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Environmental Sustainability of Waste Circulation Models for Sugarcane Biorefinery System in Thailand

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Abstract: Sugarcane leaves and trash burning during harvesting, and vinasse management, are major challenges of the Thai sugarcane industry. Identification of the appropriate valorization pathways for both the biomass waste streams using the sugarcane biorefinery concept is necessary. This study aims to assess the environmental sustainability of five CE models, including (1) sugarcane trash for electricity, (2) sugarcane trash to biochar, (3) sugarcane trash as a soil conditioner, (4) vinasse as a bio-fertilizer, and (5) vinasse for power generation. Life cycle assessment has been conducted using the ReCiPE midpoint impact assessment method. The results revealed that all waste utilization scenarios can help reduce the environmental impacts compared to the base case. The utilization of sugarcane leaves and trash for electricity generation brings about the lowest environmental impacts due to the environmental credits from the substitution of Thai grid electricity. The utilization of sugarcane leaves can reduce impacts on climate change, terrestrial acidification, and ozone formation by about 20–104%, 43–61%, and 12–54%. Recycling vinasse as bio-fertilizer and for biogas production for electricity generation can reduce climate change impact by about 28–29%. There is a significant improvement of the avoidance of pre-harvesting burning of sugarcane in the Thai sugar industry, which has led to the big potential of sugarcane leaves biomass utilization. Recommendations to enhance the efficiency of using sugarcane leaves and vinasse are discussed. The integrated waste circulation scenarios on cane leaves and vinasses in the sugar-electricity-ethanol biorefinery shows advancement in the bio-circular-green economy (BCG) aspects for enhancing the environmental sustainability of the Thai sugarcane industry.

Keywords: circular economy; sustainability; sugarcane

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1. Introduction

The Sustainable Development Goals (SDGs) have been adopted by the United Nations since 2015 to emphasize the global attention on transforming the world towards sustainable development by 2030 [1]. One of the SDGs, so called "*SDG12: Responsible consumption and production*", has been set to tackle the challenge of a rapid expansion of resources and material consumption, which in turn, would cause the over-extraction of natural resources and greenhouse gas emissions [1]. To achieve the SDG12, the circular economy (CE) is gaining traction as an approach to help industries, including the energy industry, to improve their resource use efficiency, reduce waste, and mitigate their environmental impacts [2]. The CE is defined as a regenerative system in which the resources used, energy leakage, waste and emissions to the environment, are minimized by keeping the materials and products at their highest utility and values via either technical material cycles or biological cycles [3,4].

The biorefinery concept is recognized as one of the CE strategies for the sustainable use of biomass [5]. The biorefinery represents the processing of renewable biomass including resources and waste streams into a variety of value-added products, e.g., food, feed, biofuel, bioenergy and other bio-based products [6]. The encouragement of biorefinery development, e.g., for food and biofuel, has thus been focused on by the bioeconomy policy in many countries as a measure to tackle the global environmental challenges, such as fossil resource depletion and climate change, especially in the EU and Asia [7–9]. Among the various biomass feedstocks, Sugarcane (*Saccharum*), a semi-perennial crop widely planted in tropical countries, has been playing an important role as a feedstock for food, bioenergy, ethanol and other bio-based products [10]. The advantage of sugarcane over other starch crops is the abundant amount of biomass, both sucrose-based and lignocellulosic, including waste, generated across the sugarcane industry chain. The sugarcane industry has, therefore, become a pioneer, where the biorefinery concept has been applied to produce value-added products [11]. The first-generation sugarcane biorefinery with sugar, electricity, and ethanol has been widely implemented in many countries, such as Brazil, Thailand, and Australia [10,12]. Additionally, second generation biorefineries for producing biomaterials and biochemicals are gaining traction to enhance the benefits of sugarcane biomass utilization [10,13]. For developing countries, such as Thailand where the sugarcane is an important economic sector, the exploration of circulation pathways to utilize the sugarcane-based biomass not only brings about the economic development of the industry but also environmental sustainability improvement as the biomass wastes in the production chain are fully utilized [14].

Thailand is the second-largest sugar exporter behind only Brazil [15]. In 2020, the world's sugarcane production was around 1870 Mt with Brazil as the largest sugarcane producing country sharing about 40%, followed by India 20%, China 6%, and Pakistan 4% [16]. Thailand is the world's fifth-largest sugarcane producing country, sharing about 4% of the global production [15]. The Royal Thai Government (RTG) has promoted the sugarcane industry as a key bioeconomy sector [17]. Nowadays, the Thai sugarcane industry is relatively mature in view of the sugarcane biorefinery concept, i.e., sugar-electricity-ethanol production has become common for large-scale companies. There are 57 sugar mills in Thailand with a total production capacity of about 983,500 t/day [18]. Bagasse from the sugar mills is currently used as fuel for electricity generation with the total capacity of 1734 MW [19]. In addition, there are 26 ethanol factories with the total installed capacity of about 5.97 ML ethanol/day [20]. The total capacity of molasses ethanol production is about 2.6 ML. In 2021, the ethanol production in Thailand was around 4.04 ML/day, with about 2.35 ML/day from sugarcane molasses sharing about 58% of the total ethanol production followed by cassava (1.51 ML/day) and sugarcane juice (0.17 ML/day), which shared around 38% and 4% of the total ethanol production, respectively [14]. A sugar-based feedstock like molasses is preferable to the starch-based feedstock because the saccharification process is not required to convert the starch to sugar [21].

Sugarcane juice, bagasse, and molasses are effectively utilized under the sugar-electricity-ethanol production system; however, when considering the whole supply chain of the sugarcane industry, a variety of biomass remains, especially sugarcane leaves and trash from plantations and the vinasse from the ethanol plant, that needs proper management. Cane leaves and trash management is one of the biggest challenges to the sugarcane industry where the cane growers are mainly small scale. The pre-harvest sugarcane leaves and trash burning is known as the traditional practice of manual harvesting by labor, which in turn, can cause several drawbacks to the air quality, human health, and soil degradation and ecosystem quality [22,23]. The impacts from the pre-harvest burning of sugarcane trash includes air pollution, especially particulate matter that causes societal problems such as health effects [24,25], as well as non-CO_2 greenhouse gas (GHG) emissions, such as CH_4 and N_2O, due to the incomplete combustion of trash in the open field that can contribute to global warming [26]. Vinasse, the wastewater generated from the distillation process at the ethanol factory, has a high organic content [27], which can create a significant environmental burden if discharged without proper treatment. Recycling of vinasse is gaining interest and there are various possible approaches, such as making organic fertilizers [28,29], producing biogas for electric power [30], etc. Although, the valorization of sugarcane leaves and vinasses has been proposed through various pathways, there is still a lack of information about the comparative life-cycle environmental performance of the circulation options, especially when considering the sugarcane biorefinery system.

This study aims to investigate cane trash and vinasse circulation models for improving the environmental sustainability of an existing sugar-electricity-ethanol production system in Thailand following the government policy promotion of the new economic model, the so-called "Bio-Circular-Green (BCG) economy" approach. Bio- and Circular-aspects can be clearly elaborated because the sugarcane trash and vinasse are the two bio-residues that would be utilized in waste circulation scenarios. To ensure they are green or sustainable waste circulation systems, life cycle assessment is used to evaluate and compare the environmental performances of the proposed scenarios. The results are used to provide recommendations on how waste circulation models can support policy makers in the transformation of the sugarcane industry for more mechanized harvesting along with increasing environmental sustainability.

2. Materials and Methods

The study's goal was to quantify and compare the environmental impacts of the sugarcane biorefinery system under different cane leaves and vinasse circulation scenarios using life cycle assessment (LCA). The scope of assessment covered all production steps in the sugarcane biorefinery system, from the extraction of raw materials through to the sugarcane cultivation and harvesting, sugar milling, power generation from bagasse, molasses ethanol conversion, and waste (cane leaves and vinasse) utilization scenarios. The environmental burdens from the production of materials, chemicals, and fuels used in the studied biorefinery system were also included in the assessment. The functional units have been set based on the management of the sugarcane and wastes that were processed in the biorefinery systems. Three reference units have been used for the assessment: (1) the comparison of the environmental impacts per tonne of cane leaves management, (2) the comparison of the environmental impacts per 1 m^3 of vinasse management, and (3) the comparison of the environmental impacts based on a tonne of sugarcane processed by the sugarcane biorefinery system. The impact assessments per unit of waste, i.e., cane leaves and vinasses, were set to distinguish the specific environmental performances for different waste management options. Meanwhile, the impact assessment per tonne of sugarcane processed was adopted to indicate how waste circulation affects the whole sugarcane biorefinery, as the sugarcane industry was familiar with the performance assessment in terms of the input sugarcane. The SimaPro software version 9.4.0.2 was used to compile the life cycle inventory data.

