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The Bioenergetic Potential from Coffee Processing Residues: Towards an Industrial Symbiosis

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Abstract: Coffee processing generates a large amount of organic waste, which has the potential for energy use through biogas production. Although Brazil dominates world coffee production, treating its residue with biogas technology is not a practice, especially due to this product's seasonality, which hampers continuous digester operation. The implementation of biogas production from coffee residues in a concept of industrial symbiosis could overcome this. This work evaluates the biogas energy potential from the main liquid residues of coffee processing (i.e., mucilage and wash water) and their integration with glycerin and cattle manure. Around 2773 m^3 biogas day^{-1} would be produced (75% CH_4), used as biomethane (734 thousand m^3 $year^{-1}$), or thermal energy (23,000,000 MJ $year^{-1}$), or electricity (2718 MWh $year^{-1}$), which could supply, respectively, all the liquefied petroleum gas (LPG) and diesel demands of the farm, all the thermal energy demands of the grain drying process, as well as electricity for 30 residences. Considering the short coffee season, the results have a broader context for the application of biogas production on coffee processing farms, envisaging that the Agroindustrial Eco-Park concept has the potential to integrate various agroindustrial sectors for energy production, residue exchange, and water recirculation.

Keywords: biogas; biomethane; Agroindustrial Eco-Park; industrial symbiosis; co-digestion

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1. Introduction

The coffee market is globally significant, with an average annual consumption of 5.9 million tons, making coffee one of the top-selling beverages [1–3]. It ranks second only to oil as the most valuable commodity on the world market and is among the leading products in the agricultural sector, alongside sugarcane. Brazil is the largest coffee producer in the world (63.08 million bags in 2020) [4,5], with the largest production concentrated in the state of Minas Gerais, with approximately 70% of the total [6]. During coffee processing, less than 3% of the biomass generated is used in the production of the beverage, with the remaining 97% remaining as residue in the form of pulp, husk, and mucilage, among others [7].

The process of transforming cherry coffee (ripe coffee) into green coffee (processed coffee) is known as beneficiation, which can be done either dry or wet [8,9]. In this process, one of the problems faced by producers is the large amount of husk and pulp generated. For every 1 kg of green coffee, it is necessary to process 6 kg of cherry coffee [10]. On the other hand, in wet processing, a large amount of water is used for washing, pulping, and mucilage removal processes, carrying a high concentration of organic material at the end of these steps [11]. Generally, the processing water goes through a filtration phase, with a part being recirculated for the process, another used in the fields for irrigation, and the remaining volume discarded in the rivers. The organic load generated in the post-harvest processing of coffee produced by wet means reaches values of up to 20,000 $mgO_2\ L^{-1}$ (in terms of biochemical oxygen demand) [12] and values between 15,000 and 25,000 $mgO_2\ L^{-1}$ (in terms of chemical oxygen demand) [13].

Figure 1 illustrates a flowchart of the wet processing process, emphasizing the residue produced at different stages of the process (such as pulp, mucilage, washing water, and parchment). The quantity of water involved can vary depending on the equipment used because, in certain instances, grain separation is achieved by exploiting the differences in grain density within the water. The most abundant residues generated during this process are pulp, mucilage, and washing water, with the latter accounting for the majority of the water used throughout the process and containing a significant amount of organic matter [14,15].

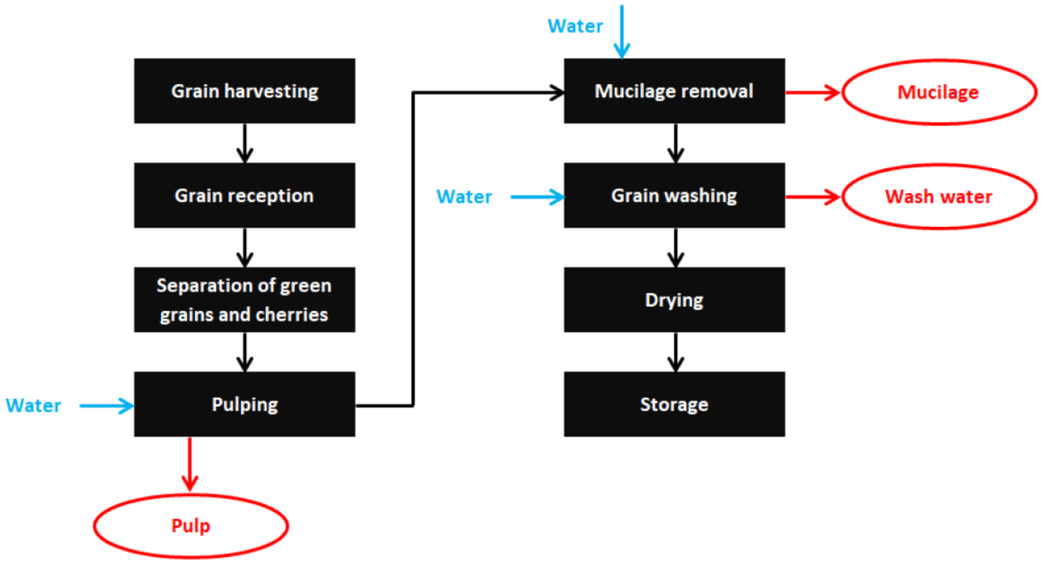

Figure 1. Flowchart of the wet coffee beneficiation step and the main residues generation.

