	9.8	4.31
Total		344.31	304.51	222.34

[1] Maintenance activity in pre-production stage (four years of maintenance); [2] Maintenance in productive stage (five years of maintenance); and [3] six years of harvesting.

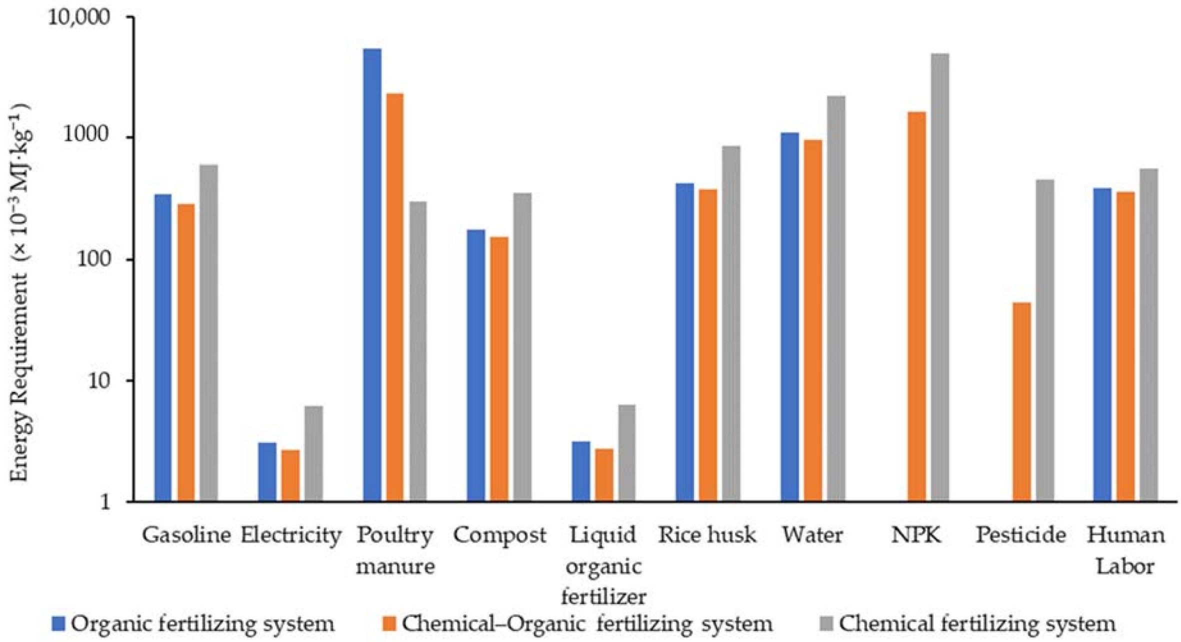

Figure 4. Energy requirement for 1 kg coffee cherry bean.

In developing countries, agricultural production is still predominantly conducted by human labor. Therefore, it is essential to calculate the energy requirement for labor. As presented in Table A1, 1 kg of coffee cherry bean production required about 0.39, 0.36, and 0.57 MJ kg^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. According to Tables A3–A5, harvesting and maintenance activities are the most significant contributors to labor energy. In particular, clearing activities required higher energy than the other maintenance activities in the *OFS*. Simultaneously, fertilizing activity consumed the highest energy in the *COFS*. Although the *OFS* has more clearing activities, it has no significant effect on labor energy consumption because harvesting still dominates the energy consumption. The high energy required for labor indicates that the coffee production system is still conventionally conducted by human labor rather than by machinery. Electricity has the lowest energy requirement. The electricity consumption is on the watering activity. Electricity only contributed 0.038, 0.043, and 0.059% to the total energy requirements in *OFS*, *COFS*, and *CFS*, respectively.

3.2. Environmental Impact Assessment and Its Contributing Factors

3.2.1. Environmental Impact

Figure 5 presents the environmental impact of 1 kg of coffee cherry bean production.

Figure 5 indicates that *OFS* has the lowest environmental impact in all impact categories compared to the *CFS*. The *OFS* presented the lowest impacts on the eight environmental impact categories GWP, TA, FE, TEc, MEc, HCT, MRS, and FRS compared to *COFS*. Simultaneously, *COFS* had the lowest impact in the three environmental impact categories: ME, FEc, and HnCT. In contrast, the *CFS* had the highest environmental impact in all impact categories. The detailed information on the environmental impact of 1 kg of coffee cherry bean production is presented in Table A2. According to Table A2, *OFS* is more environmentally friendly as indicated by the lowest impact, such as in GWP that emitted 0.0678 kg CO_2 eq kg^{-1}, and compared to *COFS* and *CFS*, which have a GWP impact of about 0.182 and 0.496 kg CO_2 eq kg^{-1}, respectively. Comparing *OFS* with *COFS*, seven other environmental indicators were dominant in the *OFS*: TA, FE, TEc, MEc, HCT, FRS, and MRS. In contrast, *CFS* has the highest environmental impact. Thus, shifting the *COFS* or *CFS* to the *OFS* system significantly reduces the environmental impact, as presented in Table A12.

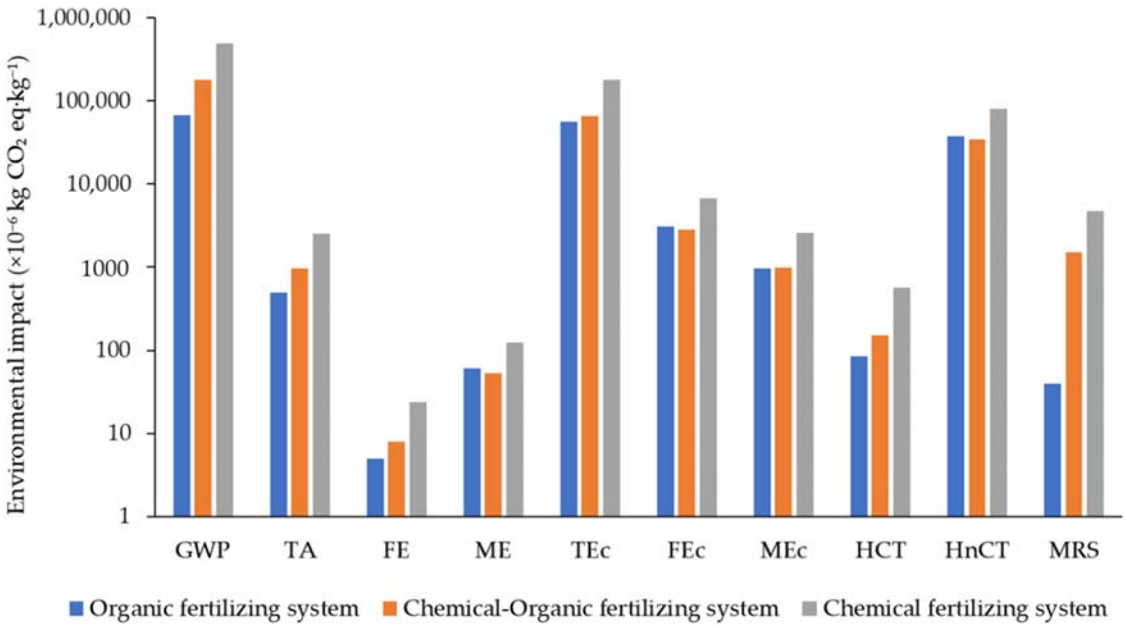

Figure 5. Environmental impact of 1 kg of cherry coffee bean production.

The other study also presented a similar result related to environmental impacts in coffee production as presented by the following table.