The "ReCiPe" midpoint impact assessment method [31] has been referred to because the midpoint impact indicators, such as life cycle GHG emissions and acidification potential, are required for environmental reporting and comparing with the several sustainability standards [32,33]. Six environmental impact categories relevant to the resources used and emissions to air and water from the sugarcane biorefinery system were considered, including climate change, acidification, freshwater eutrophication, human toxicity, ozone formation, and fossil depletion. Climate change was associated with GHG emissions in all activities of the biorefinery system including sugarcane harvesting. Acidification was mainly relevant to the acidifying substances emitted from fuel combustion over the life cycle of the biorefinery system, especially the raw material extraction stages. Human toxicity and ozone formation were relevant to the air pollutants that can originate in various activities including cane trash burning in the open field as well as cane trash utilization for energy purposes. Freshwater eutrophication was associated with the emissions to water and air, especially from vinasse management.

2.1. Sugar-Electricity-Ethanol Biorefinery System

The description of the sugarcane biorefinery system and the life cycle inventory (LCI) data sources, including the sugarcane cultivation and harvesting activities, sugar milling, electricity generation from bagasse, ethanol production from molasses, and the waste utilization scenarios, are summarized in this section. The LCIs for the raw material extraction stage, i.e., the production of materials, fertilizers, agrochemicals, and fuels used, were referred from the Thai national LCI database [34] and Ecoinvent database [35]. The inventory data of sugarcane cultivation and harvesting, both conventional (burnt cane production) and mechanized farming (green cane production), of sugarcane growers in Thailand were referred from [35]. The inventory data for sugar milling, steam and power generation plant, and molasses ethanol production plant in Thailand were collected from a plant located in the Central region complemented with literature [36,37]. Detailed information about material inputs, product outputs, and emissions and the references used for each waste utilization scenario is shown in the Appendix A.

2.1.1. Sugarcane Cultivation and Harvesting

Sugarcane production activities consist of land preparation, planting, treatment and harvesting. The study divided the sugarcane production system into two types, i.e., burnt cane and green cane. Burnt cane represents the cane product obtained from the conventional pre-harvest practice where the cane cutters burn the cane trash before harvesting. Green cane represents the cane product obtained from the mechanized farming where the burning process is avoided, and the cane trash separated [38,39]. The pre-harvest burning of cane leaves has been used so far for several reasons, e.g., ease of cutting by workers and economic feasibility for farmers. Since the sugarcane harvesting period in Thailand begins at the same time nationwide, in several regions where labor for cane cutting is limited, the laborers refuse to harvest unless there is pre-harvesting burning. Mechanization has been encouraged by the government in recent years due to concerns about air pollution from cane trash burning. A substantial amount of cane trash is, thus, generated, and it needs proper management and utilization to create added value. Table 1 shows the physicochemical properties of the sugarcane leaves [40,41]. Around 0.17 tonne of leaves are generated per tonne of sugarcane [42]. The transport distance of sugarcane from the field to the sugar milling was set as about 50 km because the contract farmers that provide sugarcane to the sugar factory usually live within a 50 km radius of the factory. To determine the environmental impacts, direct emissions to air and water from sugarcane cultivation and harvesting activities were determined based on [43,44].

Table 1. Physicochemical properties of cane leaves.

Proximate Analysis (% Weight)	
Moisture	2.65–9.20
Volatile	67.80–69.18
Fixed carbon	16.90–18.47
Ash	6.10–9.70
Ultimate Analysis (% Weight)	
Carbon	41.60
Hydrogen	4.12–5.08
Oxygen	37.42–44.09
Nitrogen	0.36–0.40
Sulfur	0.13–0.17
Ash	6.10–9.70
Density	100 kg/m^3
High Heating Value (HHV) (MJ/kg)	15.90 $\pm$ 1 MJ/kg
Low Heating Value (LHV) (MJ/kg)	15.00 $\pm$ 1 MJ/kg

2.1.2. Sugar Milling and Electricity Generation

Sugarcane delivered to the mills is crushed by rollers. Bagasse obtained from this crushing step is used as fuel for the co-generation system to produce steam and electricity. The extracted juice is clarified to remove the soil and impurities. The clarified juice is then entered into the evaporation process to obtain the syrup, which then goes to the crystallization process to produce raw sugar. At the refinery step, the raw sugar crystals are bleached to produce the refined sugar product. Molasses is a by-product that is separated from the crystals via centrifugation. Per tonne of processed cane, about 116 kg raw sugar, 30 kg molasses, and 268 kg bagasse are obtained. To produce refined sugar, raw sugar is remelted and passed through the refining process to obtain the refined sugar. The production data revealed that around 1.1 kg raw sugar is required to produce 1 kg refined sugar. At the milling step, sugar and molasses are the co-products obtained from the system. To determine the environmental burdens of molasses, which is further used as the feedstock for ethanol production, the economic allocation is used in the study and the allocation factors obtained for sugar and molasses are 0.74 and 0.26, respectively. For the co-generation system, low-pressure steam (20–22 bar) with a capacity of about 60 t steam/h is produced for electricity generation, which is internally used in the sugar milling. The exhaust steam from the turbine, at about 1.2–1.5 bar, is used for the milling and refining processes. The surplus electricity, after accounting for internal use by the sugar mills, is exported to the grid and this is considered to substitute the grid mix electricity. The environmental credits from bagasse electricity sold to the grid system is thus estimated, based on the environmental impact reduction when comparing between the bagasse electricity production of the study and the Thai national grid mix production [34].

2.1.3. Molasses Ethanol Production

Molasses obtained from the milling stage is sent to the ethanol production system in the sugar-electricity-ethanol biorefinery. There are two types of molasses ethanol plants in Thailand, i.e., the standalone ethanol plant and the ethanol plants owned by the sugar millers with the plant being located close to the sugar mill. In this case, the ethanol plant owned by the same sugar miller is referred to because it is the major type of ethanol plant in Thailand. Molasses is used for ethanol production by passing through the following process: viz., fermentation, distillation and dehydration. During the distillation process, vinasse is obtained as the wastewater, which is generally left in the open ponds of the ethanol factory. Table 2 shows the reviewed physicochemical characteristics of sugarcane vinasses derived from the distillation of ethanol, which generally has a high chemical oxygen demand (COD) and biological oxygen demand (BOD); it is necessary to have the proper measures to manage. The ethanol conversion process requires about 4 kg of molasses/L ethanol and generates about 6.6 L of vinasses/L ethanol [36]. Vinasses generated from this stage is then further used as the input for the vinasse utilization scenarios.

Table 2. Physicochemical characteristics of sugarcane vinasses.

Parameters	Unit	[27]	[28]	[29]	[30]
pH	-	4.2–5.0	3.8–4.7	3.0–4.7	3.2–5.0
Electrical Conductivity (EC)	mS/cm	-	16	15.0–25.3	8.3–15.1
Total Phosphorus (TP)	mg/L	40–130	1–190	40–750	90–420
Total Organic Carbon (TOC)	g/L	-	26–32	-	20
Total Nitrogen (TN)	mg/L	500–1600	975	-	-
Chemical Oxygen Demand (COD)	g/L	65	59–80.5	82–130	27.5–299.2
Biological Oxygen Demand (BOD)	g/L	25	31–75	36–60	5–48
Total Solids (TS)	g/L	82	63–69	-	27–82
Magnesium (Mg)	mg/L	300–900	-	-	480–1000
Calcium (Ca)	mg/L	300–3600	-	n.d.	650–1270
Zinc (Zn)	mg/L	-	15	-	1
Iron (Fe)	mg/L	-	13–203	-	8–33
Potassium (K)	mg/L	3100–6500	30,000	7000–13,000	3350–9200

2.2. Waste Circulation Models

2.2.1. Cane Leaves Utilization

Three scenarios for cane trash utilization are investigated and compared to the base case, which is the conventional practice, i.e., cane trash burning as shown in Figure 1.

