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New Sustainable Banana Value Chain: Waste Valuation toward a Circular Bioeconomy

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Abstract: According to the needs of sustainability, a new sustainable banana chip value chain, which is a combination of the traditional banana chip value chain and the banana waste value chain, was designed. Scenarios were created assuming that an anaerobic digester would be implemented to produce biogas—which can act as a substitute for liquefied petroleum gas (LPG) used in banana processing—from banana wastes. The values of banana residues throughout the value chain were determined depending on farm gate tree price, transportation cost, and the final value of LPG substitution. The value chain was optimized using two objective functions: total chain profit maximization and factory profit maximization. The tree price at the farm gate was determined and assumed to be between USD 0.067 and USD 0.093 per tree, and the transportation cost of tree transportation was assumed to be between USD 0.31 and USD 0.39 per km. Different tree prices and transportation costs affected the profits of all stakeholders throughout the chain. The scenarios that maximized total chain profits showed superior environmental performance compared to the scenarios that maximized factory profits. The proposed sustainable value chain will lead to an increase in farmers' profits of 15.5–17.0%, while the profits gained by collectors and factory will increase between 3.5 and 8.9% when compared to business as usual.

Keywords: agricultural residue; circular economy; closed loop supply chain; anaerobic digestion; mathematical model

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1. Introduction

The increasing global population results in greater food demand [1]. Agriculture provides the main source of the world's food; thus, increased agri-food production is needed, leading to an increase in the amount of agricultural waste [2,3]. A circular economy is a strategy which is proposed as a tool that can reduce waste and the use of resources, contributing to sustainability. This strategy is considered as a new business model to replace a linear economic model [4,5]. To follow circular economy principles, maximizing the value of products and wastes should be implemented in all phases of the agri-food value chain [5]. Thus, a new value chain model is encouraged, one which provides an understanding of the participation of different actors along the chain and where each link adds value to agri-food products [6–8].

Banana is an agriculture commodity which is not only utilized for food purposes but also plays an important role in generating income for smallholders in developing countries [9]. Banana can be processed into several products such as banana juice, banana chips, and banana flour [10]. Approximately 30–40% of whole banana is peel [11], which is generated from banana processing and left as industrial waste. Moreover, after bananas are harvested, the tree dies and becomes field residue. As worldwide banana production is increasing [12], agricultural waste from banana production and processing should be considered and managed to prevent negative impact on the environment.

Agricultural waste management can mitigate greenhouse gas emission, reduce climate change impacts [13], and promote a circular economy [14]. Recent studies presented technologies that can utilize banana waste to produce energy; these technologies include incineration [15], pyrolysis [16], gasification [17], fermentation [18], and anaerobic digestion [11]. Among these waste management technologies, anaerobic digestion is the most eco-friendly method, and it supports circular bioeconomy [14,19]. It can convert biowastes into valuable products such as biogas and digestate [20]. Various parts of banana plants can be utilized to produce biogas, providing various ranges of energy potentials [11,21–29]. Specific methane yields ranging from 243 to 330 L/kg VS from banana peels [23,26,30], whereas different morphological parts of banana trees demonstrated methane yields ranging from 171 to 324 L/kg VS [11,22]. Krungkaew et al. [11] reported that the energy potential of 7.9 to 12.4 MWh/ha could be obtained from methane produced using banana tree as feedstock. Moreover, Adsal et al. [31] reported that utilizing banana stem waste to produce biogas used in banana production could reduce global warming potential.

Previous studies investigated that utilizing banana residues for biofuel production was economically viable [32–36]. However, few studies presented the economic benefits of biogas production from banana residues [36]. Moreover, the price of banana residues has not been determined and it can be obtained with no cost [32,33]. If banana residues are purchased to be used as feedstock, farmers can gain additional benefits, contributing to social benefits. Regardless, this can affect the value chain, as the cost of the final product will increase. Considering banana waste utilization throughout the value chain, a banana processing factory is an ideal site to implement a biogas plant because banana fruit wastes generated at the factory can be used without the need for transportation. However, banana trees need to be managed and transported to the factory. Transportation cost is one of the important key constraints to be considered for the location of feedstock [37,38] and the cost of collecting and transporting feedstock needs to be considered [14,39].

To design a new sustainable value chain for processed banana production, a tool used to make a decision for obtaining target economic, environmental, and social performance is needed [8]. Several studies developed a mathematical optimization model to design a sustainable supply chain [40–49]. A new value chain for fresh banana was also proposed by Fiallos-Cárdenas et al. [50], presenting a closed loop concept of banana production. However, sustainable performance for the stakeholders along the chain was not presented in the study. According to the literature, a processed banana value chain using banana residues as feedstock to produce biogas has not been explored. The economic value of banana waste along the value chain has not been investigated. To close this gap, this study aims to propose a new sustainable banana value chain, integrating banana waste utilization, and proposes to estimate the sustainability performance along this value chain.

2. Materials and Methods

2.1. Case Study, Scope of Problem, and Data Collection

The selected banana processing factory is a cooperative enterprise locating in Nakhon Pathom province, Thailand. As small and medium enterprises (SMEs) are important for economic development in developing countries [7] and global economic growth [51], this cooperative, which is an SME, was selected as a case study. The factory produces banana chips from green bananas of Hom cultivar (*Musa* AAA group), with the capacity of 50 tons/month of green bananas. The main actors along the chain consist of farmers, banana traders or collectors, factory, and consumers. The process of banana chip production starts from the transportation of green bananas from farms to the factory. Green bananas are processed by frying, with liquefied petroleum gas (LPG) used as a thermal energy source. All fruit parts except banana flesh are considered as wastes generated at the factory. Banana trees become waste and remain at banana farms after harvesting. Thus, it is assumed that only farmers and factory are actors that generate waste along the value chain.

The data, including activities involving in the value chain, material flows, resource usage, and monetary values, were obtained from the factory. The banana production cost of the farm was obtained from Chanadee et al. [52]. Then, the value chain of banana chips was analyzed to determine the business as usual (BAU) scenario. Profit margin and value shares along the value chain were calculated according to Gebre et al. [6]. Profit margin is expressed as the profit percentage of the revenue. Profit share is expressed as the profit percentage of the total profit along the chain. Added value is calculated by subtracting the price of the product that an actor purchases from the price that an actor sells the product for. Value share is the added value, expressed as a percentage of the final price that consumers pay.

In the development of a new sustainable value chain, the factory is an actor that can play an important role in reducing waste and reducing fossil fuel used in the process by implementing a biogas digester. Thus, it is assumed that an anaerobic digester is purchased by the factory to produce biogas using banana residues as feedstock. Tree residues can be transported to the factory by tree collectors. Methane potential and biomass yield value of different banana parts were obtained from Krungkaew et al. [11]. Plant density was determined by collecting data at banana farms. Three different farms of Hom cultivar (*Musa* AAA group) were selected. On each farm, five quadrats were randomly set as four by four rows of banana plantation. The number of all banana trees in a quadrat was obtained. The width of each quadrat was measured to calculate the quadrat area. The plant density (PD) was calculated using the following formula:

$$\mathrm{PD} = \mathrm{N} \cdot \mathrm{A_q^{-1}} \cdot \mathrm{PC^{-1}} \quad (1)$$

where N denotes the total number of trees in a quadrat; A_q is quadrat area; and PC is banana plant growth cycle. Plant growth cycle is the time elapsed for a banana tree to grow until the fruit is harvested.

2.2. Model Formulation

A mathematical model was developed to establish a new sustainable value chain for banana chips. The model was optimized to design the anaerobic digester size and the quantity of different parts of banana substrates to be used as feedstock. Then, scenarios were created to determine the value of banana residues along the value chain. MS Office Excel solver was used to solve the optimization model. The proposed model is based on the following set of assumptions:

- The methane yield of each banana substrate is not affected by substrate mixtures [38].
- The exchange rate is THB/USD 35.
- The total cost of anaerobic digestion system is USD 230/m^3, including capital cost of USD 87/m^3, operational cost of USD 58/m^3, and maintenance and other cost of USD 85/m^3, according to Sritrakul and Hudakorn [53].
- The average cost of LPG in Thailand is USD 0.71/kg.
- Lifespan of an anaerobic digester is 15 years [53].
- Organic loading rate is 3 kg VS/m^3/day [54,55].
- The moisture content of banana residues affects transportation cost [32]. The moisture content of banana tree can be reduced by sun drying at banana farms [35], resulting in lower total transportation cost. For simplicity, the moisture content of banana tree biomass is reduced to 50% before transporting to the factory.