According to Table 5, organic coffee plantations has the lowest environmental impact compared with chemical-organic or conventional cultivation in Indonesia and previous research in other countries [14,52]. In previous research, the impact on GWP for organic was at 0.12–0.52 kg CO_2 eq kg^{-1} and 0.27 kg CO_2 eq kg^{-1}, while organic fertilizing system (*OFS*) in Indonesia has an impact at 0.068 kg CO_2 eq kg^{-1}. The lower GWP in Indonesia can potentially be affected by the boundary system that calculates all life cycle coffee production at the farm level from seeding until replanting. The higher productivity in the intensive coffee management system in this study also mainly impacted the lower GWP per kg product compared others. In this study, the farmer applied the intensive coffee cultivation management system with higher production. In the conventional system, Coffee Indonesia also has a lower environmental impact than others. A study also reported that most of the coffee farmers in Indonesia applied the lower chemical fertilizer as suggested [20]. The other study also presented a similar result related to environmental impacts in coffee production as presented by the following table.

Table 5. Comparative environmental impact evaluation with previous coffee study.

Research	Boundary	Scenario	Environmental Impact (kg CO_2 eq kg^{-1})
Martin R.A. Noponen, et al. [14]	Coffee cultivation in Costa Rica and Nicaragua with average annual coffee production since the second year of production	Conventional Organic	0.26–0.67 0.12–0.52
Basavalingaiah, K., et al. [52]	Coffee-pepper in India in general	Conventional Integrated Organic	1.24 1.07 0.27
This study	Coffee cultivation in Indonesia in all life cycle of coffee cultivation from seeding until replanting	Organic (*OFS*) Chemical-Organic (*COFS*) Chemical (*CFS*)	0.068 0.182 0.496

3.2.2. Contribution Factor of Environmental Impact

As presented in Figure 6, rice husk is dominantly contributed to GWP, TA, FE, ME, TEc, FEc, MEc, HTC, and FRS. The second-largest contributor to environmental damage in the *OFS* is gasoline, which is used for transporting materials and labor to the field. In poultry manure application, its effect on the GWP, TA, FE, ME, TEc, FEc, MEc, HTC, HnCT, FRS, and MRS was not noticeable, even though was dominantly contributed to energy consumption. In the *COFS* and *CFS* (Figures 7 and 8), the use of NPK had the most significant environmental impact. The application of NPK in the *COFS* and *CFS* contributed significantly to the GWP, TA, MRS, and FRS. A similar result also presented the domination of chemical fertilizer that contributed to the environmental impact [14,52]. For comparison, the highest contributors to TEc, MEc, FEc, and HnCT were rice husk. Simultaneously, compost contributed significantly to the FE and ME. Pesticides are primarily responsible for human carcinogenic toxicity. This result indicates that the massive NPK application in *COFS* and *CFS* significantly contributes to air, land, and resource scarcity. Simultaneously, rice husk significantly deteriorates water and contributes to ecotoxicity. At the same time, pesticides are the biggest contributing factor affecting human health. The following figure shows the detailed contribution factors of 1 kg coffee cherry bean production.

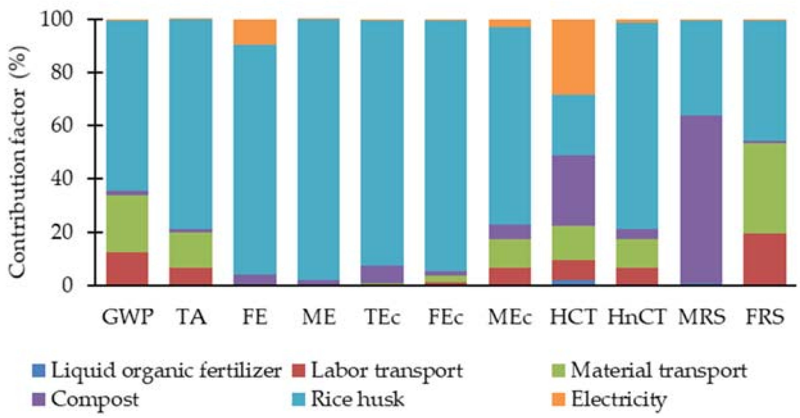

Figure 6. Contributing factors in the Organic Fertilizing System (*OFS*).

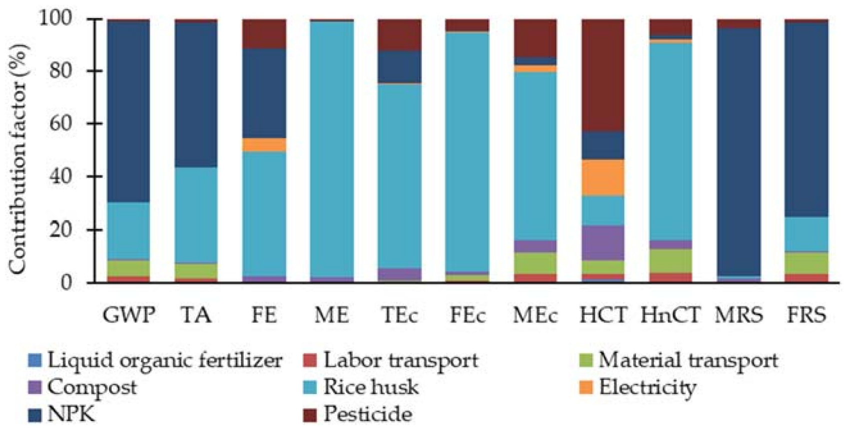

Figure 7. Contributing factors in the Chemical-Organic Fertilizing System (*COFS*).

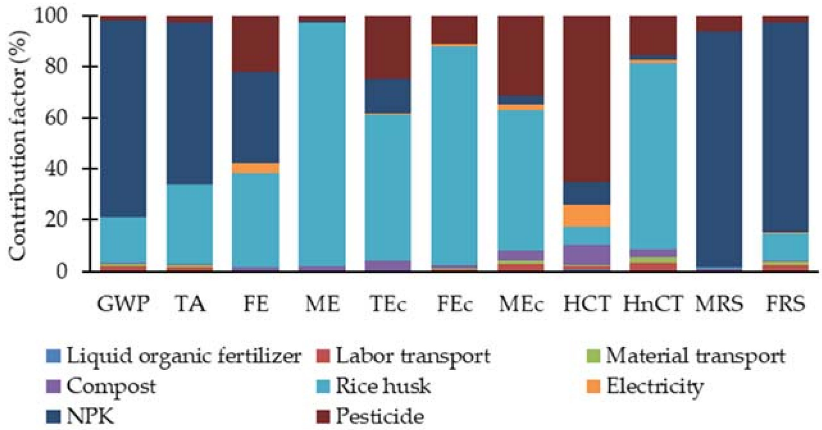

Figure 8. Contributing factors in the Chemical Fertilizing System (*CFS*).

3.2.3. Sensitivity Analysis of Environmental Impact

Figuring the uncertainty on assessing the environmental impact in LCA, the sensitivity analysis is suggested. This method involves calculating different scenarios to analyze the influence of input parameters on either LCIA output result [53]. The present study also performed the environmental impact sensitivity analysis following two variable changes: the change in production capacity and fertilizer use.

As presented in Figure 9, the fertilizer input-level change scenario significantly impacts GWP on *COFS* and *CFS*. In contrast, it has no GWP impact on *OFS* since *OFS* avoided chemical fertilizer. This result indicated that the chemical fertilizer is the hotspot to the GWP. According to system-based fertilization, the change of GWP due to the change of fertilizer input level in *CFS* is more significant than in *COFS*. This result indicated that the level of fertilizer used is sensitive to the GWP impact. The higher the chemical input impacted the higher GWP, and conversely. The impact of scenario changes to GWP was identified as presented by the following figure.