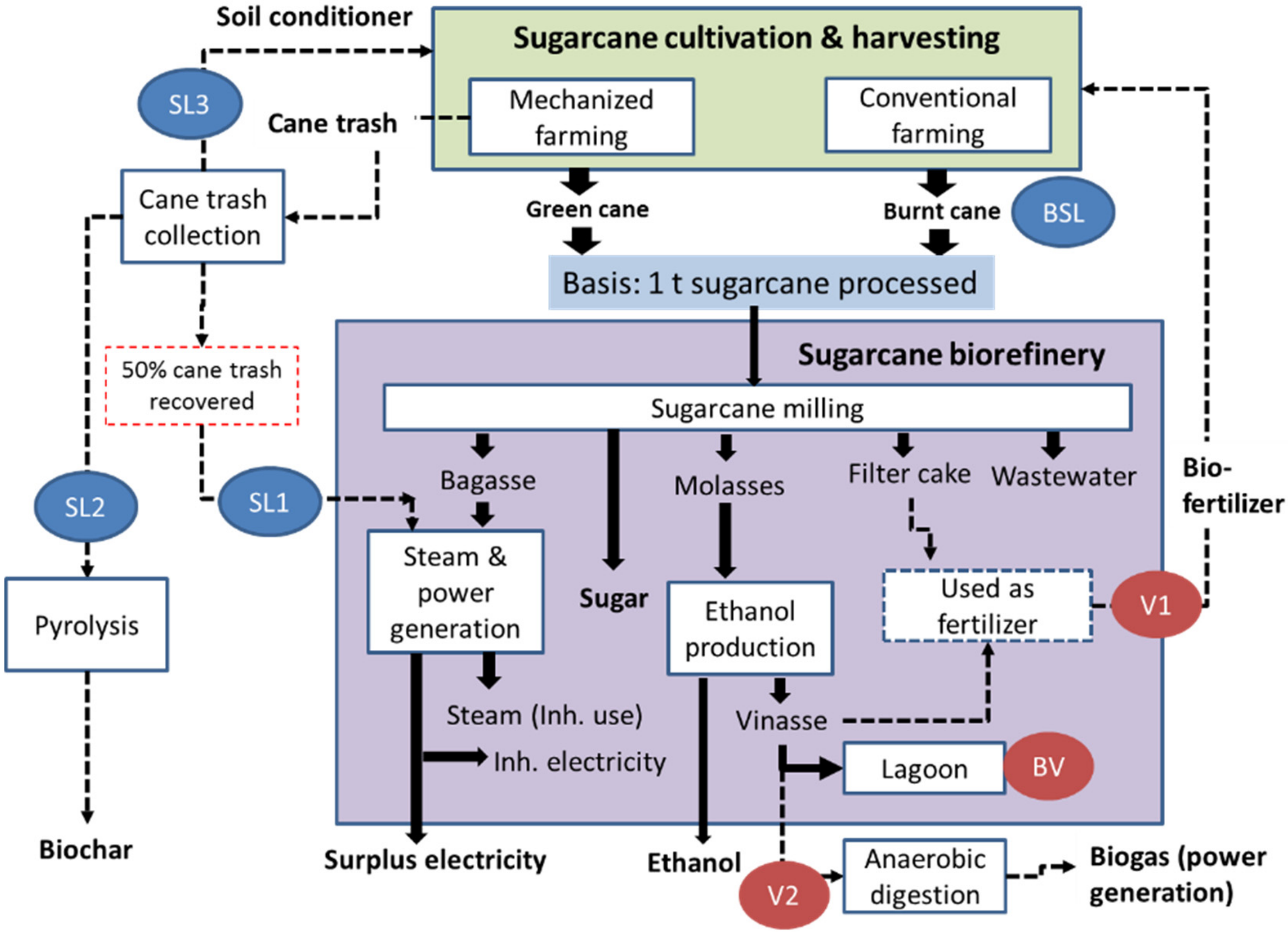

Figure 1. System boundary of the sugarcane biorefinery system under different waste utilization scenarios.

- ***Base case sugarcane trash burning (BSL)*** is the scenario where cane trash is burnt in the open field during the pre-harvest. This is a traditional practice of cane growers in Thailand and causes emissions of air pollutants, such as particulate matter, as well as the non-CO_2 GHGs [45,46]. The emissions generated from cane leaves burning in the open field is shown in Figure A1 of the Appendix A.
- ***Sugarcane trash for electricity generation (SL1)*** is the scenario where a machine is used for harvesting to avoid the need for cane trash burning. In this case, 50% of the cane trash is collected and used for electricity generation at the mills. The remaining 50% of the cane trash is left in the field as the trash blanket to maintain soil quality and for weed control. A tonne of cane leaves can be used to produce around 323 kWh of electricity [26,47]. Based on a sugarcane leaves factor of about 0.17 tonnes leaves/tonne sugarcane, 50% collection factor, and 323 kWh electricity/tonne leaves, it can be estimated that, for every tonne of cane processed in the mills, about 27 kWh electricity would be obtained. To produce the electricity from cane leaves and trash, the collected leaves are transferred and used as supplementary fuels in the boiler at the sugar mill. The soft water, electricity, and chemicals for water treatment are required as input materials, and the emissions to the air due to the combustion of cane leaves

in the boiler are shown in Figure A2. The environmental credits from utilizing cane trash for electricity are estimated based on the environmental impacts reduction due to the substitution of grid electricity production.

- ***Sugarcane trash to biochar (SL2)*** is the scenario for mechanical harvesting similar to SL1; however, in this case, the 50% of cane trash is utilized for biochar production and the other 50% is incorporated into the soil. Biochar from sugarcane leaves can be used for improving soil water retention and soil quality [48], and it can also be used as a solid fuel with good properties that can be used to substitute for coal [49]. In this study, the fast pyrolysis process at 525°C is referred from [50]. It is estimated that a tonne of cane trash processed in a fluidized bed reactor for fast pyrolysis could generate about 372 kg of biochar and 388 kg of bio-oil. Hence, using the same basis for the calculation of cane leaves availability, as indicated in SL1, it can be estimated that, for every tonne of cane processed in the mills, about 32 kg biochar would be obtained from cane trash utilization. The input materials and emissions associated with biochar production are shown in Figure A3. The environmental credits of biochar are estimated from the avoided impacts from the production and combustion of coal.
- ***Sugarcane trash as a soil conditioner (SL3)*** represents mechanical harvesting similar to SL1 and SL2; however, the cane trash is used for soil conditioner production. About 91 kg of urea is applied along with a one tonne of cane trash for producing a tonne of soil conditioner [51]. The same basis for the calculation of cane leaves availability is used as previously indicated; for every tonne of cane processed in the mills, about 85 kg of soil conditioner would be obtained as the product from SL3. The input materials and soil nutrients are shown in Figure A4. The environmental credits of the soil conditioner are estimated from the avoided impacts from chemical fertilizer production.

2.2.2. Vinasse Utilization

Two scenarios for vinasses utilization are analyzed by comparing with the base case of vinasse management, i.e., leaving the vinasses in open ponds as shown in Figure 1. Since vinasses is generated at the ethanol plant, the scope of analysis is thus considered at the "sugar-electricity-ethanol biorefinery system", whereas the vinasse will be utilized either at the plantation or at the ethanol plant.

- ***Base case vinasse (BV)*** represents the common practice of molasses ethanol factories, i.e., vinasse is collected in the open ponds inside the factories to avoid the discharge of wastewater to the environment. The internal collection of vinasse is used in many factories as it has the lowest investment cost, and for ease of operation. However, it needs a large area in the factory and can cause GHG emissions as well as the smell. The treatment process requires an input of about 600 kg lime ($Ca(OH)_2$) per m^3 of vinasse [52,53]. The input material, methane and nitrous oxide emissions from the base case vinasse have been shown in Figure A5.
- ***Vinasse as a bio-fertilizer (V1)*** represents the scenario where the vinasse is sent to a facility for producing fertilizer. Vinasse contains a high content of organic matter, potassium, and calcium, and a moderate content of nitrogen and phosphorus [54]. It can be used for fertigation to substitute chemical fertilizer. Since the density of vinasse is about 1100 kg/m^3 [55], a cubic meter of vinasse used for fertilizer is assumed to be equivalent to 1100 kg organic fertilizer. The soil nutrients, e.g., N, P_2O_5 and K_2O, etc., as well as the emissions to the air, e.g., N_2O and NH_3 generated from the application of vinasse as the fertilizer to soil are shown in Figure A6. V1 scenario's products are the same as BV plus 73 kg organic fertilizer. The environmental credits from bio-fertilizer are estimated based on the substitution of chemical fertilizers.
- ***Vinasse for power generation (V2)*** represents the scenario where the vinasse is treated by anaerobic digestion to obtain biogas, which is then used as fuel gas for power generation after removing the H_2S. A cubic meter of vinasse generates around 11.82 m^3 biogas, which in turn, can generate around 23.9 kWh electricity [56,57]. The final products of the V2 scenario are the same as BV plus 1.6 kWh additional electricity

produced from biogas. The description of the material inputs, product outputs as well as the related emissions generated from V2 are shown in Figure A7 of the Appendix A. The environmental credits from electricity produced from vinasse can be estimated by the substitution of grid electricity production in Thailand.

3. Results and Discussion

3.1. Environmental Performance of Cane Leaves Utilization Scenarios

Table 3 shows the environmental impacts for the different scenarios of cane leaves management. The results revealed that burning of cane leaves before harvesting (BSL) has the highest impact on climate change, acidification, and ozone formation. Implementing mechanized farming for green harvesting and circulating the cane leaves and trash for power generation (SL1) showed the best environmental performance especially for climate change mitigation, followed by using cane leaves for biochar (SL2) and soil amendment (SL3), respectively. The negative environmental impacts for SL1, SL2 and SL3 stem from the environmental credits of bioelectricity, biochar, and soil conditioner that can avoid the fossil-based grid-mix electricity generation, coal production, and chemical fertilizer production, respectively. Although fossil fuel consumption would be increased due to mechanized farming, its promotion is still an essential factor to help avoid cane leaves burning during harvesting and supports the increased collection of cane trash.