2.2.1. Profit Determination

The profits of each actor were determined to determine profits along the value chain. The farmers can gain revenue from selling banana trees after harvesting. As the trees are generally cut and left on the farms as waste with zero value, all revenues from selling the trees are considered as farmers' profits (Prf), calculated using Equation (2):

$$\mathrm{Prf} = \sum_k \sum_l \sum_m \mathrm{QF_{klm}} \cdot \mathrm{D_p} \cdot \mathrm{C_t} \quad (2)$$

where QF_{klm} is the quantity of fresh biomass of tree part l of cultivar k cultivated at farm m to be used as feedstock per day; D_p is days of production; and C_t denotes farm gate price of tree biomass per kg.

For tree collectors, the benefits include the fact that the total transportation cost is paid by processing factory for collecting and transporting tree biomass from farms to factory. The profits obtained for the collectors (Prc) were calculated using Equation (3):

$$\mathrm{Prc} = \sum_k \sum_l \sum_m \mathrm{QF_{klm}} \cdot \mathrm{DM_{kl}} \cdot \mathrm{MC_{kl}^{-1}} \cdot \mathrm{D_p} \cdot \mathrm{C_{tr,m}} - \sum_k \sum_l \sum_m \mathrm{QF_{klm}} \cdot \mathrm{DM_{kl}} \cdot \mathrm{MC_{kl}^{-1}} \cdot \mathrm{D_p} \cdot \mathrm{C_{main,m}} \quad (3)$$

where DM_{kl} is dry matter content of tree part l of cultivar k; MC_{kl} denotes moisture content of tree part l of cultivar k; $C_{tr,m}$ is the transportation cost per kg of tree substrates from farm m; and $C_{main,m}$ is the cost of fuel and maintenance cost for transportation per kg of tree substrates from farm m.

The factory is considered as an actor that utilized waste, including fruit waste and tree biomass, to produce biogas. Benefits can be obtained by replacing fossil fuel with biogas produced using banana waste as feedstock. The factory profits (Prp) were calculated following Equation (4):

$$\begin{aligned}\mathrm{Prp} = {} & \sum_i \sum_j \sum_k \mathrm{SMY_{ijk}} \cdot \mathrm{QF_{ijk}} \cdot \mathrm{DM_{ijk}} \cdot \mathrm{CF_f} \cdot \mathrm{C_f} \cdot \mathrm{D_p} + \sum_k \sum_l \sum_m \mathrm{SMY_{kl}} \cdot \mathrm{QF_{klm}} \cdot \mathrm{DM_{kl}} \cdot \mathrm{CF_f} \cdot \mathrm{C_f} \cdot \mathrm{D_p} - \mathrm{S_d} \cdot \mathrm{C_d} \cdot \mathrm{L_d^{-1}} - \\ & \sum_k \sum_l \sum_m \mathrm{QF_{klm}} \cdot \mathrm{DM_{kl}} \cdot \mathrm{MC_{kl}^{-1}} \cdot \mathrm{D_p} \cdot \mathrm{C_{tr,m}} - \sum_k \sum_l \sum_m \mathrm{QF_{klm}} \cdot \mathrm{D_p} \cdot \mathrm{C_t}\end{aligned} \quad (4)$$

where SMY_{ijk} is specific methane yield of fruit part i at ripening stage j of cultivar k; QF_{ijk} represents quantity of fresh biomass of fruit part i at ripening stage j of cultivar k to be used as feedstock per day; DM_{ijk} is dry matter content of fruit part i at ripening stage j of cultivar k; CF_f denotes conversion factor of quantity from methane to fuel f; C_f represents cost of fuel f; SMY_{kl} is specific methane yield of tree part l of cultivar k; S_d denotes the size of digester to be invested; C_d is total digestion system cost per volume of digester; and L_d represents lifespan of digester.

The total profits along the chain (Prt) were determined by the sum of profits obtained by all stakeholders, using Equation (5):

$$\mathrm{Prt} = \mathrm{Prf} + \mathrm{Prc} + \mathrm{Prp} \quad (5)$$

2.2.2. Model Constraints

Model constraints were developed to ensure the characteristics of the value chain.

$$\sum_i \sum_j \sum_k \mathrm{SMY_{ijk}} \cdot \mathrm{QF_{ijk}} \cdot \mathrm{DM_{ijk}} \cdot \mathrm{CF_f} + \sum_k \sum_l \sum_m \mathrm{SMY_{kl}} \cdot \mathrm{QF_{klm}} \cdot \mathrm{DM_{kl}} \cdot \mathrm{CF_f} \le \mathrm{MQ_f} \quad \forall\, f \quad (6)$$

$$\mathrm{QF_{ijk}} \le \mathrm{MQF_{ijk}} \qquad \forall\, i,\ j,\ k \quad (7)$$

$$\mathrm{QF_{klm}} \le \mathrm{MQF_{klm}} \qquad \forall\, k,\ l,\ m \quad (8)$$

$$\mathrm{S_d} \ge \mathrm{V_d} \qquad \mathrm{S_d} \in \mathbb{Z} \quad (9)$$

where MQ_f is maximum quantity of fuel f needed per day for the production process; MQF_{ijk} denotes maximum quantity of fresh biomass of fruit part i at ripening stage j of cultivar k available per day; MQF_{klm} is maximum quantity of fresh biomass of tree part l of cultivar k cultivated at farm m available per day; and V_d represents minimum volume needed for the digester.

Equation (6) ensures that the produced methane must not exceed the required quantity of methane replacing the LPG used in the process. Equation (7) assures that fruit wastes used for feedstock are not more than the maximum wastes generated from banana processing. Equation (8) ensures that the supplied tree biomass is lower than the maximum available tree biomass. Equation (9) assures that the selected digester size is not smaller than the size that is needed for utilizing the specified amount of banana waste feedstock.

$$V_d = \sum_i \sum_j \sum_k QF_{ijk} \cdot DM_{ijk} \cdot VS_{ijk} \cdot OLR^{-1} + \sum_k \sum_l \sum_m QF_{klm} \cdot DM_{kl} \cdot VS_{kl} \cdot OLR^{-1} \quad (10)$$

$$C_{tr,m} = D_m \cdot C_{dis,to} \cdot MQF_{tr}^{-1} \quad \forall\, m \quad (11)$$

$$C_{main,m} = D_m \cdot C_{dis,main} \cdot MQF_{tr}^{-1} \quad \forall\, m \quad (12)$$

$$MQF_{klm} = FR_{kl} \cdot FW_k \cdot A_{km} \cdot PD_k \cdot D_p^{-1} \quad \forall\, k,\, l,\, m \quad (13)$$

where VS_{ijk} is volatile solid content of fruit part i at ripening stage j of cultivar k; OLR denotes organic loading rate; VS_{kl} is volatile solid content of tree part l of cultivar k; D_m represents distance (km) from farm m; $C_{dis,to}$ is total transportation cost per unit of distance (km); MQF_{tr} denotes maximum quantity of fresh biomass that can be transported in each transportation trip; $C_{dis,main}$ represents fuel and maintenance cost for transportation per unit of distance (km); FR_{kl} is fresh weight fraction of tree part l of cultivar k; FW_k is average fresh weight of tree cultivar k; A_{km} denotes cultivating area of tree cultivar k at farm m; and PD_k denotes plant density of tree cultivar k.

The size of digester needed for utilizing feedstock was calculated using Equation (10). Equation (11) shows the calculation of total transportation cost per kg of tree biomass. The calculation of fuel and maintenance cost for transportation per kg of tree biomass was performed using Equation (12). Maximum available tree biomass was calculated following Equation (13); the plant density (PD_k) obtained from Section 2.1 was 0.56 plant/m^2.

$$QF_{ijk} \geq 0 \quad \forall\, i,\, j,\, k \quad (14)$$

$$QF_{klm} \geq 0 \quad \forall\, k,\, l,\, m \quad (15)$$

Equations (14) and (15) ensure that the quantity of fruit and tree biomass are non-negative values.