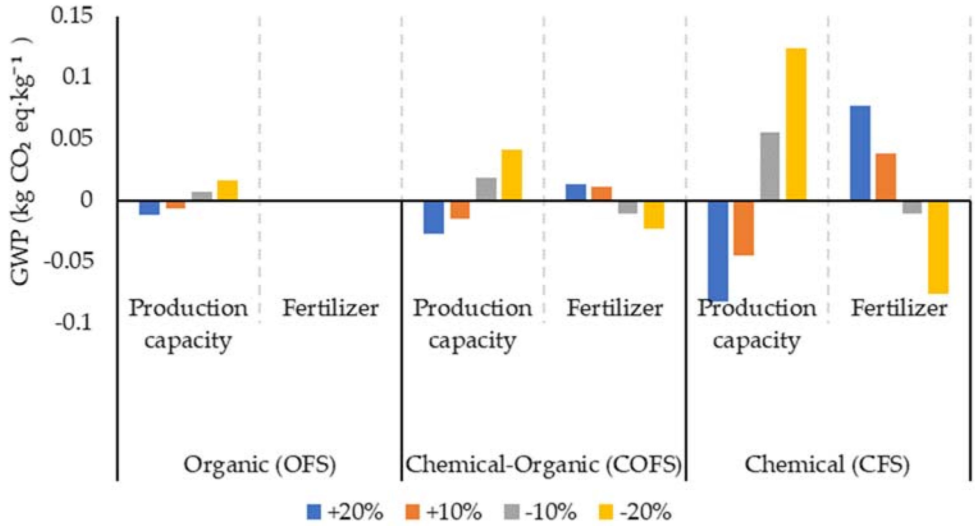

Figure 9. Environmental sensitivity analysis.

This study also conducted the environmental sensitivity analysis related to production capacity change. In this scenario, the GWP change due to the change of production level in *CFS* dominates while the GWP impact in *OFS* is the lowest. This result indicated that *CFS* and *COFS* are vulnerable to the change input and output aspects. Overall, the linear result has been shown following the level change of production and fertilizer used. In this case, it was indicated that the environmental impact result follows the linear trend impact when the uncertainty has occurred in production and fertilizer application.

3.3. Life Cycle Cost Analysis

Table 6 presents the LCC analysis. Overall, *OFS* generates superior performance in the economic aspect, as indicated by the highest value in revenue and net profit as presented by the following figure:

Table 6. Life cycle cost (LCC) analysis.

Indicators	Unit	Fertilizing System		
		Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
Production Cost	USD ha^{-1}	8936	9084	6176
	USD kg^{-1}	0.2031	0.1816	0.2800
Emission cost	USD ha^{-1}	29.07	88.42	106.02
	USD kg^{-1}	0.0006	0.0017	0.0048
Revenue	USD ha^{-1}	30,537	29,496	12,978
	USD kg^{-1}	0.69	0.59	0.59
Net profit	USD ha^{-1}	21,571	20,330	6720
	USD kg^{-1}	0.49	0.41	0.30

According to Table 6, the result highlights that the highest production cost per hectare coffee plantation is required by *COFS* with total expenses of 9084 USD ha^{-1}. For comparison, the *OFS* and *CFS* required 8936 and 6176 USD ha^{-1}, respectively. The different results showed in production cost per 1 kg coffee cherry bean production, which is the highest required by the *CFS*. The highest cost in *CFS* is caused by its lowest productivity. More detail in production cost, the highest cost was required for human labor in all fertilizing systems. Specifically, human labor for harvesting primarily contributed to the cost. This result indicates that human labor cost is a hotspot regarding economic expenditure (Tables A3–A5, A13 and A14).

The *OFS* had the lowest emission cost with a significant margin compared to the other fertilizing systems in terms of emission cost. Therefore, applying the *OFS* to the *COFS* will reduce the emission cost by approximately 0.0011 USD kg^{-1} (62.63%), and shifting the *CFS* to the *OFS* can potentially reduce the production cost by 0.0042 USD kg^{-1} (86.29%). *OFS* is also dominantly providing the highest revenue and net profit performance. The results revealed that although the *OFS* generates a lower production capacity than the *COFS*, the *OFS* provides the highest profit for the farmer due to the higher selling price and lower production cost compared with the other systems. For example, a farmer earned 21,571 USD after managing a 1 ha coffee plantation as well as 0.49 USD earned from 1 kg of coffee cherry bean production. For comparison, managing a 1 ha coffee plantation nurtured by the *COFS* generated 20,330 USD; the *CFS* provided the lowest profit of 6720 USD ha^{-1}, which is approximately 31.1% of the total profit in a hectare of the *OFS*. Therefore, according to the net profit result, the *OFS* is more profitable than the other systems. However, the current situation in farmers, is that the higher productivity resulting from *COFS* has attracted farmers to manage their plantations by practicing its system. Fortunately, this result finds essential information for other farmers that managing coffee using the intensive *OFS* will attain a higher economic benefit.

3.4. Sustainability Interpretation

Table 7 presents the three of sustainability assessment: Environmental-Economic-Energy aspect. *OFS* provided better performance in environmental and economic aspects. The *OFS* had the lowest environmental impact in eight environmental indicators compared to the *CFS*. Simultaneously, in economic benefit, 1 kg of organic coffee cherry beans generated the highest net profit at 0.49 USD kg^{-1}. In energy aspect, *COFS* provided the high performance that consumed the lowest energy compared to *OFS* and *CFS*. Even though *OFS* requires more energy than the *COFS*, but still less than the *CFS*. The following table summarizes all the results of the sustainability assessment in this study.

Table 7. Results of the sustainability assessment.

Category	Indicators	Unit	Fertilizing System		
			Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
Environmental Impact	GWP	kg CO_2 eq kg^{-1}	0.068 Lowest (++)	0.182 Modest (+−)	0.496 Highest (−−)
	TA	kg SO_2 eq kg^{-1}	0.0005 Lowest (++)	0.001 Modest (+−)	0.0025 Highest (−−)
	FE	kg P eq kg^{-1}	0.000005 Lowest (++)	0.000008 Modest (+−)	0.000023 Highest (−−)
	Mec	kg N eq kg^{-1}	0.00006 Modest (+−)	0.00005 Lowest (++)	0.00012 Highest (−−)
	TEc	kg 1,4-DCB kg^{-1}	0.056 Lowest (++)	0.066 Modest (+−)	0.182 Highest (−−)
	Fec	kg 1,4-DCB kg^{-1}	0.0031 Modest (+−)	0.0028 Lowest (++)	0.0068 Highest (−−)
	MEc	kg 1,4-DCB kg^{-1}	0.00096 Lowest (++)	0.00098 Modest (+−)	0.0026 Highest (−−)
	HCT	kg 1,4-DCB kg^{-1}	0.00008 Lowest (++)	0.00015 Modest (+−)	0.00057 Highest (−−)
	HnCT	kg 1,4-DCB kg^{-1}	0.038 Modest (+−)	0.034 Lowest (++)	0.08 Highest (−−)
	MRS	kg 1,4-DCB kg^{-1}	0.00004 Lowest (++)	0.0015 Modest (+−)	0.0047 Highest (−−)
	FRS	kg 1,4-DCB kg^{-1}	0.0139 Lowest (++)	0.043 Modest (+−)	0.1178 Highest (−−)
Economic benefit	Net profit	USD kg^{-1}	0.49 Highest (++)	0.41 Modest (+−)	0.31 Lowest (−−)
Energy Requirement	Total energy	MJ kg^{-1}	7.92 Modest (+−)	6.19 Lowest (++)	10.35 Highest (−−)

Considering the three aspects of sustainability, *OFS* provided superior performance in two sustainability aspects as indicated by the lowest environmental impact and the highest economic benefit. Therefore, it indicated that *OFS* is more environmentally sustainable and economically viable.

4. Discussion

4.1. Energy, Environment, and Economic Hotspots and Its Strategies on Reducing the Negative Impact Factor

Identifying the hotspots in energy, environmental, and economic aspects will provide proper insights and strategies to effectively reduce energy usage, environmental damage, and production expenses. For example, the inputs of fertilizer, water, rice husk, and labor required higher energy during the coffee plantation. In particular, considering the fertilizer input, manure needs the highest energy in the *OFS* and *COFS*, whereas the NPK predominantly uses the energy in the *CFS*. Thus, our results highlight that fertilizer is a hotspot in terms of the energy requirements of the life cycle of coffee plantations. A similar study also revealed the most significant amount of energy contributed by fertilizer at 32–38% [52]. Therefore, Reducing the chemical input and managing the fertilizer can potentially reduce the energy used.