The environmental impacts classified by the life cycle stages of cane leaves utilization scenarios, i.e., raw material extraction (RM), transport, processing, and the environmental credits have also been summarized in Table 3. The use of raw material, i.e., urea, to help spur the decomposition of cane leaves and trash for soil conditioner production (SL3) causes a high impact for almost all impact categories, especially climate change and fossil depletion. However, for the processing stage, biochar production (SL2) has the highest environmental impact as compared to the other scenarios. This is especially for the climate change impact due to the release of large amounts of carbon monoxide and methane.

3.2. Environmental Performances of Vinasse Utilization Scenarios

Table 4 shows the environmental impact potentials for vinasse circulation scenarios. The results revealed that the base case (BV) of vinasse management, i.e., treatment of vinasse in the open ponds by adding lime to control the acidity, resulted in the highest environmental impact for all impact categories. The use of vinasse as a bio-fertilizer in the sugarcane field (V1) resulted in the lowest impacts on climate change and acidification. Meanwhile, the use of vinasse for biogas and electricity generation has resulted in the lowest impact on fossil depletion, toxicity, and eutrophication due to the credits from grid-electricity substitution. Either vinasse utilization as a bio-fertilizer or for electricity generation results in significant environmental benefits as compared to the conventional vinasse treatment in open ponds. Transporting vinasse contributes the highest environmental impact for the use of vinasse as a bio-fertilizer. Concentrating the vinasse before transport by using exhaust energy from the ethanol plant can be an option to help increase the environmental performance of using vinasse as a bio-fertilizer. For the utilization of vinasse for electricity generation, the high climate change impact is due to the fugitive methane emissions from the anaerobic digestion system for the biogas production.

Table 3. Environmental impact potentials classified by the life cycle stages of different cane leaves management scenarios.

	Environmental Impacts Per Tonne of Cane Leaves													
	BSL	SL1					SL2					SL3		
	Total	RM	Transport	Processing	Credits	Total	RM	Transport	Processing	Credits	Total	RM	Processing	Credits	Total
Climate Change (kg CO_2e)	43	19	11	94	−238	−115	36	12	207	−314	−59	304	-	−312	−8
Terrestrial Acidification (kg SO_2e)	1.22	0.04	0.04	0.66	−0.53	0.21	0.11	0.04	-	−0.23	−0.08	1.5	-	−1.39	0.11
Freshwater Eutrophication (kg Pe)	-	0.01	0.00	-	−0.15	−0.14	0.02	0.00	-	−0.02	0.00	0.04	0.09	−0.04	0.09
Human Toxicity (kg 1,4-DCBe)	-	0.76	0.28	-	−9.66	−8.62	2.53	0.4	-	−1.54	1.39	6.5	-	−4.75	1.75
Ozone Formation (kg NO_xe)	2.01	0.03	0.07	1.37	−0.33	1.14	0.05	0.07	2.21	−0.41	1.92	0.46	-	−0.74	−0.28
Fossil Depletion (kg oile)	-	5.5	3.67	-	−69.8	−60.6	5.97	4.06	-	−13.2	-3.17	114	-	−43.4	70.6

Table 4. Environmental impact potentials for vinasse management scenarios.

	Environmental Impacts Per 1 m^3 of Vinasse									
	BV	V1					V2			
	Total	RM	Transport	Process	Credits	Total	RM	Process	Credits	Total
Climate Change (kg CO_2e)	522	-	26	10	−32	3	5	117	−12	109
Terrestrial Acidification (kg SO_2e)	0.37	-	0.09	0.08	−0.16	0.01	0.01	0.23	−0.03	0.21
Freshwater Eutrophication (kg Pe)	0.00	-	0.00	0.00	−0.00	0.00	0.00	-	−0.01	−0.01
Human Toxicity (kg 1,4-DCBe)	0.79	-	0.06	0.85	−0.49	0.42	0.20	0.00	−0.50	−0.30
Ozone Formation (kg NO_xe)	0.30	-	0.16	-	−0.09	0.07	0.01	0.02	−0.02	0.01
Fossil Depletion (kg oile)	46.10	-	8.64	-	−4.23	4.41	1.40	-	−3.64	−2.24

3.3. Contribution of Cane Leaves and Vinasse Utilization on the Environmental Performance of the Sugarcane Biorefinery System

The sugar milling industry would generally like to know how the waste utilization options can contribute to reducing the overall environmental impact of the sugarcane biorefinery system when compared with the "tonne cane processed". This study, therefore, evaluated the cane leaves management scenarios based on the "sugar-electricity biorefinery system". This is because the cane leaves management is directly related to the sugarcane growers and the sugar mills where the power generation plant is generally owned by the mill. Table 5 shows the environmental impact potentials of the sugar-electricity biorefinery system under three cane leaves circulation scenarios. Per tonne cane processed at the sugar-electricity biorefinery system, the final products obtained from the BSL system are 105 kg refined sugar, 41 kg molasses, 60 kWh surplus electricity, and 170 kg of cane leaves. The amount of cane leaves that used to be burnt during pre-harvesting in the base case (BSL) would be diverted for use in the scenarios SL1, SL2, and SL3. The results revealed that the open burning of cane leaves in the field (BSL) has the highest environmental impact. Implementing mechanized farming for cane trash collection and the utilization of cane trash for power generation (SL1) has the highest environmental performance, followed by the use of cane trash for biochar (SL2) and soil amendment (SL3), respectively. Although fossil fuel consumption would be increased by the mechanical farming, the promotion of mechanized farming is still an essential factor to help avoid cane trash and leaves burning during harvesting by farmers and support the increased collection of cane trash. The utilization of sugarcane trash can reduce the climate change impact by about 20–104%. The environmental impacts per unit of sugar product are decreased for all cane leaves utilization scenarios when compared to the base case. For example, the life cycle GHG emissions, known as the carbon footprint of refined sugar, obtained from the BSL, SL1, SL2 and SL3 scenarios would be around 662, -29.5, 446 and 528 kg CO_2e/tonne refined sugar, respectively.

Table 5. Environmental impact potentials per tonne of cane processed for different cane leaves utilization scenarios.

	BSL	SL1	SL2	SL3
Climate Change (kg CO_2e)	69	−3	47	55
Terrestrial Acidification (kg SO_2e)	1.3	0.5	0.7	0.7
Freshwater Eutrophication (kg Pe)	0.01	−0.04	0.01	0.03
Human Toxicity (kg 1,4-DCBe)	1.02	−2.02	1.29	1.35
Ozone Formation (kg NO_xe)	0.91	0.49	0.80	0.42
Fossil Depletion (kg oile)	9.89	−11.5	9.88	22.5

Figure 2 shows the percent contribution of environmental impact of the sugar-electricity system classified by life cycle stages of the biorefinery system, i.e., sugarcane cultivation (with mechanical harvesting), sugarcane transport, raw sugar production, and refined sugar production. The results revealed that sugarcane cultivation and harvesting is the main contributor, sharing about 78% of the climate change impact, 61% of acidification, 94% of eutrophication, 70% of the human toxicity impact, 52% of ozone formation, and 76% of the fossil depletion impact. The environmental credits for climate change, eutrophication, human toxicity, and fossil depletion are found at the raw sugar production stage due to the credits obtained from surplus bagasse electricity generation.

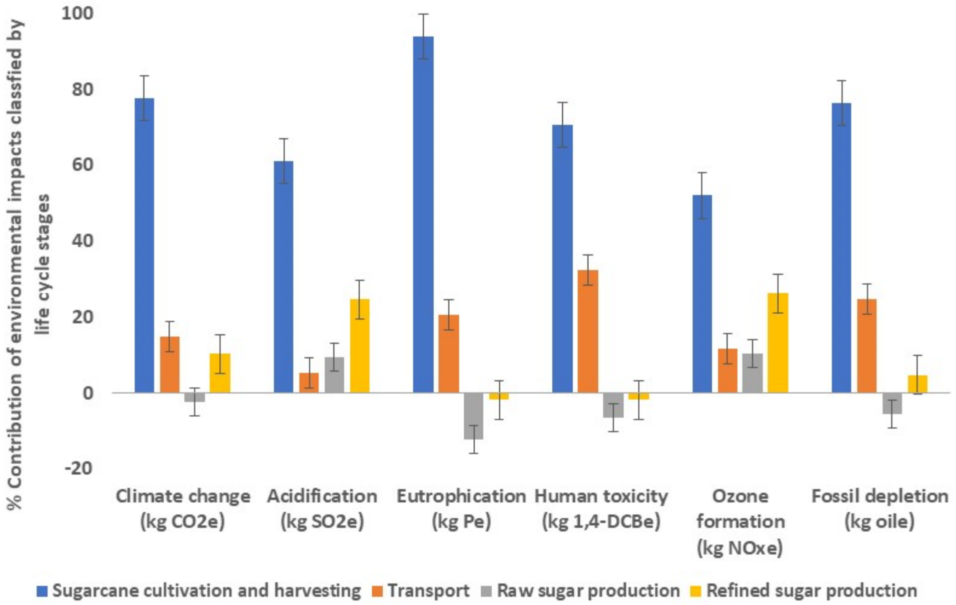

Figure 2. Environmental impact potentials of the sugar-electricity biorefinery system classified by life cycle stages.