2.2.3. Waste Chain Valuation

The values of banana residues along the chain consist of the values at the stage of farmers, collectors, and factory. As the value of the residues have not been estimated, different scenarios were constructed to present different performance of waste value chain depending on the different values of banana residues and different transportation cost. The scenarios developed are presented in Table 1. Two objective functions are used to represent two perspectives of the value chain, considering the power of stakeholders in the chain. The objective function of factory profit maximization (Equation (4)) is used in a scheme in which the factory is an influential stakeholder that has the power to design the implementation of an anaerobic digestion system. Another scheme considers the total profit of a value chain for which the objective function is to maximize total chain profit (Equation (5)).

Scenario F assumes that only fruit waste generated from banana chip processing at factory is utilized. The tree residues at the banana farm are not included in the waste utilization strategy. The optimization objective in this scenario is to maximize factory profit (Equation (4)). The other five scenarios present waste value chains that use both fruit waste and tree residues at banana farms to produce biogas.

Table 1. Different scenarios presenting assumptions for banana wastes value chain development. The symbol ✓ indicates the type of banana waste to be used as feedstock.

Scenario	Utilized Wastes		Farm Gate Tree Price	Transportation Cost	Optimization Objective
	Fruit	Tree			
F	✓	-	-	-	Maximize factory profit
T1	✓	✓	Varied	Fixed	Maximize chain profit
T2	✓	✓	Varied	Fixed	Maximize factory profit
C1	✓	✓	Fixed	Varied	Maximize chain profit
C2	✓	✓	Fixed	Varied	Maximize factory profit
E	✓	✓	Solved	Solved	Maximize chain profit

Scenario T1 and scenario T2 are investigated to determine the possible farm gate price of banana tree. The transportation cost in these two scenarios is fixed to prevent it from influencing the chain performance. The transportation cost is assumed based on collectors' cost and collectors' profit. The cost for the collectors is fuel and maintenance cost for transporting biomass, which is USD 0.115/km according to Sritong et al. [56] and Wongwiriya et al. [57]. As it is round trip transportation (farm-to-factory and factory-to-farm), the fuel and maintenance cost is doubled, resulting in USD 0.23/km. The profit for the tree collectors is calculated using the value of daily minimum wage divided by the longest distance between farm and factory. The daily minimum wage in Thailand is approximately USD 10/day/person and the longest distance between banana farm and factory is 128 km. Thus, the calculated profit for tree collectors is USD 0.08/km. The transportation cost to be used for tree biomass valuation is the sum of fuel and maintenance cost and tree collectors' profit, which is USD 0.31/km, so the value of USD 0.31/km is used as fixed parameter in scenario T1 and T2.

The determination of farm gate tree biomass value is performed by optimizing the utilization of waste generated along the chain. The difference between scenario T1 and scenario T2 is that the objective function in scenario T1 is to maximize total chain profit (Equation (5)), whereas the objective function in scenario T2 is to maximize factory profit (Equation (4)). As the suitable farm gate price of tree biomass has not been investigated, the farm gate price was varied to present different profits for both farmers and factory in both scenarios. All stakeholders in the value chain want the best opportunities to maximize their profits [58]. Considering fair trade [59] and to minimize the tradeoff among stakeholders, the farm gate price of the tree that provided equal profits for both farmers and factory was selected and assumed to be the value used for banana waste value chain development.

Scenario C1 and scenario C2 were investigated to determine the transportation cost. To exclude the influence of banana tree price, the selected farm gate price of the tree obtained from scenario T1 and scenario T2 were used as fixed parameters. Scenario C1 assumes that farm gate price of the tree is the selected value from scenario T1. The objective function used in this scenario is to maximize total chain profit (Equation (5)). Scenario C2 uses the fixed farm gate price at the rate of the selected value obtained from scenario T2. The objective function used in this scenario is to maximize factory profit (Equation (4)). The transportation cost was varied to present different profits for all stakeholders in both scenarios. The rate that provided equal profits for both collectors and factory was selected and assumed to be the value used for waste value chain development in these two scenarios. The last scenario is scenario E, in which both farm gate price of the tree and transportation cost are solved to obtain equal profits for all stakeholders using the maximization of total chain profit (Equation (5)) as objective function.

2.3. Economic and Environmental Performance

Economic indicators, including net present value (NPV) and payback period (PBP), were determined to evaluate economic performance for the factory in each scenario. NPV and PBP were calculated using Equations (16) and (17), respectively.

$$NPV = \sum_{t=0}^{t=L_d}\Big(\Big(\sum_i\sum_j\sum_k SMY_{ijk}\cdot QF_{ijk}\cdot DM_{ijk}\cdot CF_f\cdot C_f\cdot D_p+\sum_k\sum_l\sum_m SMY_{kl}\cdot QF_{klm}\cdot DM_{kl}\cdot CF_f\cdot C_f\cdot D_p - \sum_k\sum_l\sum_m QF_{klm}\cdot DM_{kl}\cdot MC_{kl}^{-1}\cdot D_p\cdot C_{tr,m}-\sum_k\sum_l\sum_m QF_{klm}\cdot D_p\cdot C_t\Big)\cdot(1+d)^{-t}\Big)-S_d\cdot C_d \quad (16)$$

$$PBP = S_d\cdot C_d\cdot\Big(\sum_i\sum_j\sum_k SMY_{ijk}\cdot QF_{ijk}\cdot DM_{ijk}\cdot CF_f\cdot C_f\cdot D_p+\sum_k\sum_l\sum_m SMY_{kl}\cdot QF_{klm}\cdot DM_{kl}\cdot CF_f\cdot C_f\cdot D_p - \sum_k\sum_l\sum_m QF_{klm}\cdot DM_{kl}\cdot MC_{kl}^{-1}\cdot D_p\cdot C_{tr,m}-\sum_k\sum_l\sum_m QF_{klm}\cdot D_p\cdot C_t\Big)^{-1} \quad (17)$$

where d is discount rate and t is year of investing.

Carbon dioxide emission mitigation is an indicator used for evaluating environmental performance, including carbon dioxide emitted by transportation of tree biomass (E_{tr}), carbon dioxide emission reduction from fruit waste reduction (E_{waste}), and carbon dioxide emission reduction from reducing fossil fuel used for frying banana chips (E_{fuel}), which were calculated following Equations (18)–(20), respectively. Net carbon dioxide emission mitigation (E_{net}) was calculated using Equation (21).

$$E_{tr} = \sum_k\sum_l\sum_m QF_{klm}\cdot EF_{tr,m} \quad (18)$$

$$E_{waste} = \sum_i\sum_j\sum_k QF_{ijk}\cdot DM_{ijk}\cdot EF_w\cdot D_p \quad (19)$$

$$E_{fuel} = \sum_i\sum_j\sum_k SMY_{ijk}\cdot QF_{ijk}\cdot DM_{ijk}\cdot CF_f\cdot EF_f\cdot D_p+\sum_k\sum_l\sum_m SMY_{kl}\cdot QF_{klm}\cdot DM_{kl}\cdot CF_f\cdot EF_f\cdot D_p \quad (20)$$

$$E_{net} = E_{waste}+E_{fuel}-E_{tr} \quad (21)$$

where $EF_{tr,m}$ is emission factor of tree transportation from farm m; EF_w is emission factor of waste management; and EF_f is emission factor of using fuel f.