In environmental impact results, NPK most contributed to the environmental damage in *COFS* and *CFS*. At the same time, rice husk contributes significantly to the environmental impact in the *OFS*. These findings indicated that chemical fertilizer is the hotspot contributing to the environmental damage during coffee production. A similar study in agriculture commodity also reported that fertilizer mainly contributed to the environmental damage [34,52]. Therefore, some strategies can significantly reduce the environmental impact, such as reducing the NPK application, switching the chemical substances into organic ones, and substituting the rice husk with a more environmentally friendly material.

According to the net profit result, our economic analysis identified that *OFS* is more profitable than the other systems. In production cost, labor and fertilizer usage were the hotspots of production cost. In particular, approximately 60.7–75.88% of the labor cost is used for the harvesting activity. Manure predominantly accounted for 22.6% and 11.36% of the fertilizer cost in the *OFS* and *COFS*, respectively. Simultaneously, NPK accounted for 21.61% of the fertilizer cost in the *CFS*. Therefore, the following scenarios can predictively reduce the production cost: (1) reducing the labor during harvesting using appropriate technology and tools; and (2) reducing the NPK application in the *COFS* and *CFS*, and substituting it with the *OFS*.

4.2. Future Challenges of the Green Coffee Plantation System

Developing the green industry from the upstream to downstream in the agricultural sector is essential for promoting sustainable agriculture [27]. Thus, the business framework warrants a transformation [22]. To adopt the most environmentally and economically viable approach, coffee production must be evaluated and improved. This study suggests that practicing the *OFS* should be extended to sustainable coffee production in Indonesia. However, there are several challenges in implementing such green coffee plantation systems. First, most coffee farmers employed conventional practices using a large amount of chemical fertilizer and still depended on labor for all activities [13,20]. Second, most farmers practiced a low-intensity coffee management system. However, only a few farmers practiced intensive coffee plantation systems. Low maintenance in managing the plantations will inevitably result in low productivity. Lower productivity resulted in more serious environmental damage and had lower economic performance per 1 ha of coffee plantation. Third, although this research recommends that the *OFS* be extensively applied, the higher energy requirements for providing manure are an important challenge. Therefore, research should be conducted to determine the optimum sustainable coffee plantation management system, considering the energy requirement, environmental impact, and economic performance.

5. Conclusions

The comprehensive sustainability evaluation of coffee production systems in Indonesia was conducted considering three sustainability aspects: energy requirement, environmental impact, and economic performance. From the energy perspective, managing 1 kg of coffee cherry bean using *CFS* is not recommended due to its higher energy requirements. Conversely, *COFS* and *OFS* were recommended because of the lower energy consumption. Our results highlight that fertilizer is a hotspot in terms of the energy requirements of the life cycle of coffee plantations. From an environmental perspective, the *OFS* is recommended for managing coffee plantations. The *OFS* provides the lowest environmental impact compared to those managed by the *COFS* and *CFS*. Due to the lower environmental impact provided by the *OFS*, the potential reduction of emissions was also a significant result. Chemical fertilizer was identified as the most significant contributing factor to all emissions in the *COFS* and *CFS* and followed by the rice husk. Therefore, our result findings that NPK and rice husk are the hotspot contributing to the environmental damage during coffee production. From the economic perspective, managing 1 ha of coffee plantations nurtured by the *OFS* generated the highest revenue and net profit for farmers compared with those of the *COFS* and *CFS*. In terms of energy perspective, the *COFS* and *OFS* are recommended due to the lower energy consumption compared to *CFS*. Considering the environmental impact and economic analysis results, the *OFS* is recommended due to its lower impact on environmental damage and the highest net profit for farmers. The massive *OFS* practice will be followed by higher energy consumption. From an energy requirement perspective, *COFS* can be the second alternative to be applied.

This study result provided a positive implication and valuable information related to managing organic coffee cultivation (*OFS*) as suggested by this result. As *OFS* provided more benefit not only for the environmental but also to the higher economic benefit, farmers are becoming more attracted to practicing *OFS* which represents green coffee cultivation. As the majority of farmers are still applying *COFS* with a significant level of chemical substances, shifting to the *OFS* will significantly impact the environmental and economic sustainability of coffee production in Indonesia. Practically, this research contributed a practical method of how to reduce environmental impact through the hotspots in environmental, economic, ad energy impacts that are found in this research. The hotspots of emission, cost, and energy will help farmers reduce the negative impact on environmental, economic, and energy aspects. This research also contributes to the academic purposes of providing scientific literature to fulfill the research gap and limited information related to comprehensive sustainability assessment in Indonesia.

Author Contributions: D.M.R.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Resources, Validation, Visualization, Writing—original draft Writing—review & editing; A.S.P.: Formal analysis, Software, Supervision, and Writing—review & editing; R.I.: Supervision, Validation, Visualization, and Writing—review & editing; R.N.: Conceptualization, Methodology, Supervision, and Writing—review & editing; and T.A.: Conceptualization, methodology, Supervision, and Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding, but for publication, this manuscript was funded by the Indonesia Endowment Funds for Education (LPDP) as the awardee scholarship scheme facility.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The primary data for inventory is obtained by direct survey and interview the farmer who manages all three coffee plantation systems and managed a small-medium coffee industry and farmer groups in West Bandung Regency, West Java, Indonesia.

Acknowledgments: The authors thank the Indonesia Endowment Funds for Education (LPDP) Scholarship for providing the scholarship to the author during the study at The University of Tsukuba, Japan.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

COFS	Chemical-Organic fertilizing system	kg	Kilogram
CFS	Chemical fertilizing system	LCA	Life cycle assessment
d	day	LCC	Life cycle costing
DCB	Dichlorobenzene	ME	Marine eutrophication
EF	Energy factor	MEc	Marine ecotoxicity
EI	Environmental impact	MRS	Mineral resource scarcity
FE	Freshwater eutrophication	*n*	Number of input system
FEc	Freshwater ecotoxicity	*OFS*	Organic fertilizing system
FRS	Fossil resource scarcity	TA	Terrestrial acidification
GWP	Global warming potential	TE	Terrestrial ecotoxicity
h	hour	TLCC	Total life cycle cost
HCT	Human carcinogenic toxicity	USD	United States Dollar
HnCT	Human non-carcinogenic toxicity	y	year
IDR	Indonesia Rupiah		

Appendix A

Table A1. Energy requirement for 1 kg coffee cherry bean production.

Input Energy	Fertilizing System		
	Organic (*OFS*)	**Chemical-Organic (*COFS*)**	**Chemical (*CFS*)**
	Energy Requirement (MJ kg^{-1})		
Direct energy			
Gasoline	0.34	0.29	0.6
Electricity	0.0031	0.0027	0.006
Indirect energy			
Poultry manure	5.47	2.35	0.3
Compost	0.16	0.16	0.35
Liquid organic fertilizer	0.003	0.003	0.006
Rice husk	0.43	0.38	0.86
Water	1.1	0.97	2.2
NPK	-	1.64	4.97
Pesticide	-	0.044	0.455
Human Labor	0.39	0.36	0.57
Total	7.92	6.19	10.35

Table A2. Environmental impact for 1 kg of coffee cherry bean.