For the vinasse utilization scenarios, the sugar-electricity-ethanol system is investigated. The final products for the BV scenario are 105 kg refined sugar, 10 L molasses ethanol, 56 kWh surplus electricity, 170 kg cane trash that is burnt in the field, and 66 L vinasse that is treated in open ponds. The comparative results shown in Table 6 reveal that the base case (BV) of vinasse management, i.e., the treatment of vinasse in open ponds by adding lime to control the acidity, result in the highest environmental impacts for almost all impact categories. The use of vinasse as a bio-fertilizer in the sugarcane field (V1) and vinasse for electricity generation (V2) could help reduce the environmental impacts of the biorefinery system. Recycling vinasse as a bio-fertilizer or for electricity can reduce the climate change impact by about 28–29%. Figure 3 shows the percent contribution of environmental impacts of the sugar-electricity biorefinery system classified by life cycle stages (based on the BV scenario). Sugarcane cultivation and harvesting and ethanol conversion are the two production stages that mainly contribute to the generation of the environmental impacts.

Table 6. Environmental impact potentials per tonne of cane processed for different vinasse utilization scenarios.

	BV	V1	V2
Climate Change (kg CO_2e)	119	85	86
Terrestrial Acidification (kg SO_2e)	0.92	0.90	0.90
Freshwater Eutrophication (kg Pe)	0.02	0.02	0.02
Human Toxicity (kg 1,4-DCBe)	1.56	1.51	1.50
Ozone Formation (kg NO_xe)	0.61	0.59	0.59
Fossil Depletion (kg oile)	17.6	14.6	14.5

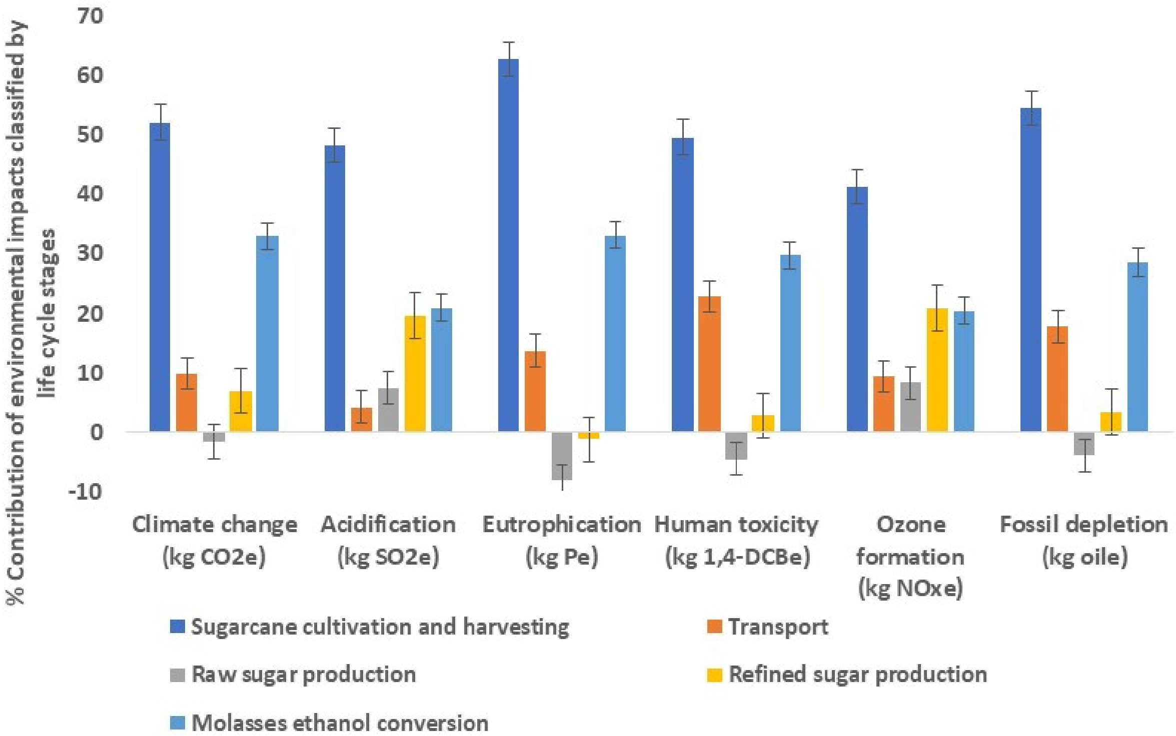

Figure 3. Environmental impact potentials of the sugar-electricity-ethanol biorefinery system classified by life cycle stages.

3.4. Recommendations for Cane Trash and Vinasse Utilization

Different approaches for waste circulation have their pros and cons. For the sustainable use of cane leaves, the results revealed that the SL1 scenario, i.e., 50:50 percentage sharing of the available cane trash for electricity generation and for maintaining the soil quality has about 53% lower climate change impact than the 100% use of sugarcane trash as a soil conditioner (SL3). This is due to the environmental credits from electricity production along with the soil fertility that is still maintained [51]. Nevertheless, the use of sugarcane leaves as a soil conditioner will reduce the herbicides used during sugarcane cultivation because the sugarcane leaves will help retain moisture and prevent weeds [58], which in turn, would return the benefits of cane leaves utilization to the farmers. Biochar produced from cane leaves (SL2) can be used as a fuel or even be used as the soil conditioner to reduce the pH, improve the quality of soil that has deteriorated, and be used as long-term carbon storage [59,60]. The high porosity of biochar can be a reservoir of microorganisms that are beneficial to plants [61]. Nevertheless, the production of bio-charcoal from sugarcane leaves causes a relatively high amount of methane. Hence, the production process should be controlled as a closed system to avoid environmental emissions. Additionally, the use of a slow pyrolysis process resulted in increased biochar content [62].

Over the past decades, the harvesting of sugarcane in Thailand has been dominated by the burning of cane trash before harvesting. There are environmental burdens from the burning of cane trash during harvesting; however, the changing of practices is difficult due to many factors, especially the socioeconomic situation of farmers, e.g., a shortage of labor, difficulty to access the harvesting machinery, burning is a quick and easy option for further crop growing, etc. [63]. One of the factors is that there is no demand for the residues, e.g., the cane leaves and trash when farmers avoid burning. Nevertheless, there is a significant trend of increasing cane trash biomass resources available from the Thai sugarcane industry. Based on the sugar milling production data over the past 10 years (2011–2021) from the Office of Cane and Sugar Board (OCSB), Ministry of Industry, Figure 4 shows the ratio between burnt cane and green cane production in Thailand, and the estimated amount of cane leaves available. The analyzed data revealed that during 2011–2019, green cane shared only about 33–38% of the total cane processed in the Thai sugar factories [18]. However, in recent years (during 2020–2021), there is a significant increase in green cane production in Thailand, sharing about 50% in 2020 and 74% in 2021. This is due to government policy promotion and strict enforcement to avoid burnt cane production. The line shows the estimated amount of cane trash available, which in 2021 is about 8.3 Mt/year. There is, thus, a high potential of cane leaves and trash available in Thailand due to the change in agricultural practices. There were significant reductions in sugarcane production in Thailand during the years 2020–2021 as compared to the years 2018–2019 due to the severe drought, which hit the country over those two years. However, another observation from the trends is the increased proportion of green cane in 2022 and 2021, which could be due to the reduction in total sugarcane production. When the total production of sugarcane decreased, there was less competition, with time for cutting the sugarcane during the harvesting period; so the labor shortage problem during cane harvesting was reduced. In addition, the government and sugar millers could better prohibit the burning of cane trash, and mechanization could be enhanced.

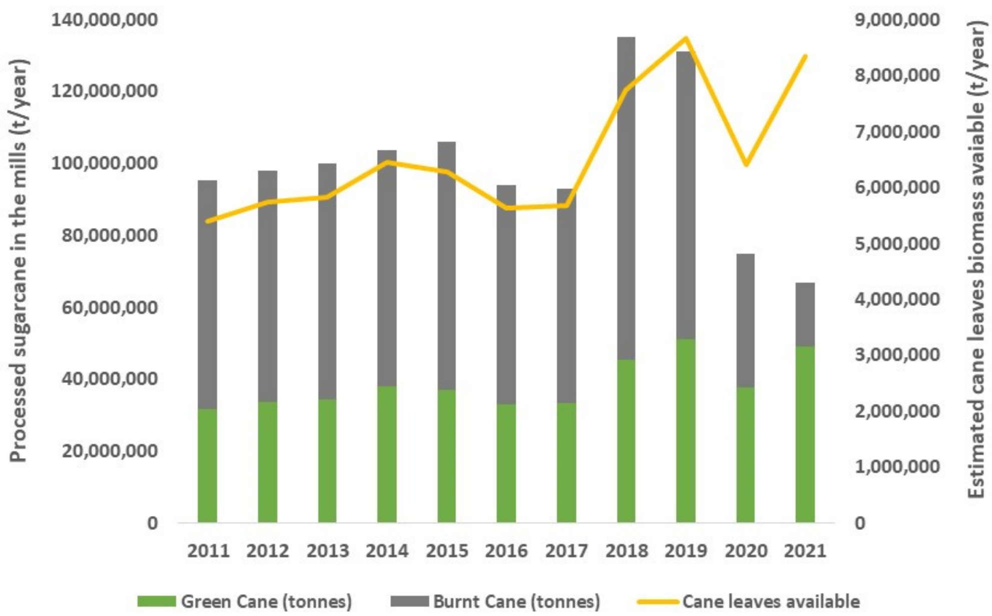

Figure 4. The share between green and burnt cane in the Thai sugarcane industry and the estimated availability of cane leaves and trash.