The percentage of waste utilization was calculated using Equation (22) to present the efficiency of waste reduction along the chain.

$$\%Utilization = \Big(\sum_i\sum_j\sum_k QF_{ijk}+\sum_k\sum_l\sum_m QF_{klm}\Big)\cdot\Big(\sum_i\sum_j\sum_k MQF_{ijk}+\sum_k\sum_l\sum_m MQF_{klm}\Big)^{-1} \quad (22)$$

2.4. New Sustainable Value Chain Modeling

Regarding scenarios described in Section 2.2.3, there are two perspectives of value chain considering the power of stakeholders. One scenario from each group was selected to represent waste value chain. The selection was based on the concept of fair trade [59], so the scenario presenting the smallest difference of profits among all stakeholders was selected. Waste value chain, representing the flow of fruit wastes and tree residues as a new valuable product, was developed using the values of tree price at farm gate and the transportation cost determined from each scenario. The final product of banana waste value chain is biogas. The value of biogas is the cost of LPG that the factory can reduce. The estimation of profits of each stakeholder was based on parameter assumptions. As an issue of energy price fluctuation [60], LPG cost and fuel and maintenance cost for transportation are parameters that can affect the performance of the value chain. Moreover, investment and maintenance cost have significant impacts on economic viability [61]. Therefore, sensitivity analysis was conducted regarding LPG cost, fuel and maintenance cost for transportation, and digester cost.

New sustainable value chain was developed representing the combination of banana chip value chain and banana waste value chain. Total values gained by each actor were the sum of the values obtained from main product chain and waste value chain. Profit, profit margin, profit share, added value, and value share of each actor in waste value chain and new sustainable value chain were calculated.

3. Results and Discussion

3.1. Banana Chips Value Chain

The banana chips value chain of the BAU case is presented in Figure 1. Smallholder farmers obtained USD 171,429 by selling 600 tons of green bananas to banana traders or collectors. The main activities of the traders or collectors were collecting bananas at banana farms and transporting bananas to processing factories. The value found at collection was 70% higher than the value at the farm gate.

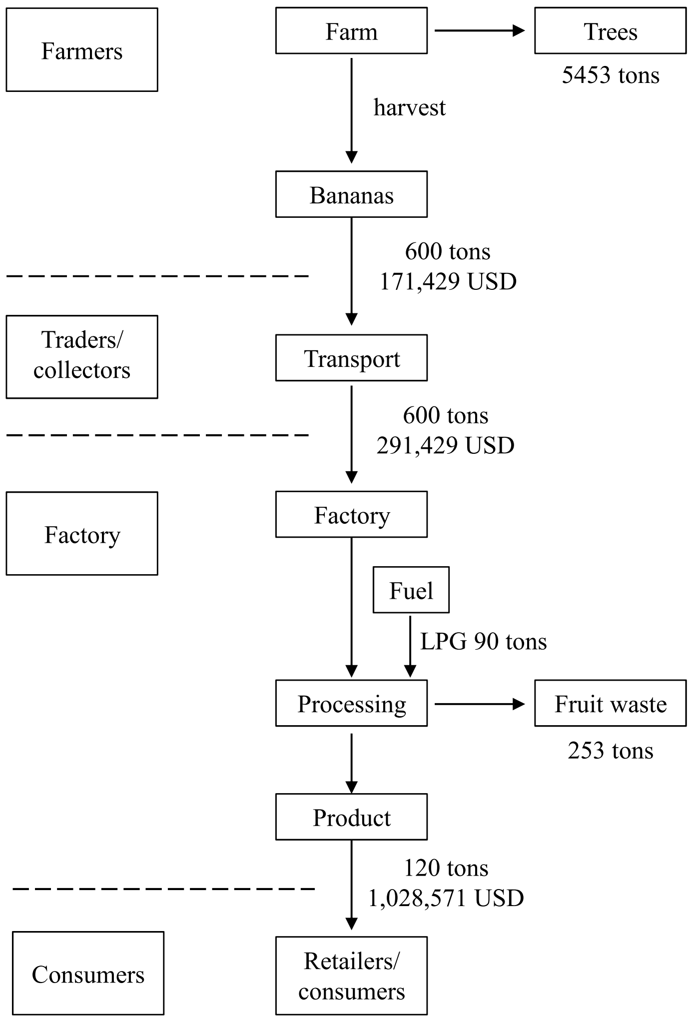

Figure 1. Banana chips value chain and material flow in business-as-usual case.

At the processing site, green bananas were sliced and fried using LPG as an energy source. A total of 90 tons of LPG was used annually. Moreover, there were other resources needed for processing banana chips, such as labor and factory facilities. As numerous activities were carried out at the processing plant, the added value produced at the factory was much higher than the added value produced by farmers and collectors (Table 2). This showed that the factory could increase the banana values obtained from traders by 253%. The factory also gained the highest profit among all stakeholders.

Table 2. Added value and profit of different stakeholders in business-as-usual case.

Stakeholders	Added Value (USD)	Profit (USD)
Farmers	171,429	65,281
Collectors	120,000	113,028
Factory	737,143	243,429

Farmers and traders obtained profit margins of 38.1 and 38.8%, respectively, whereas the factory showed the lowest profit margin, 23.7% (Figure 2). However, the factory had a profit share of 57.7% along the chain. Farmers showed the lowest profit share among all stakeholders, which could be due to little market power [9]. As the highest added value was produced at the factory, it demonstrates the highest value share, 71.7%, throughout the chain. This is because the factory improved the product by processing, which could be considered as innovative activity comparing to the activities carried out by other stakeholders [9].

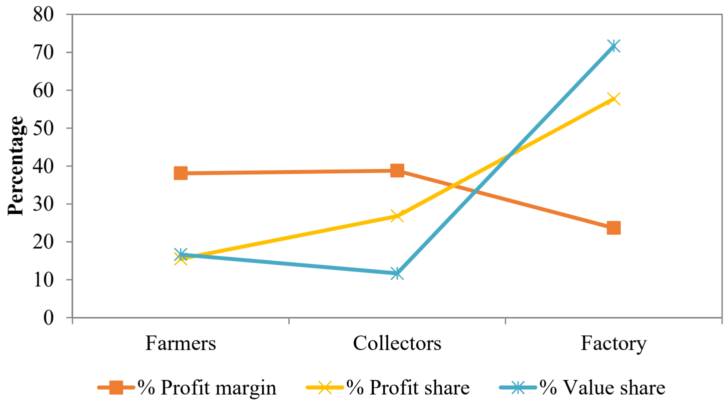

Figure 2. Profit and added value for different stakeholders throughout the banana chips value chain in business-as-usual case.

Farmers and the processing factory were the actors who generated agricultural wastes. Tree residues of 5453 tons/year were left at banana farms and 253 tons/year of fruit wastes were generated at the factory (Figure 1). Thus, only 5.7% of total banana biomass, which was banana flesh, was utilized as valuable products.

3.2. Waste Chain Valuation

3.2.1. Fruit Waste

In scenario F, all fruit wastes generated at the processing factory were utilized to produce biogas without the need for transportation, replacing 4934 kg of LPG annually. The factory can obtain USD 3187/year in savings, providing additional profits for the factory. The additional benefits obtained from utilizing fruit wastes can increase factory profit by 1.3%.

3.2.2. Banana Tree

The profits obtained for each stakeholder at different farm gate prices for banana trees are shown in Figure 3. For the scenario in which the transportation cost was fixed, the valuation method, by maximizing total chain profit, as presented in scenario T1, showed a linear decrease in factory profits and a linear increase in farmers' profits as tree value increased. To maximize the chain's profits, all trees provided at the farms would be utilized at all tree biomass costs, which will result in constant benefits obtained for tree collectors at all farm gate prices. The tree value at the farm gate of USD 0.084/tree provided equal profit for farmers and factory. However, the benefits obtained for both stakeholders at the tree price at the farm gate of USD 0.084/tree were 156% higher than the benefits obtained for tree collectors.

The valuation method, by maximizing factory profits in scenario T2, showed that the total profits obtained by collectors tended to decrease as the farm gate tree price increased (Figure 3). It could be seen that the monetary benefits of tree collectors decreased after the tree price increased above USD 0.075/tree. This indicates that the quantity of tree biomass to be utilized as feedstock was reduced. This could be explained by the fact that the different optimum biogas digester sizes and different amounts of tree biomass were designed to obtain maximum factory profit at different tree prices. The increase in the tree value at the farm gate increased the total feedstock cost for the factory and decreased factory profit. Thus, the optimization model provided the solution to decrease total cost for the factory. In order to decrease total transportation cost, from the farms that were far from the factory, only some morphological parts of the tree biomass would be selected. The reduced biomass quantity requires a smaller size of digester, resulting in lower investment cost. The farm gate price of the tree of USD 0.093/tree provided equal profits for farmers and factory. Although a higher farm gate price was obtained in scenario T2, compared to the value obtained in scenario T1, some parts of the trees were still left at the farms, resulting in lower collectors' benefits.