Impact Category	Unit	Fertilizing System		
		Organic (*OFS*)	**Chemical-Organic (*COFS*)**	**Chemical (*CFS*)**
Global warming potential (GWP)	kg CO_2 eq kg^{-1}	0.0678	0.182	0.496
Terrestrial acidification (TA)	kg SO_2 eq kg^{-1}	0.0005	0.00096	0.00254
Freshwater eutrophication (FE)	kg P eq kg^{-1}	0.0000049	0.000008	0.000023
Marine eutrophication (ME)	kg N eq kg^{-1}	0.000059	0.000053	0.00012
Terrestrial ecotoxicity (TEc)	kg 1,4-DCB kg^{-1}	0.0564	0.0655	0.1819
Freshwater ecotoxicity (FEc)	kg 1,4-DCB kg^{-1}	0.0031	0.0028	0.00678
Marine ecotoxicity (MEc)	kg 1,4-DCB kg^{-1}	0.00096	0.00098	0.0026
Human carcinogenic toxicity (HCT)	kg 1,4-DCB kg^{-1}	0.000085	0.00015	0.00056
Human non-carcinogenic toxicity (HnCT)	kg 1,4-DCB kg^{-1}	0.0378	0.0345	0.0804
Mineral resource scarcity (MRS)	kg Cu eq kg^{-1}	0.000039	0.00149	0.0046
Fossil resource scarcity (FRS)	kg oil eq kg^{-1}	0.014	0.043	0.118

Table A3. Working hour on managing 1 ha of Organic fertilizing system (*OFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Subtotal (h y^{-1})	Total Working Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.47
	Maintenance	42	1	2	84	84	1.23
Nursery	Preparation	5	8	2	80	80	1.18
	Maintenance	240	1	1	240	240	3.53
Planting	Planting	30	8	2	480	480	7.05
Subtotal at 1st year					916	916	13.46
Maintenance in pre-productive stage	Clearing	6	8	2	96	192	2.82
	Pruning	1	8	2	16	32	0.47
	Fertilizing	3	8	2	48	96	1.41
Subtotal 2nd–3rd year					160	320	4.70
Maintenance in productive stage and harvesting	Clearing	6	8	2	96	576	8.47
	Pruning	1	8	2	16	96	1.41
	Fertilizing	3	8	2	48	288	4.23
	Harvesting	24	4	8	768	4608	67.72
Subtotal at the 4–9th year					928	5568	81.83
Total working hour						6804	100

Table A4. Working hour on managing 1 ha of Chemical-Organic fertilizing system (*COFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Sub Total (h y^{-1})	Total Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.47
	Maintenance	42	1	2	84	84	1.22
Nursery	Preparation	5	8	2	80	80	1.16
	Maintenance	240	1	1	240	240	3.49
Planting	Planting	30	8	2	480	480	6.99
Subtotal at the 1st year					916	916	13.34
Maintenance in pre-productive stage	Clearing	1	8	2	16	32	0.47
	Pruning	1	8	2	16	32	0.47
	Fertilizing	4	8	2	64	128	1.86
Subtotal at the 2nd–3rd year					96	192	2.8
Maintenance in productive stage and harvesting	Clearing	1	8	2	16	96	1.4
	Pruning	1	8	2	16	96	1.4
	Fertilizing	4	8	2	64	384	5.59
	harvesting	24	4	9	864	5184	75.48
Subtotal 4–9th					960	5760	83.87
Total working hour						6868	100

Table A5. Working hour on managing 1 ha of Chemical fertilizing system (*CFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Sub Total (h y^{-1})	Total Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.84
	Maintenance	42	1	2	84	84	2.21
Nursery	Preparation	5	8	2	80	80	2.11
	Maintenance	240	1	1	240	240	6.32
Planting	Planting	30	8	2	480	480	12.64
Subtotal at the 1st year					916	916	24.13
Maintenance in pre-productive stage	Clearing	1	8	2	16	32	0.84
	Pruning	1	8	2	16	32	0.84
	Fertilizing	4	8	2	64	128	3.37
Subtotal at the 2nd–3rd year					96	192	5.06
Maintenance in productive stage and harvesting	Clearing	1	8	2	16	96	2.53
	Pruning	1	8	2	16	96	2.53
	Fertilizing	2	8	2	32	192	5.06
	Harvesting	24	4	4	384	2304	60.7
Subtotal at the 4–9th year					448	2688	70.81
Total working hour						3796	100

Table A6. Environmental impact contributor factor in Organic fertilizing system (*OFS*).

Impact Category	Unit ($\times 10^{-6}$)	Liquid Organic Fertilizer	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	130.11	8328.0	14,280	1,290	43,071	299.92
TA	kg SO_2 eq	0.89	31.99	65.87	7.08	387.10	1.04
FE	kg P eq	0.02	-	-	0.19	4.24	0.47
ME	kg N eq	0.14	0.04	0.07	1.08	58.02	0.03
TEc	kg 1,4-DCB	223.21	149.31	252.90	3598	51,293	369.36
FEc	kg 1,4-DCB	3.48	45.41	76.91	42.14	2880.05	20.68
MEc	kg 1,4-DCB	4.29	61.19	103.64	50.78	704.53	27.11
HCT	kg 1,4-DCB	2.02	6.31	10.68	21.98	19.40	23.88
HnCT	kg 1,4-DCB	60.83	2447	4145	1328	28,977	509.04
MRS	kg Cu eq	0.36	-	-	24.90	14.09	0.16
FRS	kg oil eq	9.17	2736.9	4635.8	125.7	6256.3	76.46

Table A7. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Unit ($\times 10^{-6}$)	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	125,102	114.89	1694	4092	10,915	1146	38,260	264.05
TA	kg SO_2 eq	528.26	0.78	12.74	15.72	50.35	6.29	343.85	0.92
FE	kg P eq	2.72	0.02	0.91	-	-	0.16	3.77	0.41
ME	kg N eq	0.13	0.12	0.51	0.02	0.06	0.96	51.53	0.03
TEc	kg 1,4-DCB	7999	197.10	7965	73.36	193.32	3196	45,563	325.18
FEc	kg 1,4-DCB	2.93	3.07	130.96	22.31	58.79	37.43	2558	18.20
MEc	kg 1,4-DCB	29.54	3.79	144.59	30.06	79.22	45.11	625.82	23.87
HCT	kg 1,4-DCB	16.19	1.78	65.07	3.10	8.17	19.52	17.23	21.02
HnCT	kg 1,4-DCB	506.23	53.71	2188	1202	3168	1179	25,740	448.16
MRS	kg Cu eq	1412	0.32	52.50	-	-	22.12	12.51	0.14
FRS	kg oil eq	31,746	8.10	578.41	1345	3544	111.66	5557	67.32

Table A8. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Unit ($\times 10^{-6}$)	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	381,541	261.04	9627	9299	5368	2602	86,886	599.61
TA	kg SO_2 eq	1611	1.78	72.37	35.72	24.76	14.29	780.87	2.09
FE	kg P eq	8.30	0.05	5.19	-	-	0.37	8.56	0.94
ME	kg N eq	0.39	0.28	2.88	0.05	0.03	2.17	117.03	0.06
TEc	kg 1,4-DCB	24,394	447.83	45,255	166.72	95.07	7257	103,472	738.43
FEc	kg 1,4-DCB	8.93	6.98	744.08	50.70	28.91	85.01	5810	41.34
MEc	kg 1,4-DCB	90.08	8.61	821.56	68.32	38.96	102.43	1421	54.20
HCT	kg 1,4-DCB	49.38	4.05	369.72	7.04	4.02	44.34	39.13	47.74
HnCT	kg 1,4-DCB	1544	122.04	12,430	2732	1558	2678	58,455	1018
MRS	kg Cu eq	4306	0.73	298.27	-	-	50.23	28.42	0.33
FRS	kg oil eq	96,821	18.40	3286	3056	1743	253.58	12,621	152.86

Table A9. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Liquid Organic Fertilizer	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	0.19	12.6	21.19	1.91	63.90	0.44
TA	0.18	6.48	13.33	1.43	78.37	0.21
FE	0.48	-	-	3.77	86.19	9.56
ME	0.23	0.07	0.12	1.81	97.71	0.05
TEc	0.40	0.27	0.45	6.44	91.78	0.66
FEc	0.11	1.48	2.51	1.37	93.85	0.67
MEc	0.45	6.43	10.9	5.34	74.04	2.85
HCT	2.39	7.48	12.7	26.1	23.02	28.3
HnCT	0.16	6.53	11.1	3.54	77.34	1.36
MRS	0.92	-	-	63.0	35.65	0.42
FRS	0.07	19.7	33.5	0.91	45.20	0.55

Table A10. Percentage of contribution factor in Chemical-Organic fertilizing system (*COFS*) (%).