As there are various options for cane leaves and vinasse utilization, the sustainable circulation of waste must be considered. For cane trash, in principle, the maintaining of cane trash in the field for soil quality control should be set as the first priority to ensure the long-term cultivation of land use for sugarcane. The 50% basis of cane trash left in the field is recommended by several studies [26]. However, the recent publication of good practices for cane plantation by the OCSB of Thailand has mentioned that retaining about 25% of cane trash is possible to maintain soil quality and for weed control [64]. Even though the use of cane leaves for electricity (SL1) brings about the highest environmental sustainability, especially in terms of climate change mitigation, followed by the SL2 and SL3; biochar or bio-fertilizer production are still attractive for not only the industry but also the sugarcane growers because they are easy to produce and can be utilized by returning them to the sugarcane plantation, which is a familiar activity for both the cane growers and the sugar industry.

Hence, to select the appropriate waste circulation options for implementation by the sugarcane industry, environmental sustainability, based on LCA results, can be one of the decisive factors for the company. However, there are other factors also incorporated in decision making. For example, although the biogas and power generation from vinasse (V2) has better performance indications; based on the field survey and the discussion with the ethanol factory owned by the sugar millers, the use of vinasse as a bio-fertilizer (V1) is more attractive for the industry. This is due to two reasons: (1) investment cost and the difficulty in operating the anaerobic digestion system; meanwhile, the sugar mill already has the surplus energy from the bagasse; and (2) the sugar millers generally prefer to focus on the agriculture basis so that the bio-fertilizer returned to their sugarcane growing members is thus more attractive. The provision of bio-fertilizer from vinasse to the contracted sugarcane growers could bring more engagement of industry, cane growers and society. This vinasse bio-fertilizer provision is, therefore, somehow used as the corporate social responsibility (CSR) activity of the industry. In addition, the efficient transport of bulky waste, such as cane leaves and vinasse as fertilizers must be considered. For the case that the sugar mill, power plant, and ethanol process are owned by a single company, which corresponds to the sugarcane biorefinery system, the integrated waste utilization management system of both sugarcane leaves to generate electricity and the use of vinasse as an organic fertilizer can be combined. The combination of those two waste options, i.e., the SL1 + V1 scenarios would significantly reduce the environmental impacts from the BV scenario of Table 6 to be about −37 kgCO_2e, 0.5 kg SO_2e, 0 kg Pe, −2 kg 1,4-DCBe, 0.5 kg NO_xe and −14 kg Oile.

4. Conclusions

Cane trash and vinasse are the two major wastes of the current Thai sugarcane biorefinery; the sustainable management of those two waste streams is crucial for a transition to a sustainable and low-carbon circular bioeconomy. This study thus evaluated the environmental performance of five valorization pathways for creating value-added products from cane leaves and vinasse: viz., electricity from cane trash (SL1), biochar (SL2), soil conditioner (SL3), bio-fertilizer from vinasse (V1), and electricity from vinasse biogas (V2) using an LCA. The results revealed that all five circulation scenarios are beneficial compared to the base case of the sugarcane biorefinery, but there were differences in environmental sustainability performances among the scenarios. The use of sugarcane leaves for electricity generation (SL1) and vinasse as organic fertilizer (V1) led to the lowest environmental impacts in several impact categories, especially climate change. Nevertheless, some environmental hotspots in the waste circulation processes were identified in the study, e.g., leakage of carbon monoxide and methane from the biochar production process (SL2), application of urea to spur the composting of cane trash (SL3), transportation of cane trash to the powerplant (SL1), and transport of vinasse bio-fertilizer to farmers (V1). The analysis of the sugarcane processing data indicated that, in the year 2021, there was a significant improvement in the avoidance of pre-harvesting burning of sugarcane in Thailand, which led to a big potential of sugarcane leaves biomass utilization. Measures for improving the environmental sustainability of cane leaves and vinasse utilization are thus recommended to enhance the environmental sustainability of the Thai sugarcane industry.

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

Appendix A

Figures A1–A7 show the details of material inputs, product outputs, and the related emissions used for the seven scenarios, i.e., BSL, SL1, SL2, SL3, BV, V1 and V2.

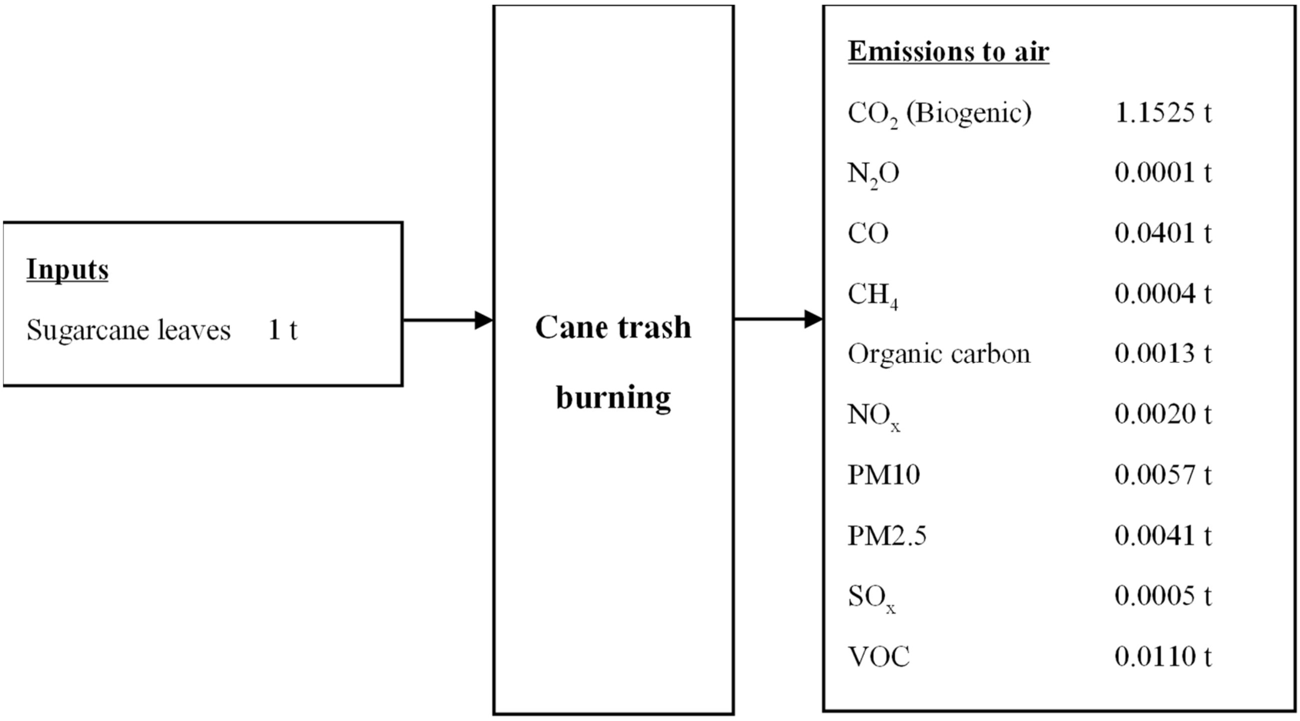

Figure A1. Inputs-Outputs for the base case sugarcane trash burning (BSL). Remark: Emissions to air are calculated based on [43–46].