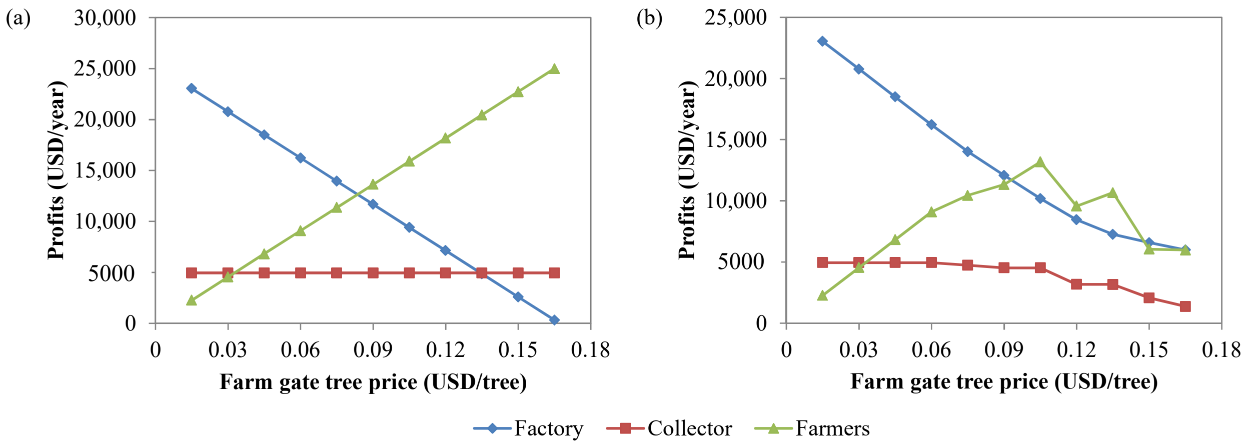

Figure 3. Profits obtained for each stakeholder from (**a**) scenario T1 and (**b**) scenario T2.

3.2.3. Transportation Cost

To estimate the value obtained for tree collectors, the farm gate tree value was fixed at USD 0.084/tree in scenario C1. The collectors could receive greater benefits as the transportation cost increased, whereas the factory profit decreased (Figure 4). Farmers' profit remained constant at all transportation costs because all tree biomass was utilized. The transportation cost of USD 0.37/km provided equal profits for collectors and factory. However, the profits gained for both stakeholders were 31% lower than the profit that the farmers could obtain. The differences of profits gained among all stakeholders when transportation cost was USD 0.37/km in scenario C1 were lower than the differences presented in scenario T1.

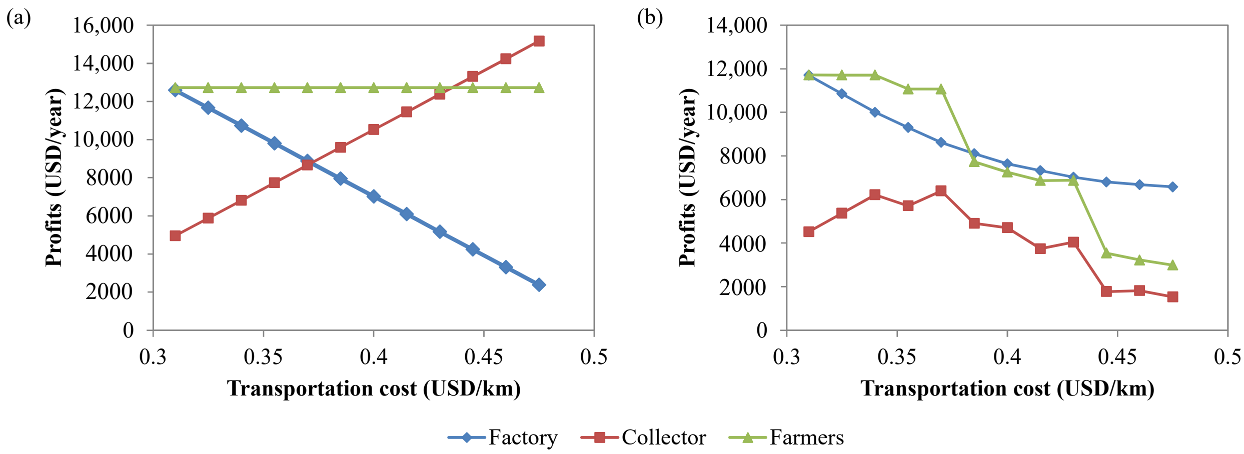

Figure 4. Profits obtained for each stakeholder from (**a**) scenario C1 and (**b**) scenario C2.

In scenario C2, the transportation cost of USD 0.37/km provided the highest profit for the collectors (Figure 4). The collectors' profits tended to decrease as the transportation cost increased above USD 0.37/km because the factory was designed to reduce the quantity of tree biomass used as feedstock to reduce total transportation cost. However, at the rate of USD 0.37/km, the total profits gained by collectors were lower than factory and farmers' profits. The greatest profits were gained by farmers; these were 71% higher than those obtained by the collectors. Nonetheless, the least difference in profits among all stakeholders was observed in scenario C2 compared to scenarios T1 and T2, using the transportation cost of USD 0.31/km. Considering the profits obtained among all stakeholders, the cost of USD 0.37/km was the appropriate rate for the collectors in scenario C1 and scenario C2.

To obtain equal profits for all stakeholders along the chain in scenario E, the farm gate value of the tree was solved to be USD 0.067/tree and the transportation cost was USD 0.39/km. The calculated transportation cost was the highest among all scenarios, increasing profit gained for the collectors, because other scenarios showed that the profit obtained for collectors was the lowest. The increase in transportation cost caused a greater total cost for the factory. Thus, the calculated farm gate price of the tree needed to be decreased, resulting in prices that were 20% and 28% lower than those obtained from scenario T1 and scenario T2, respectively. Although the farm gate price of the tree determined in scenario E provided equal profits for all stakeholders, the rate might not be appealing for the farmers if they had other choices to sell at the rate of USD 0.084/tree or USD 0.093/tree. The summarized values of the farm gate price of the tree and the transportation rate obtained from all scenarios are shown in Table 3.

Table 3. Selected rates of farm gate tree price and transportation cost for different scenarios.

Scenario	Farm Gate Tree Price (USD/tree)	Transportation Cost (USD/km)
F	-	-
T1	0.084	0.31
T2	0.093	0.31
C1	0.084	0.37
C2	0.093	0.37
E	0.067	0.39

3.3. Sustainability Performance

3.3.1. Economic Performance

The profits gained by each stakeholder from different scenarios are shown in Figure 5. When only fruit wastes were utilized, as presented in scenario F, only the factory could gain economic benefits and the values were lower than the scenarios in which both fruit wastes and trees were utilized. In scenario T1 and scenario T2, the collectors' profits were 61% lower than other stakeholders' profits. The differences of profits gained among stakeholders presented in scenario C1 and scenario C2 were lower than in scenario T1 and scenario T2, whereas there was no difference among stakeholders' profits in scenario E. Comparing between the scenarios that fixed the same parameters, the scenarios that maximized factory profit showed lower profit for all stakeholders than the scenarios that maximized total chain profit.

Although scenario F provided the lowest NPV, the PBP value was also the lowest; thus, the factory could recover its investment in 1.4 years. The shorter PBP appears to be more attractive for the factory. However, it might not be an ideal solution for a sustainable value chain because only one actor along the chain could gain economic benefits. Scenario T1 and scenario T2 showed a PBP of 4.6 years, shorter than the PBP of other scenarios that utilized both fruit waste and tree residues. The transportation cost presented in these two scenarios was lower than other scenarios, resulting in higher profits for a factory which provided a shorter PBP. Scenario C2 showed higher NPV and a lower PBP than scenario C1, which indicates that scenario C2 was more attractive for the factory. The factory is an actor that adds value to the residues by implementing innovative activity which requires an investment, whereas other actors in the chain prepare, collect, and transport the tree biomass to the factory. Thus, the factory should have more power to determine the cost throughout the chain. Moreover, scenario C2 provided a higher farm gate tree price than scenario C1, while the transportation cost showed the same rate at USD 0.37/km.