Impact Category	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	68.89	0.06	0.93	2.25	6.01	0.63	21.07	0.15
TA	55.09	0.08	1.33	1.64	5.25	0.66	35.86	0.10
FE	34.00	0.26	11.40	-	-	2.06	47.09	5.18
ME	0.24	0.23	0.95	0.04	0.10	1.79	96.60	0.05
TEc	12.21	0.30	12.16	0.11	0.30	4.88	69.55	0.50
FEc	0.10	0.11	4.62	0.79	2.08	1.32	90.34	0.64
MEc	3.01	0.39	14.72	3.06	8.07	4.59	63.73	2.43
HCT	10.65	1.17	42.79	2.04	5.37	12.84	11.33	13.82
HnCT	1.47	0.16	6.34	3.49	9.19	3.42	74.64	1.30
MRS	94.16	0.02	3.50	-	-	1.48	0.83	0.01
FRS	73.90	0.02	1.35	3.13	8.25	0.26	12.94	0.16

Table A11. Percentage of contribution factor in Chemical fertilizing system (*CFS*) (%).

Impact Category	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	76.89	0.053	1.94	1.87	1.08	0.52	17.51	0.12
TA	63.35	-	2.85	1.405	0.97	0.56	30.7	0.08
FE	35.45	0.2	22.15	-	-	1.59	36.56	4.02
ME	0.32	0.225	2.34	0.039	0.02	1.76	95.23	0.047
TEc	13.41	0.24	24.89	0.09	0.05	3.99	56.9	0.4
FEc	0.13	0.1	10.98	0.75	0.43	1.25	85.74	0.61
MEc	3.45	0.33	31.53	2.62	1.49	3.93	54.55	2.08
HCT	8.73	0.71	65.39	1.246	0.71	7.84	6.92	8.44
HnCT	1.91	0.15	15.43	3.39	1.93	3.32	72.58	1.26
MRS	91.93	0.015	6.37	-	-	1.07	0.607	0.007
FRS	82.08	0.016	2.78	2.59	1.47	0.21	10.7	0.13

Table A12. Potential increase or decrease of applying the Organic fertilizing system (*OFS*).

Impact Category	Unit	Potential Decrease or Increase			Percentage Decrease or Increase (%)		
		OFS vs. *CFS*	*OFS* vs. *CFS*	*COFS* vs. *CFS*	*OFS* vs. *COFS*	*OFS* vs. *COFS*	*COFS* vs. *CFS*
GWP	kg CO_2 eq	−0.114	−0.428	−0.314	−62.6	−86.3	−63.4
TA	kg SO_2 eq	−0.00046	−0.00204	−0.00158	−48.1	−80.4	−62.3
FE	kg P eq	−3.1E-06	−0.000018	−0.000015	−38.8	−78.7	−65.2
ME	kg N eq	0.000006	−0.000064	−0.00007	11.3	−52	−56.9
TEc	kg 1,4-DCB	−0.009	−0.126	−0.116	−13.9	−69	−64
FEc	kg 1,4-DCB	0.0003	−0.0037	−0.0039	9.3	−54.3	−58.2
MEc	kg 1,4-DCB	−0.00002	−0.00164	−0.00162	−2.4	−63.2	−62.3
HCT	kg 1,4-DCB	−0.000067	−0.00048	−0.00041	−44.4	−85	−73.1
HnCT	kg 1,4-DCB	0.0033	−0.0427	−0.046	9.5	−53.1	−57.1
MRS	kg Cu eq	−0.0015	−0.0046	−0.0032	−97.4	−99.2	−68
FRS	kg oil eq	−0.029	−0.104	−0.075	−67.6	−88.2	−63.5

According to Table A12, the minus value indicates the shifting from organic fertilizing system to chemical fertilizing system will decrease its environment impact; and the positive value indicates the shifting from organic fertilizing system to chemical fertilizing system will increase its environment impact. The potential decrease or increase and its percentage were obtained using the Equations (A1)–(A3):

$$\%\ decrease\ or\ increase\ OFS\ vs.\ COFS = \frac{potential\ reduction\ OFS\ vs.\ COFS}{impact\ in\ COFS} \times 100\% \quad (A1)$$

$$\%\ decrease\ or\ increase\ OFS\ vs.\ CFS = \frac{potential\ reduction\ OFS\ vs.CFS}{impact\ in\ CFS} \times 100\% \quad (A2)$$

$$\%\ decrease\ or\ increase\ COFS\ vs.\ CFS = \frac{potential\ reduction\ COFS\ vs.CFS}{impact\ in\ CFS} \times 100\% \quad (A3)$$

Table A13. Production cost per 1 ha coffee plantation (USD).

Item of Cost	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Fixed cost		
Equipment	17.35	17.35	17.35
Device maintenance	249.85	249.85	249.85
	Variable cost		
Human labor cost	4577.79	4638.87	2517.92
NPK	-	990.64	1329
Rent transportation	1811.41	1894.69	1728.12
Compost	180.45	180.45	180.45
Manure	2025.44	1031.60	54.41
Polybag	19.09	19.09	19.09
Rice Husk	45.11	45.11	45.11
Seed	10.41	10.41	10.41
Pesticide	-	6.25	24.98
Total cost	8936.90	9084.31	6176.69

Table A14. Production cost per 1 kg coffee cherry bean (USD kg^{-1}) and its percentage (%).

Item of Cost	Cost per kg (USD)			Percentage (%)		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
			Fixed cost			
Equipment	0.0004	0.0003	0.0008	0.19	0.19	0.28
Device maintenance	0.006	0.005	0.011	2.8	2.75	4.05
			Variable cost			
Labor	0.104	0.093	0.114	51.22	51.06	40.76
NPK	-	0.02	0.06	-	10.9	21.52
Transportation	0.04	0.04	0.08	20.27	20.86	27.98
Compost	0.004	0.004	0.008	2.02	1.99	2.92
Manure	0.046	0.021	0.002	22.66	11.36	0.88
Polybag	0.0004	0.0004	0.001	0.21	0.21	0.31
Rice Husk	0.001	0.001	0.002	0.5	0.5	0.73
Seed	0.0002	0.0002	0.0005	0.12	0.11	0.17
Pesticide	-	0.0001	0.0011	0	0.07	0.4
Total cost	0.203	0.182	0.28	100	100	100

The Production cost per kilogram coffee cherry bean is obtained by Equations (A4) and (A5).

$$Production\ cost\ per\ kg = \frac{cost\ per\ hectar}{coffee\ production\ per\ hectar} \times 100 \quad \text{(A4)}$$

$$Cost\ percentage\ per\ item\ input = \frac{cost\ per\ item\ input}{total\ life\ cycle\ cost} \times 100 \quad \text{(A5)}$$

Table A15. Emission cost.

Fertilizing Systems	Coffee Cherry Bean Production (kg)	Emission per Kilogram Coffee Cherry Bean (kg CO_2 eq kg^{-1})	Emission Tax (USD t^{-1})	Total Emission (USD ha^{-1})
Organic (*OFS*)	44,000	0.068	9.7	29.07
Chemical-Organic (*COFS*)	50,000	0.182	9.7	88.42
Chemical (*CFS*)	22,000	0.496	9.7	106.03

Table A16. Revenue and Net profit.