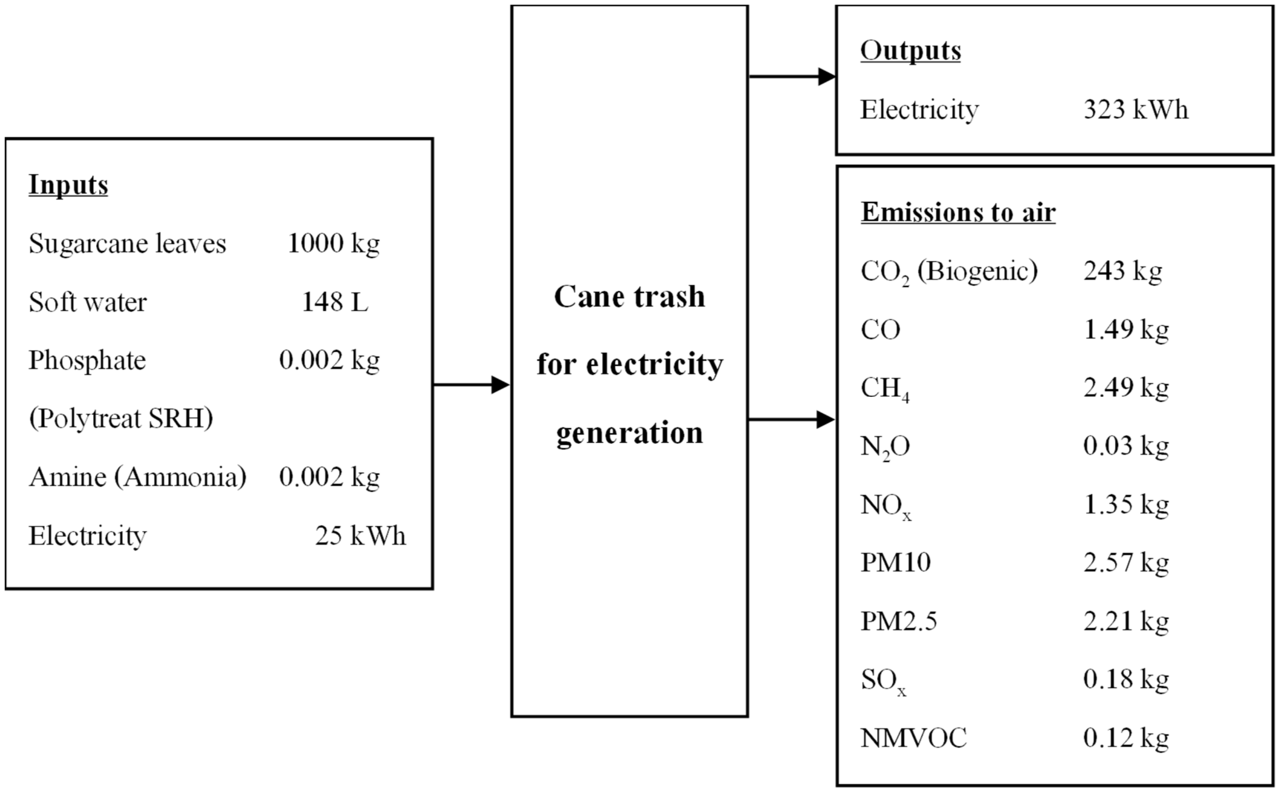

Figure A2. Inputs-Outputs for the sugarcane trash for electricity generation scenario (SL1). Remark: Emissions to air are calculated based on [43,44].

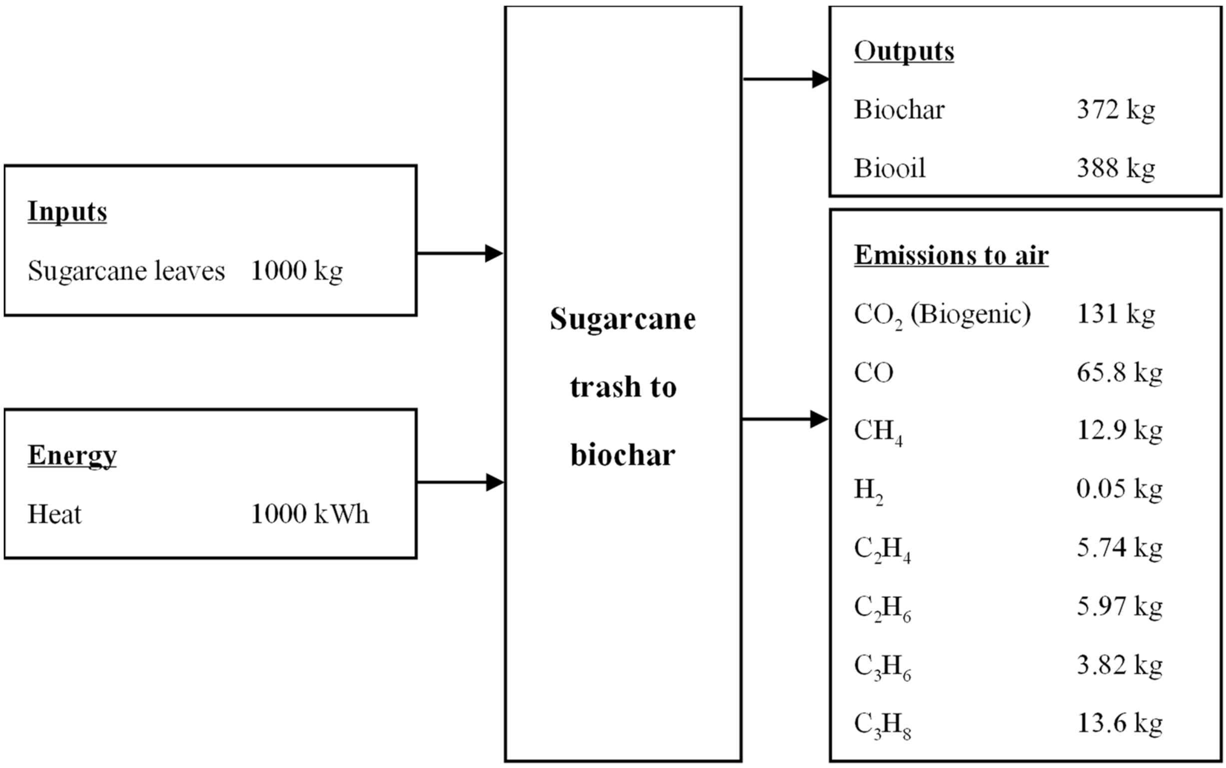

Figure A3. Inputs-Outputs of Scenario SL2: Cane trash to biochar. Remark: Data is referred from [50].

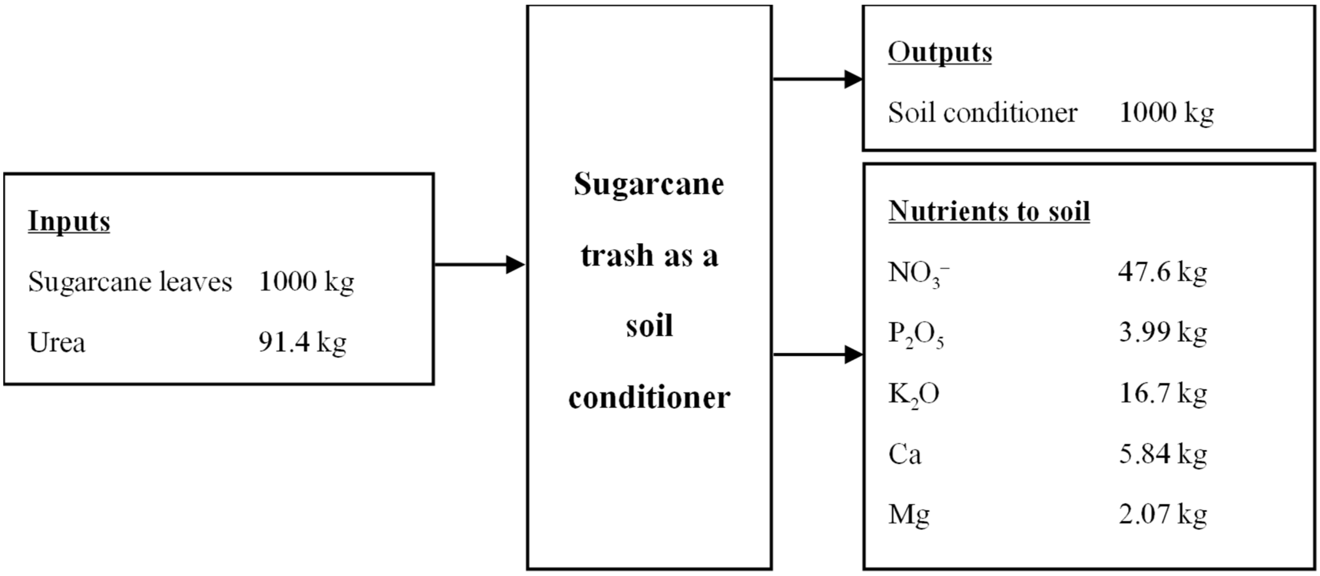

Figure A4. Inputs-Outputs of Scenario SL3: Cane trash as a soil conditioner. Remark: Production data is referred from [51]; Urea is referred from [65].