Scenario E presented equal profits for all stakeholders along the value chain. Compared to scenario C2, it showed higher NPV but also a higher PBP. Although the transportation cost was solved to be USD 0.39/km, the highest among all scenarios, the farm gate price of the tree was the lowest, at USD 0.067/tree. Gupta et al. [62] demonstrated that negative NPV obtained from anaerobic co-digestion of organic waste was due to high costs for waste collection and transportation. The present study, on the other hand, showed positive NPV in all scenarios because the costs along the chain were optimized to provide profits for all stakeholders. Different farm gate tree prices and transportation costs, which provided different benefits to all actors, were observed in all cases. Thus, all stakeholders in the chain can collaborate to improve the new product chain and develop a suitable rate throughout the chain [6].

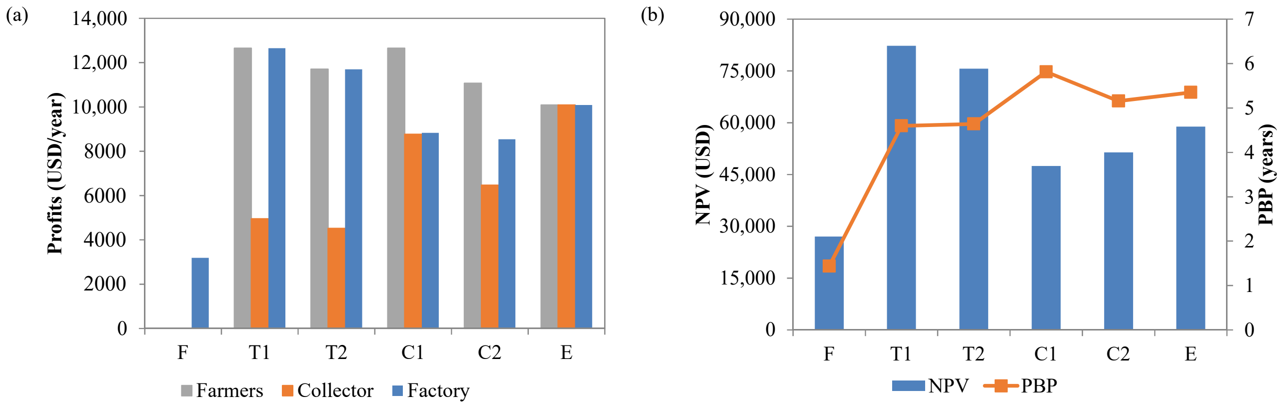

Figure 5. (**a**) Profits of all stakeholders and (**b**) economic performance obtained from different scenarios.

3.3.2. Environmental Performance

Scenario F showed the lowest CO_2 emission mitigation, 40,475 $kgCO_2e$/year, because only 4.4% of available residues were utilized along the chain (Figure 6). The lower quantity of waste utilization resulted in a lower quantity of LPG replaced by biogas produced. Scenario T1, scenario C1, and scenario E showed equal CO_2 emission mitigation potential, of 221,587 $kgCO_2e$/year, because all residues were utilized. This showed that the optimization method, by maximizing the total chain profit, provided better environmental performance. The emission mitigation from these scenarios resulted in approximately 2.6 times less emission than the BAU case, in which 90 tons of LPG were used, and the emission would be 357,435 $kgCO_2e$/year. This was comparable to a study by Hossain et al. [33] which showed that 2.5 times less emissions could be produced by replacing diesel fuel with bioethanol produced from banana stem.

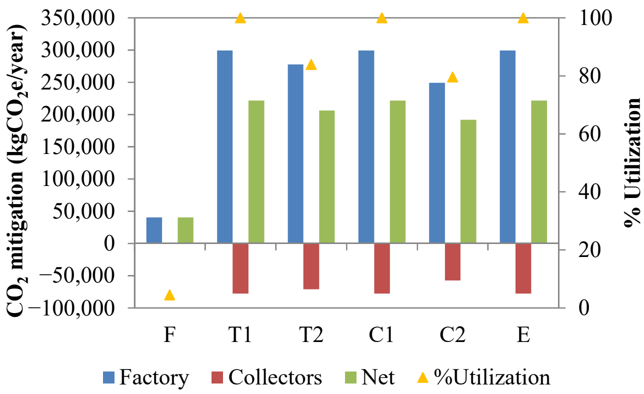

Figure 6. Environmental performance obtained from different scenarios.

Scenario T2 and scenario C2 utilized 84% and 80% of available residues, respectively, resulting in lower CO_2 emission from tree transportation compared to the scenarios in which all tree residues were utilized. However, the net CO_2 emission mitigation was lower than other cases that utilized all residues. The net CO_2 emission mitigation from scenario C2 was 12% lower than that presented in scenario T2, but it showed better solution in economic terms among all stakeholders. The remaining residues could be utilized by farmers for household purposes, such as implementing a household digester [63], providing more farmers' benefits.

3.4. Sustainable Value Chain Modeling

All scenarios in which the optimization objective was to maximize total chain profit showed similar environmental performance, while scenario E provided equal profit for all stakeholders. Thus, scenario E was selected as a sustainable value chain. Among the scenarios in which the optimization objective was to maximize factory profit, scenario C2 showed the smallest differences among stakeholders' profits. Therefore, as a scheme in which the factory was an influential actor, scenario C2 was selected as a sustainable value chain.

Waste value chains were developed from scenario C2 and scenario E (Figure 7). Although only 80% of available residues were utilized in scenario C2, the farmers could earn greater profits than those obtained in scenario E due to the higher farm gate price of the tree. The higher quantity of tree residues that were utilized and the higher transportation cost in scenario E provided higher revenues for the collectors. As more biomass was utilized to produce biogas in scenario E, it showed a 22% greater quantity of LPG that could be replaced, in comparison to scenario C2.

The quantity of banana residues and its value presented in the proposed waste value chain could be calculated to be USD 1.9 and 2.6/ton at the farmers' stage and USD 6.3 and 6.5/ton at the collectors' stage (Figure 7). The estimated costs at both stages were lower than the cost of banana stem presented in the study by Duque et al. [35], which was USD 17.3/ton. This could be explained by the difference in transportation cost. In contrast, banana residue cost at the farmers' stage in the present study was higher than that presented by Uchôa et al. [32] and Hossain et al. [33], in which there was no cost for banana residues. The energy produced per ton of biomass could be calculated to be 0.62 and 0.60 GJ/ton of residues in scenario C2 and scenario E, respectively, which were higher than those in a study by Fiallos-Cárdenas et al. [50].

Regarding the waste value chain, the highest profit gained by farmers could be social benefits, as smallholder farmers can earn increased revenues (Table 4). Higher farmers' profit was demonstrated in scenario C2 compared to scenario E. Although farmers obtained the highest profit in scenario C2, added value was the lowest among all actors for both scenarios. Less activity performed by farmers, in comparison to that of other actors, can be an explanation for this. The same trend was found in a study of the banana value chain by Gebre et al. [9]; they determined that farmers had lower added values than traders, indicating inefficient revenues gained by farmers. However, the banana waste value chain in this study demonstrated that farmers obtained the highest benefits, generally, when banana residues were left on the field, producing no economic value. The profit margin, profit share, and value share of different stakeholders in the waste value chain are shown in Figure 8. The profit margin gained by the farmers was 100% in the waste chain because the trees are generally left as non-value residues. The profit share of farmers in scenario C2 was the highest, whereas the profit share in scenario E showed no difference among all stakeholders. Tree collectors showed the highest value share in both scenarios, but the profit gained was the lowest in scenario C2, and it was not greater than that of other actors in scenario E. This indicates that transportation cost greatly affected the profit gained by tree collectors in comparison to the factory, which had lower value share but higher profit.