Fertilizing Systems	Coffee Cherry Bean Production (kg ha^{-1})	Selling Price (USD kg^{-1})	Revenue (USD ha^{-1})	Net Profit (USD ha^{-1})
Organic (*OFS*)	44,000	0.69	30,537	21,571
Chemical-Organic (*COFS*)	50,000	0.59	29,496	20,323
Chemical (*CFS*)	22,000	0.59	12,978	6695

Table A17. Percentage contribution of life cycle cost.

Item of Cost	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Percentage (%)		
	Fixed cost		
Equipment	0.19	0.19	0.28
Device maintenance	2.8	2.75	4.05
	Variable cost		
Human labor cost	51.22	51.06	40.76
Fertilizer (NPK)	-	10.9	21.52
Rent transportation	20.27	20.86	27.98
Compost	2.02	1.99	2.92
Manure	22.66	11.36	0.88
Polybag	0.21	0.21	0.31
Rice Husk	0.5	0.5	0.73
Seed	0.12	0.11	0.17
Pesticide	-	0.07	0.4
Total	100	100	100

The percentage cost is calculated using the Equation (A6).

$$\text{Cost percentage per item input} \quad \text{(A6)}$$

Table A18. Cumulative energy requirement per 1 ha coffee plantation.

Input Energy	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Energy Requirement ($\times 10^3$ MJ ha^{-1})		
	Direct energy		
Electricity	0.13	0.13	0.13
Gasoline	15.14	14.32	13.22
	Direct energy		
Poultry manure	240.77	117.48	6.6
Compost	7.8	7.8	7.8
Liquid organic fertilizer	0.14	0.14	0.14
Rice husk	18.98	18.98	18.98
Water	48.42	48.42	48.42
NPK	-	81.91	109.92
Pesticide	-	2.22	10.01
HUman labor	12.93	13.1	7.11
Total	344.31	304.51	222.34

Table A19. Energy requirement per stage of coffee plantation.

Stage	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Energy per Hectare ($\times 10^3$ MJ ha^{-1})		
Seeding	2.92	2.92	2.92
Nursery	76.95	77.03	77.11
Planting	5.68	5.68	5.68
Maintenance 1	54.32	49.41	27.44
Maintenance 2	185.92	149.76	94.97
Harvesting	18.53	19.71	14.22
Total	344.31	304.51	222.34

References

1. Li, M.; Fu, Q.; Singh, V.P.; Liu, D.; Li, T.; Li, J. Sustainable management of land, water, and fertilizer for rice production considering footprint family assessment in a random environment. *J. Clean. Prod.* **2020**, *258*, 120785. [CrossRef]
2. Al-Mansour, F.; Jejcic, V. A model calculation of the carbon footprint of agricultural products: The case of Slovenia. *Energy* **2017**, *136*, 7–15. [CrossRef]
3. Amini, S.; Rohani, A.; Aghkhani, M.H.; Abbaspour-Fard, M.H.; Asgharipour, M.R. Sustainability assessment of rice production systems in Mazandaran Province, Iran with emergy analysis and fuzzy logic. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100744. [CrossRef]
4. Fiore, M.; Spada, A.; Contò, F.; Pellegrini, G. GHG and cattle farming: CO-assessing the emissions and economic performances in Italy. *J. Clean. Prod.* **2018**, *172*, 3704–3712. [CrossRef]
5. Nowak, A.; Krukowski, A.; Różańska-Boczula, M. Assessment of sustainability in agriculture of the European Union countries. *Agronomy* **2019**, *9*, 890. [CrossRef]
6. Troiano, S.; Novelli, V.; Geatti, P.; Marangon, F.; Ceccon, L. Assessment of the sustainability of wild rocket (Diplotaxis tenuifolia) production: Application of a multi-criteria method to different farming systems in the province of Udine. *Ecol. Indic.* **2019**, *97*, 301–310. [CrossRef]
7. Vinyes, E.; Asin, L.; Alegre, S.; Muñoz, P.; Boschmonart, J.; Gasol, C.M. Life Cycle Assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. *J. Clean. Prod.* **2017**, *149*, 313–320. [CrossRef]
8. Joyce, A.; Paquin, R.L. The triple layered business model canvas: A tool to design more sustainable business models. *J. Clean. Prod.* **2016**, *135*, 1474–1486. [CrossRef]
9. Zhang, X.; Zhang, M.; Zhang, H.; Jiang, Z.; Liu, C.; Cai, W. A review on energy, environment and economic assessment in remanufacturing based on life cycle assessment method. *J. Clean. Prod.* **2020**, *255*, 120160. [CrossRef]
10. United Nation. Sustainable Development Goals. 2015. Available online: https://sdgs.un.org/goals. (accessed on 16 March 2022).
11. Olabi, A.G.; Obaideen, K.; Elsaid, K.; Wilberforce, T.; Sayed, E.T.; Maghrabie, H.M.; Abdelkareem, M.A. Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators. *Renew. Sustain. Energy Rev.* **2021**, *153*, 111710. [CrossRef]
12. International Coffee Organization (ICO). World Coffee Consumption. 2021. Available online: https://ico.org/prices/new-consumption-table.pdf (accessed on 1 June 2021).
13. Widaningsih, R.; Susanti, A.A.; Musyafak, A.; Putra, R.K.; Suyati, Y. Coffee Outlook Indonesia. Agriculture Data Information Center. Indonesia Agricultural Ministre. 2020. Available online: https://epublikasi.pertanian.go.id/arsip-outlook/75-outlook-perkebunan/723-outlook-kopi-2020 (accessed on 25 December 2020).
14. Noponen, M.R.A.; Edwards-Jones, G.; Haggar, J.P.; Soto, G.; Attarzadeh, N.; Healey, J.R. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. *Agric. Ecosyst. Environ.* **2012**, *151*, 6–15. [CrossRef]
15. Biernat-Jarka, A.; Trębska, P. The Importance of Organic Farming in the Context of Sustainable Development of Rural Areas in Poland. *Acta Sci. Pol. Oecon.* **2018**, *17*, 39–47. [CrossRef]
16. Hassard, H.; Couch, M.; Techa-Erawan, T.; McLellan, B. Product carbon footprint and energy analysis of alternative coffee products in Japan. *J. Clean. Prod.* **2014**, *73*, 310–321. [CrossRef]
17. Acosta-Alba, I.; Boissy, J.; Chia, E.; Andrieu, N. Integrating diversity of smallholder coffee cropping systems in environmental analysis. *Int. J. Life Cycle Assess.* **2019**, *25*, 252–266. [CrossRef]
18. Jiménez-Ortega, A.D.; Ibarra, A.A.; Galeana-Pizaña, J.M.; Núñez, J.M. Changes over Time Matter: A Cycle of Participatory Sustainability Assessment of Organic Coffee in Chiapas, Mexico. *Sustainability* **2022**, *14*, 2012. [CrossRef]
19. Coltro, L.; Mourad, A.; Oliveira, P.; Baddini, J.; Kletecke, R. Environmental Profile of Brazilian Green Coffee. *Int. J. Life Cycle Assess.* **2006**, *11*, 16–21. [CrossRef]
20. Byrareddy, V.; Kouadio, L.; Mushtaq, S.; Stone, R. Sustainable Production of Robusta Coffee under a Changing Climate: A 10-Year Monitoring of Fertilizer Management in Coffee Farms in Vietnam and Indonesia. *Agronomy* **2019**, *9*, 499. [CrossRef]
21. Neilson, J.; Wright, J.; Aklimawati, L. Geographical indications and value capture in the Indonesia coffee sector. *J. Rural Stud.* **2018**, *59*, 35–48. [CrossRef]
22. Halog, A.; Manik, Y. Life Cycle Sustainability Assessments. *Encycl. Inorg. Bioinorg. Chem.* **2016**, 25–41. [CrossRef]
23. Dabkienė, V.; Baležentis, T.; Štreimikienė, D. Calculation of the carbon footprint for family farms using the Farm Accountancy Data Network: A case from Lithuania. *J. Clean. Prod.* **2020**, *262*, 121509. [CrossRef]
24. Mancini, M.S.; Galli, A.; Niccolucci, V.; Lin, D.; Bastianoni, S.; Wackernagel, M.; Marchettini, N. Ecological Footprint: Refining the carbon Footprint calculation. *Ecol. Indic.* **2016**, *61*, 390–403. [CrossRef]
25. González-Cencerrado, A.; Ranz, J.P.; Jiménez, M.T.L.-F.; Gajardo, B.R. Assessing the environmental benefit of a new fertilizer based on activated biochar applied to cereal crops. *Sci. Total Environ.* **2020**, *711*, 134668. [CrossRef] [PubMed]
26. Putra, A.S.; Noguchi, R.; Ahamed, T.; Nakagawa-Izumi, A.; Ohi, H. Development of integrated oil palm empty fruit bunches (EFB)-based dissolving pulp and furfural production: A consequential LCA approach. *Int. J. Life Cycle Assess.* **2021**, *26*, 175–188. [CrossRef]
27. International Coffee Organization (ICO). New ICO Study: Assessing the Economic Sustainability of Coffee Growing. 2016. Available online: https://ico.org/show_news.asp?id=567 (accessed on 10 March 2022).