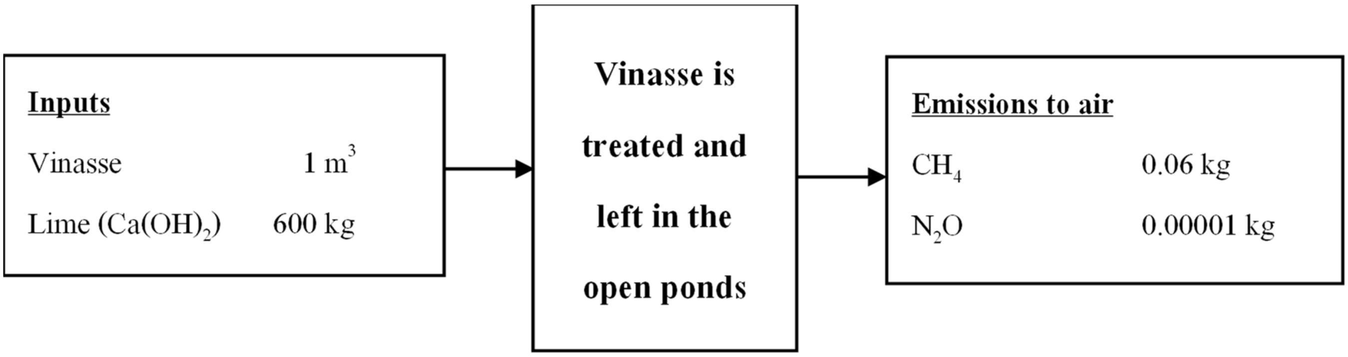

Figure A5. Inputs-Outputs of Scenario BV: Vinasse is treated and left in the open ponds. Remark: Data is referred from [52]; Lime used is referred from [53].

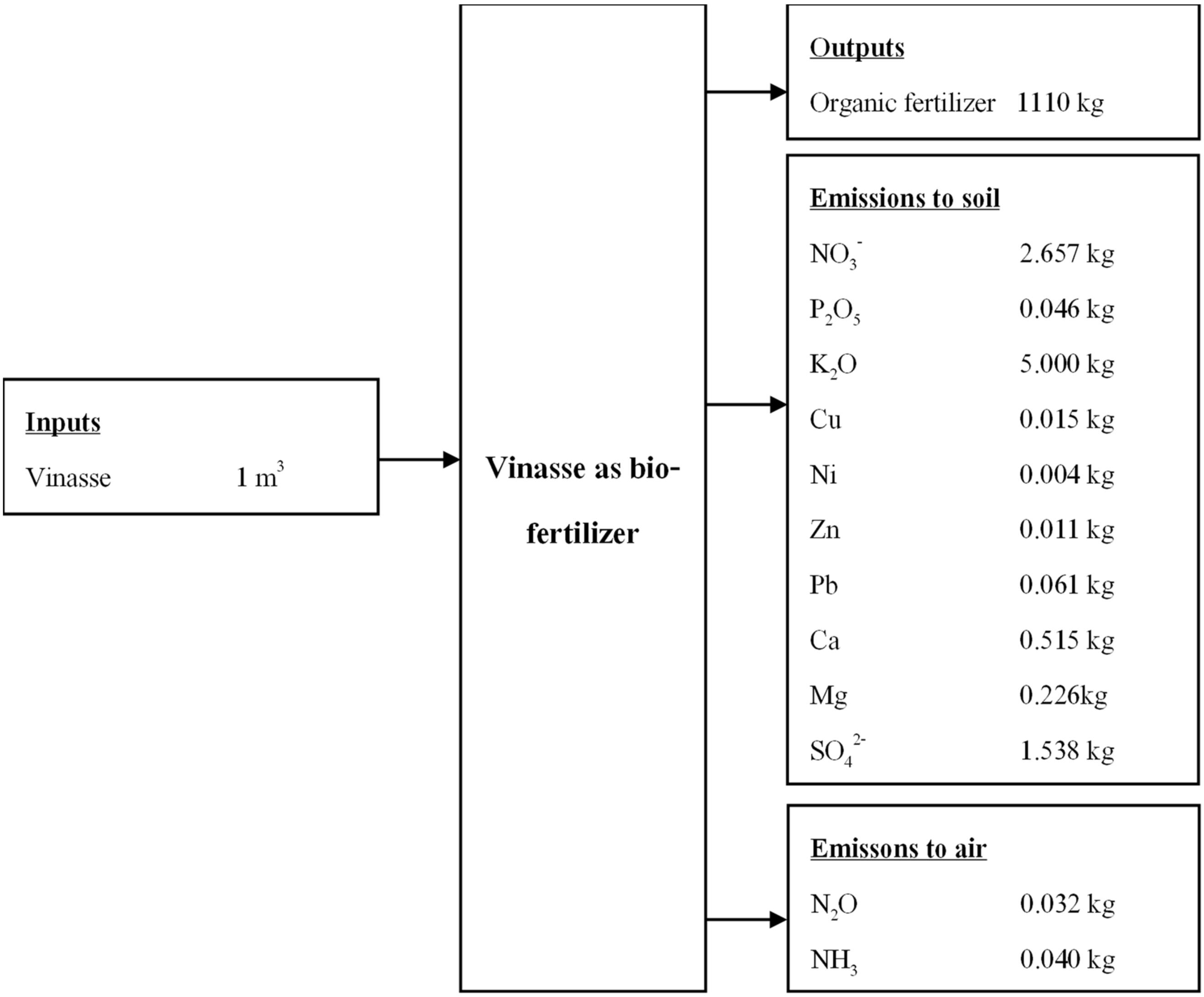

Figure A6. Inputs-Outputs of Scenario V1: Vinasse as bio-fertilizer (V1). Remark: Organic fertilizer production is referred from [55]; Emissions to soil are referred from [66,67]; Emissions to air are referred from [68].

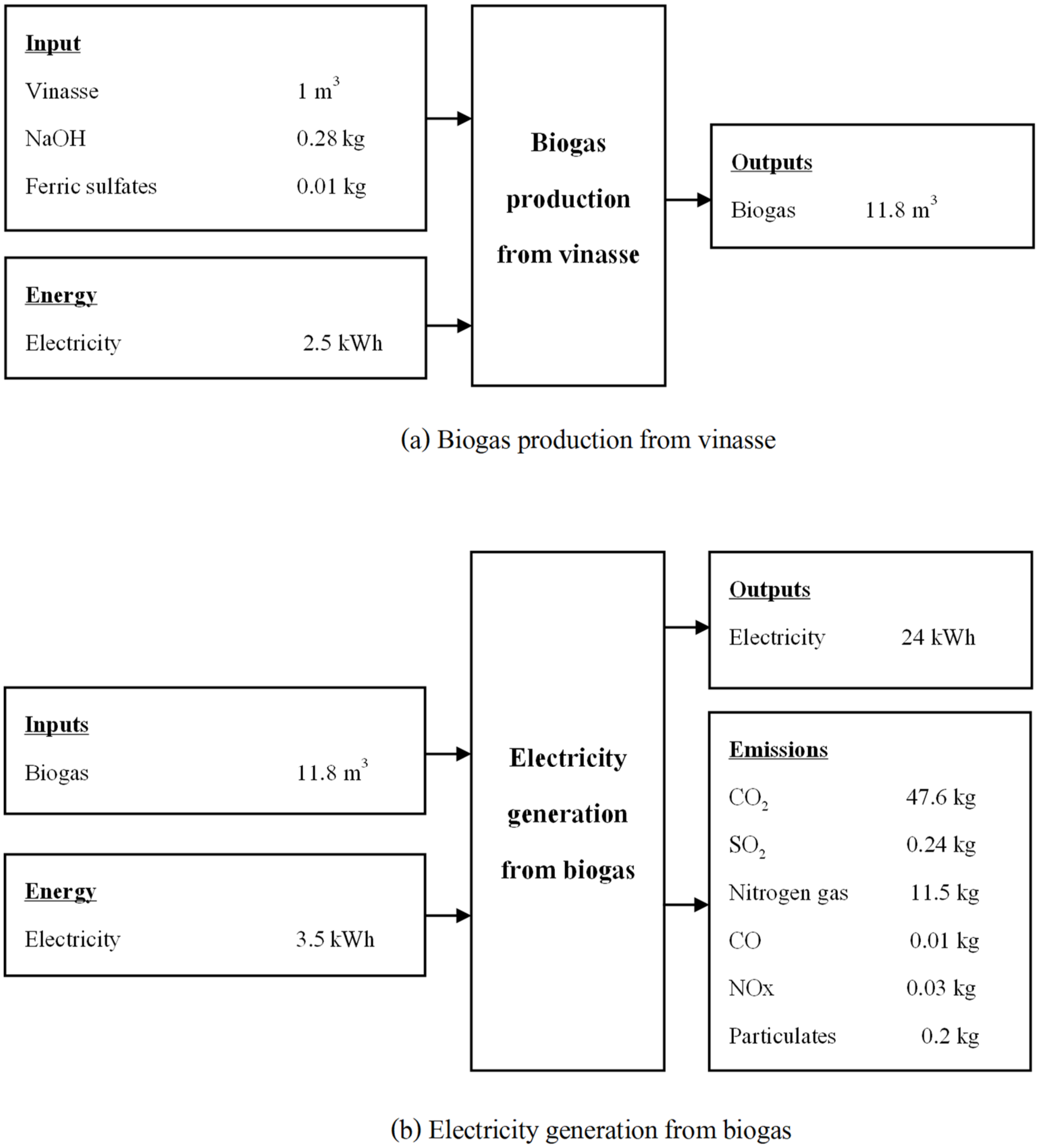

Figure A7. Inputs-Outputs of Scenario V2: Vinasse for biogas and power generation (V2). Remark: Production data is referred from [57].

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