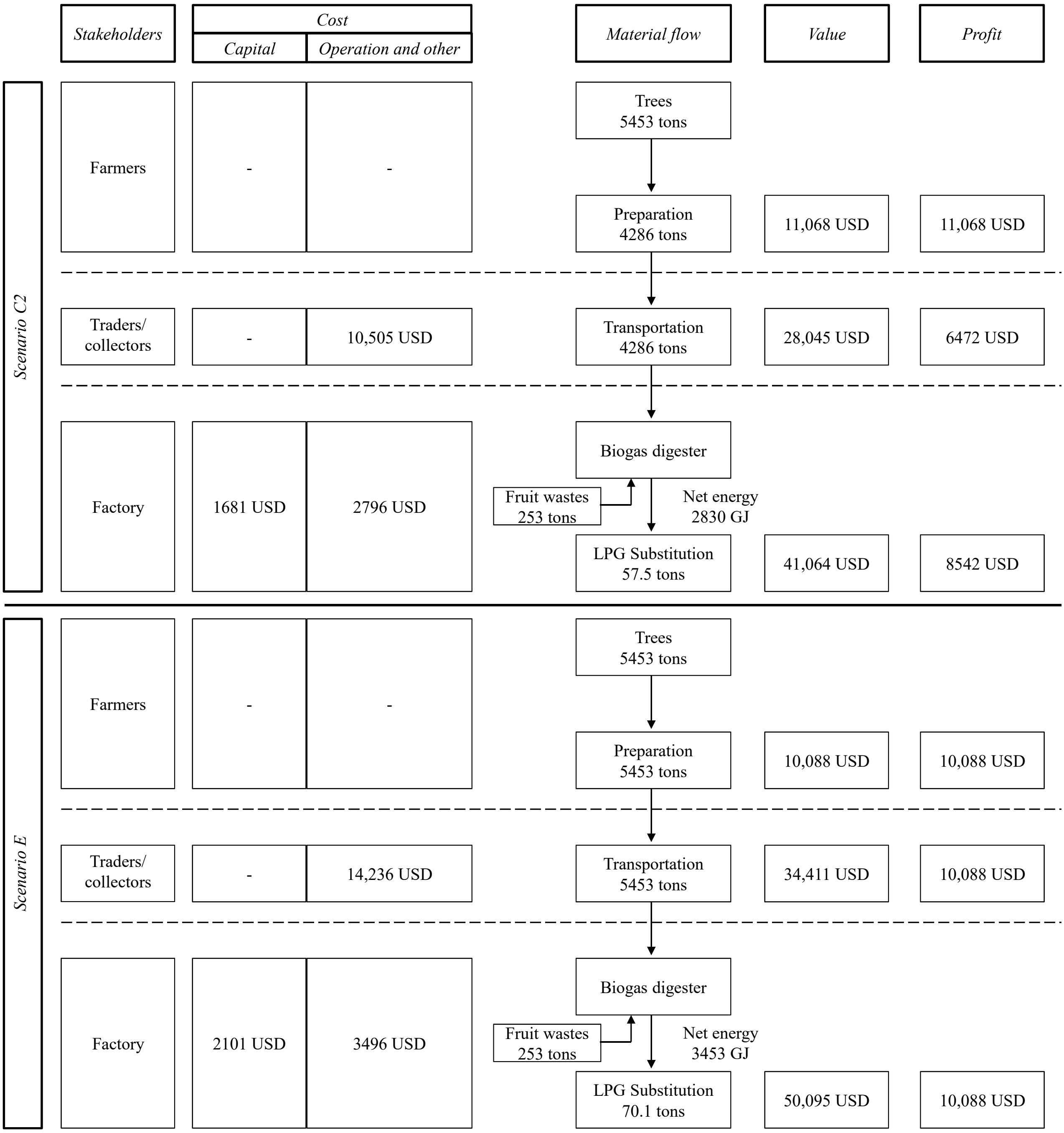

Figure 7. Waste value chain modeling from scenario C2 and scenario E.

Table 4. Added value and profit obtained for each stakeholder in waste value chain.

Stakeholders	Scenario C2		Scenario E	
	Added Value (USD)	Profit (USD)	Added Value (USD)	Profit (USD)
Farmers	11,068	11,068	10,088	10,088
Collectors	16,977	6472	24,323	10,088
Factory	13,019	8542	15,684	10,088

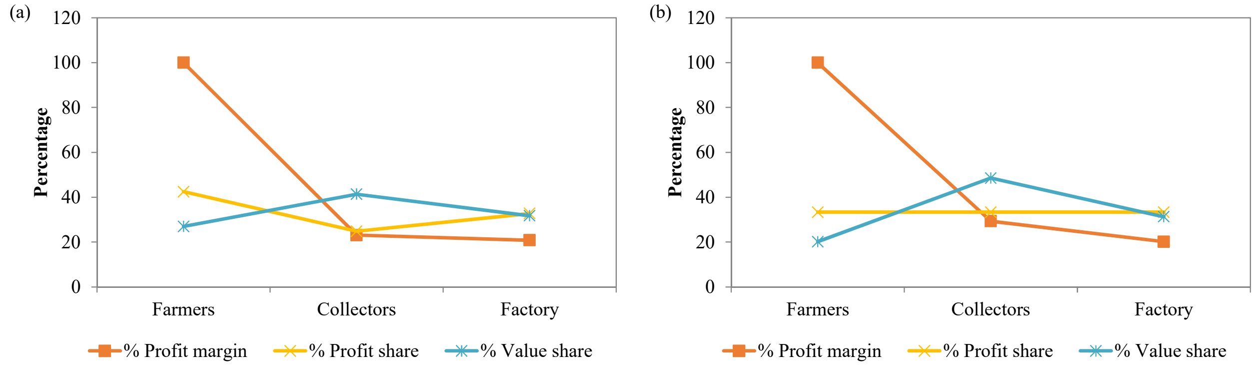

Figure 8. Profit margin, profit share, and value share of different stakeholders in waste value chain from (**a**) scenario C2 and (**b**) scenario E.

The results of sensitivity analysis are shown in Figures 9 and 10. LPG cost had the largest influence on all stakeholders' profits in scenario C2 (Figure 9). This can be explained by the fact that LPG cost is considered as the value of the final product of the waste value chain. A lower LPG cost indicates that lower savings were obtained by the factory from LPG substitution. The factory will reduce the size of its digestion system to maintain its profit, resulting in less biomass utilized and lower profits obtained for both farmers and collectors. In contrast, regarding the scheme of total chain profit maximization in scenario E (Figure 10), digester cost, LPG cost, and fuel and maintenance cost for transportation did not present a large impact on farmers' and collectors' profit because all residues were utilized. The cost of LPG also had a great impact on factory profits. Considering both scenarios, digester cost had the lowest impact on profits compared to other parameters. However, Chinese et al. [64] and Yalcinkaya [61] reported that investment and capital cost had the greatest impact on the economic performance of biogas plants.

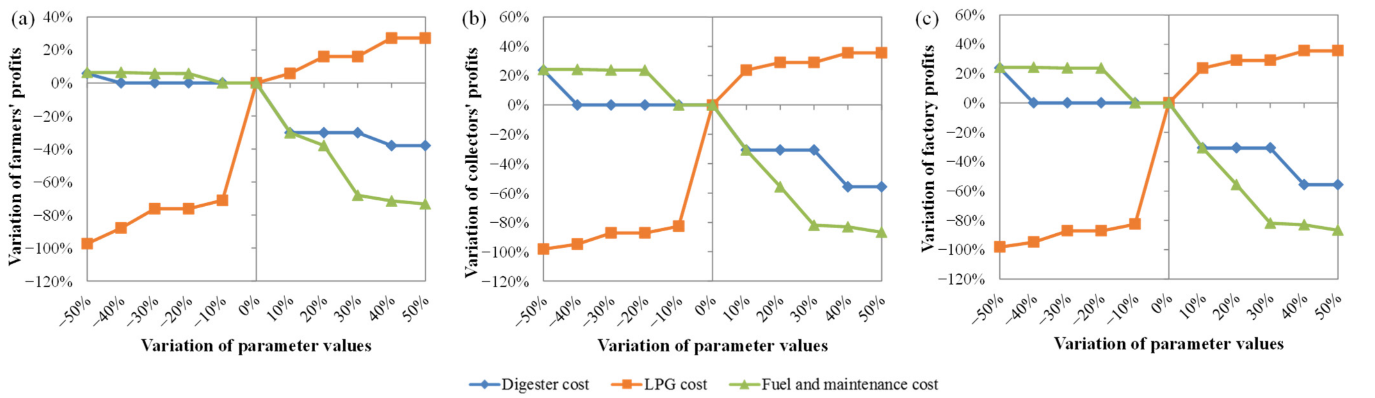

Figure 9. Sensitivity analysis of parameters on (**a**) farmers' profits, (**b**) collectors' profits, and (**c**) factory profits in scenario C2.