28. Bosona, T.; Gebresenbet, G.; Dyjakon, A. Implementing life cycle cost analysis methodology for evaluating agricultural pruning-to-energy initiatives. *Bioresour. Technol. Rep.* **2019**, *6*, 54–62. [CrossRef]
29. Swarr, T.E.; Hunkeler, D.; Klöpffer, W.; Pesonen, H.-L.; Ciroth, A.; Brent, A.; Pagan, R. Environmental life-cycle costing: A code of practice. *Int. J. Life Cycle Assess.* **2011**, *16*, 389–391. [CrossRef]
30. Wang, H.; Oguz, E.; Jeong, B.; Zhou, P. Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry. *Ocean Eng.* **2018**, *161*, 20–28. [CrossRef]
31. Kamali, F.P.; van der Linden, A.; Meuwissen, M.P.; Malafaia, G.C.; Lansink, A.G.O.; de Boer, I.J. Environmental and economic performance of beef farming systems with different feeding strategies in southern Brazil. *Agric. Syst.* **2016**, *146*, 70–79. [CrossRef]
32. Kizilaslan, H. Input–output energy analysis of cherries production in Tokat Province of Turkey. *Appl. Energy* **2009**, *86*, 1354–1358. [CrossRef]
33. West Bandung Regency Profile. Medium-Term Investment Program Plan of West Bandung Regency. 2015. Available online: https://sippa.ciptakarya.pu.go.id/sippa_online/ws_file/dokumen/rpi2jm/DOCCRPIJM_3a3c8d3e3b_BAB%20IIBAB%202.pdf (accessed on 17 March 2022).
34. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant Acidification in Major Chinese Croplands. *Science* **2010**, *327*, 1008–1010. [CrossRef]
35. *ISO 14040*; Environmental Management E Life Cycle Assessment-Principles and Framework. International Standard Organization: Geneva, Switzerland, 2016. Available online: https://www.iso.org/standard/37456.html?browse=tc(accessed on 22 February 2022).
36. Vinyes, E.; Gasol, C.M.; Asin, L.; Alegre, S.; Muñoz, P. Life Cycle Assessment of multiyear peach production. *J. Clean. Prod.* **2015**, *104*, 68–79. [CrossRef]
37. IOR Energy Pty Ltd-University of California, Berkeley. List of Common Conversion Factor. Available online: https://w.astro.berkeley.edu/~{}wright/fuel_energy.html (accessed on 25 December 2021).
38. Kaab, A.; Sharifi, M.; Mobli, H.; Nabavi-Pelesaraei, A.; Chau, K.-W. Use of optimization techniques for energy use efficiency and environmental life cycle assessment modification in sugarcane production. *Energy* **2019**, *181*, 1298–1320. [CrossRef]
39. Hosseinzadeh-Bandbafha, H.; Safarzadeh, D.; Ahmadi, E.; Nabavi-Pelesaraei, A.; Hosseinzadeh-Bandbafha, E. Applying data envelopment analysis to evaluation of energy efficiency and decreasing of greenhouse gas emissions of fattening farms. *Energy* **2017**, *120*, 652–662. [CrossRef]
40. Unakitan, G.; Hurma, H.; Yilmaz, F. An analysis of energy use efficiency of canola production in Turkey. *Energy* **2010**, *35*, 3623–3627. [CrossRef]
41. Ozkan, B.; Akcaoz, H.; Fert, C. Energy input–output analysis in Turkish agriculture. *Renew. Energy* **2004**, *29*, 39–51. [CrossRef]
42. Avval, S.H.M.; Rafiee, S.; Sharifi, M.; Hosseinpour, S.; Notarnicola, B.; Tassielli, G.; Renzulli, P.A. Application of multi-objective genetic algorithms for optimization of energy, economics and environmental life cycle assessment in oilseed production. *J. Clean. Prod.* **2017**, *140*, 804–815. [CrossRef]
43. Rafiee, S.; Avval, S.H.M.; Mohammadi, A. Modeling and sensitivity analysis of energy inputs for apple production in Iran. *Energy* **2010**, *35*, 3301–3306. [CrossRef]
44. Antizar-Ladislao, B.; Irvine, G.; Lamont, E.R. Energy from Waste: Reuse of Compost Heat as a Source of Renewable Energy. *Int. J. Chem. Eng.* **2010**, *2010*, 627930. [CrossRef]
45. Zea, P.; Chilpe, J.; Sánchez, D.; Chica, E.J. Energy efficiency of smallholder commercial vegetable farms in Cuenca (Ecuador). *Trop. Subtrop. Agroecosyst.* **2020**, *23*, 1–8.
46. McLaughlin, N.B.; Hiba, A.; Wall, G.J.; King, D.J. Comparison of energy inputs for inorganic fertilizer and manure based corn production. *Can. Agric. Eng.* **2000**, *42*, 9–18.
47. Neira, D.P.; Montiel, M.S.; Fernández, X.S. Energy Analysis of Organic Farming in Andalusia (Spain). *J. Sustain. Agric.* **2012**, *37*, 231–256. [CrossRef]
48. Pimentel, D.; Burgess, M. An Environmental, Energetic and Economic Comparison of Organic and Conventional Farming Systems. *Integr. Pest Manag.* **2014**, *3*, 141–166. [CrossRef]
49. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
50. OECD. Taxing Energy Use. Using Taxes for Climate Action. 2019. Available online: https://www.oecd.org/tax/tax-policy/brochure-taxing-energy-use-2019.pdf (accessed on 20 December 2021).
51. Indonesian Bank. Statistics Economic and Finance in Indonesia. Available online: https://www.bi.go.id/en/statistic/informasi-kurs/transaksi-bi/Default.aspx. (accessed on 16 December 2021).
52. Basavalingaiah, K.; Paramesh, V.; Parajuli, R.; Girisha, H.; Shivaprasad, M.; Vidyashree, G.; Thoma, G.; Hanumanthappa, M.; Yogesh, G.; Misra, S.D.; et al. Energy flow and life cycle impact assessment of coffee-pepper production systems: An evaluation of conventional, integrated and organic farms in India. *Environ. Impact Assess. Rev.* **2021**, *92*, 106687. [CrossRef]
53. Guo, M.; Murphy, R. LCA data quality: Sensitivity and uncertainty analysis. *Sci. Total Environ.* **2012**, *435–436*, 230–243. [CrossRef] [PubMed]