The utilization of trees provided a 6.5% and 5.9% increase in farmers' earnings in scenario C2 and scenario E, respectively. The profit and added value of each stakeholder are presented in Table 5. The total value added by collectors in scenario C2 and scenario E was 14% and 20% higher, than the value added in the BAU case, respectively, while the factory showed the lowest change in added value. The profit that farmers could gain from selling fruit and trees in both scenarios increased by 15.5–17.0% compared to the profit obtained from selling fruit only. Among all stakeholders, the highest percentage change in profit was observed for farmers. The tree collectors and processing factory could increase profits by 3.5–8.9% of profits compared to the BAU case. The increase in smallholder farmers' income can improve socioeconomic benefits, promoting social sustainability [65]. Although income can be increased by increasing production yield, some practices, resources, and farm management are needed, leading to additional cost [66]. This study presented a new source of income from selling farm residues without any additional resource requirement. New income of farmers is linked to Sustainable Development Goal 1 (SDG 1), which is to reduce poverty, providing positive socioeconomic impact [67]. Higher income also improves social well-being and standard of living. Both the waste chain and the new sustainable value chain, in both scenarios, showed a similar trend: farmers had the highest profit margin and the factory had the lowest profit margin (Figures 8 and 11). The value share of farmers and tree collectors in the new sustainable value chain increased, whereas the value share of the factory decreased compared to the BAU case. This is because the value added by farmers and tree collectors increased more than that of the factory.

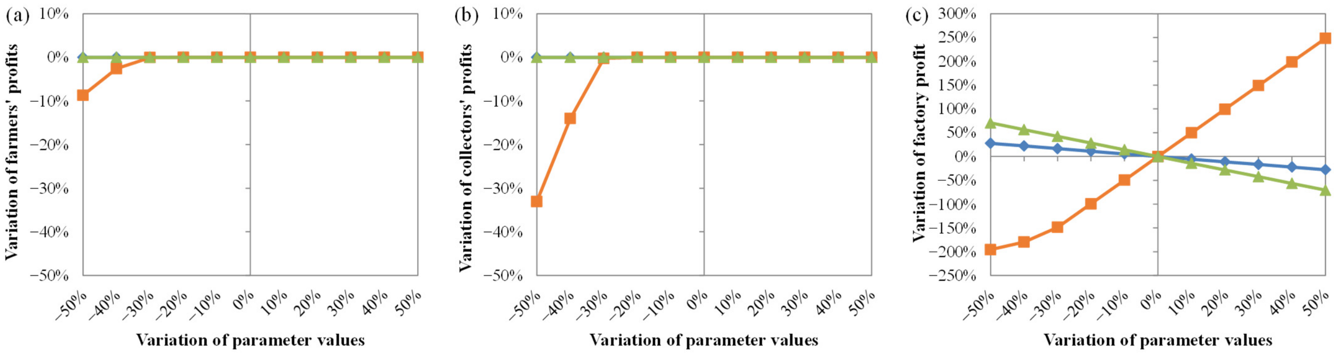

Figure 10. Sensitivity analysis of parameters on (**a**) farmers' profits, (**b**) collectors' profits, and (**c**) factory profits in scenario E.

Table 5. Added value and profit obtained for each stakeholder in new sustainable value chain.

Stakeholders	Scenario C2		Scenario E	
	Added Value (USD)	Profit (USD)	Added Value (USD)	Profit (USD)
Farmers	182,497	76,349	181,516	75,368
Collectors	136,977	119,500	144,323	123,116
Factory	750,162	251,970	752,827	253,516

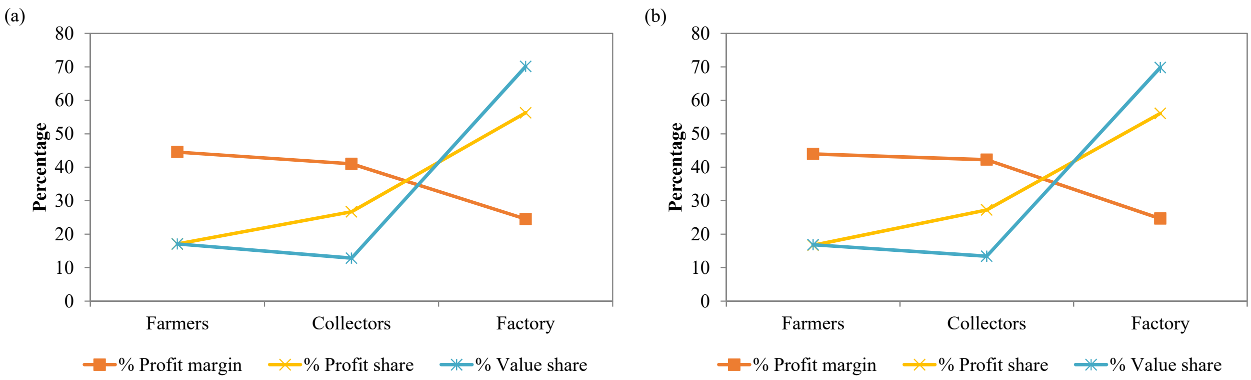

Figure 11. Profit margin, profit share, and value share of different stakeholders in new sustainable value chain from (**a**) scenario C2 and (**b**) scenario E.

Modeling of the new value chain of banana chip production provides benefits, in terms of sustainability, for all stakeholders. Farmers, traders, collectors, and factories can increase revenues and profits without increasing the price of their main products. The consumers can pay the same price and obtain products with higher value in term of environmental benefits. Moreover, the consumers will support social sustainability by purchasing products that are produced from a new sustainable value chain which provides the farmers increased revenues. The benefits for all stakeholders along the chain can result from collaboration among all stakeholders. Stakeholders' engagement has been reported as an important factor for sustainable development, in which decision making should involve all actors in the chain [68]. The collaboration of all stakeholders in the proposed banana value chain can promote the development of a community that utilizes agricultural waste for biogas production within the agri-food value chain, representing a circular bioeconomy. The replacement of LPG used in the value chain results in a reduction of the dependence on fossil fuels, which enhances energy security [69].

The proposed banana value chain in this study was developed based on a number of assumptions. It should be noted that different situations can lead to different performances of each stakeholder. The cost of banana residues was determined and assumed in this study, but in reality, demand and supply will play a role in price determination. However, this study demonstrates the idea of utilizing banana residues, which introduces a new product loop produced by recovered agricultural waste, creating a circular bioeconomy.

4. Conclusions

A new sustainable banana chips value chain was proposed to illustrate sustainable performance among all stakeholders of the chain. Instead of rotting in the fields, the banana trees were designed to be utilized as feedstock for biogas production, leading to a new valuable product chain which created economic benefits for farmers, tree collectors, and factories. Farmers' profit margin increased by 100% from selling the trees. The increase in farmers' profits by 15.5–17.0% compared to the BAU case was considered as not only as economic benefit but also a social benefit. The collectors' profits and factory profits will increase by approximately 3.5–8.9% if the waste value chain framework is implemented. The utilization of banana waste showed the highest CO_2 emission mitigation, of 221,587 kgCO_2e/year, when all residues were utilized. Different scenarios and sensitivity analysis showed that the profit obtained for each stakeholder and the performance of the value chain could be affected by trees' price, energy cost, and digester cost; therefore, future studies should be considered that would examine willingness to pay for the banana residues and fluctuations of energy price. Future research can be conducted by integrating the market equilibrium of banana residues and real-time pricing of energy to obtain a more realistic solution. In addition, other banana processing plants using different types of fossil fuel can be investigated to explore sustainability performance when different types of fuel are replaced.

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