Coffee processing residues can be treated through anaerobic digestion (AD) processes, reducing their polluting potential and using biogas to generate energy [16]. Among the advantages of anaerobic treatment are the high efficiency in the removal of organic matter, low energy consumption in the process, straightforward construction, production of gas (biogas) with high calorific value (methane—CH_4), and the use of the resulting digestate as a valuable fertilizer. In this case, the use of digestate has proven to be an effective mechanism for recycling nutrients within farms [17,18]. Fertilizer expenses have accounted for approximately 19% of overall operational costs in the coffee production sector in recent years [19]. Incorporating digestate into coffee plantations is a promising strategy for alleviating the financial burdens associated with farm agricultural operations.

The aforementioned benefits make biogas an appealing alternative for various agroindustrial sectors, particularly those that generate substantial waste volumes, such as the coffee industry [20]. The literature has documented the utilization of coffee production residues in biogas production. According to Corro et al. [21], when coffee pulp is mixed with cow manure in adequate proportions, it can generate biogas with a high CH_4 content (52%). According to Espinosa [22], biogas generation from coffee pulp in a Plug Flow Reactor (PFR) is an interesting process due to the amount of biogas obtained: 93.83 L of biogas per kg of coffee pulp, with 61% CH_4 content. Sossa [23] evaluated the production of biogas through semi-continuous AD of three residues from coffee processing (mucilage, pulp, and washing water) using a mixture of 90%, 3%, and 7%, respectively, and obtained biogas productivity of 0.81 m^3 $kgVS^{-1}$ with high CH_4 content (68%). Baêta et al. [24] reported yields between 90.89 and 127.52 NmL-CH_4 $gCOD^{-1}$ from coffee husk AD. Kivaisi and Rubindamayugi [25] obtained laboratory-scale CH_4 yields of 650 m^3 $tonVS^{-1}$ from coffee solid waste. Chala et al. [26] reported CH_4 yields from pulp and mucilage coffee of 244.7 and 294.5 L $kgVS^{-1}$, respectively. Nonetheless, additional research is required to gain a deeper understanding of biogas energy potential within coffee farms and its potential applications for fuel and energy generation. However, one of the major challenges in biogas production using coffee production residues is the off-season period, which lasts approximately six months in most of the Brazilian regions [27], resulting in a lack of substrates to feed the reactor for half the year. To maintain continuous biogas production on farms, integration with another waste stream through the anaerobic co-digestion process is necessary, enabling consistent biogas operation and energy generation. Among the potential waste streams that could be integrated, glycerin and even animal manure stand out, as both are liquid residues, simplifying the operation.

Glycerin is a byproduct from biodiesel production generated in a 1:1 ratio and is easily digestible. It can be stored for extended periods without compositional changes. These advantages make glycerin an ideal co-substrate for the AD process. The increased biogas production resulting from glycerin supplementation can contribute to a higher yield of valuable biofuel, all while utilizing a waste product that may require minimal modifications, potentially enhancing biogas production efficiency [28]. The literature demonstrates, for example, that the co-digestion of sewage sludge with glycerin achieved an 85 ± 5% reduction in volatile fatty acids (VFAs) and a methane (CH_4) production yield of approximately 0.8 L CH_4 per day [29].

Animal manure is rich in nitrogen, which can promote the nutritional balance of the reactor. It also contains microbiota from the animals' digestive tract that can contribute to enriching the anaerobic microbial community and provide the necessary buffering capacity [30]. In Aboudi et al.'s study [30], they achieved a CH_4 production of 9.91 L CH_4 per liter of reactor in the co-digestion of pig manure and dried sugar beet pellets (50:50 w/w).

Considering the energy potential that coffee waste can offer and keeping the biogas plant operating during the coffee off-season, this work evaluates the CH_4 production potential from mucilage and washing water of coffee in co-digestion with cattle manure and glycerin. The present study conducts a technical–economic evaluation of three different scenarios, taking into account the integration of coffee production residues with other residues (glycerin and animal manure). Scenario (S1): the thermal energy generated from the biogas burning; Scenario (S2): considers the electricity generation; and Scenario (S3): considers the replacement of LPG and diesel with biomethane.

2. Materials and Methods

2.1. Residue Characterization

Mucilage and washing water were collected from a farm located in the city of São Sebastião da Grama, state of São Paulo, Brazil. The farm beneficiation process is conducted mechanically using the wet method, with a recirculation system to reduce water consumption. Residue characterization was based on the chemical oxygen demand (COD) and solids series, including total solids (TS), total volatile solids (TVS), and inorganic ash [31]. The theoretical biogas potential was estimated from the residues generated from the coffee farm during the season based on their compositional characterization. The characterization of mucilage and washing water was, respectively, 35.7 kg COD m^{-3} and 12.5 kg COD m^{-3}; 28 kg TS m^{-3} and 5.3 kg TS m^{-3}; 25.3 kg TVS m^{-3} and 4.6 kg TVS m^{-3}; pH of 3.89 and 3.82. The input data for this investigation are summarized in Table 1, referring to data sourced from the literature. Because glycerol and manure were considered as alternative substrates, no field characterizations were carried out.

Table 1. Input data for the biogas potential estimation from the residues.

Parameter	Value	Unit	Reference
Farm			
Farm Area	257	ha	Santa Alina Farm
Productivity	19.45	Bags ha^{-1}	Santa Alina Farm
Harvest residue			
Mucilage/kg green coffee	540	mL	Dias et al. [32]
Wash water/kg green coffee	40	L	Sousa e Silva et al. [33]
Off-season residue			
COD glycerin	1.22	g COD g^{-1}	Theoretical value
COD cattle manure	0.135	g COD g^{-1}	Garcia et al. [34]
N cattle manure	0.017	g N g^{-1}	Duan et al. [35]

2.2. Biogas Production Calculations

The calculations for biogas production prospecting were conducted using data from the literature. A structured fixed bed reactor with a hydraulic retention time (HRT) of 24 h and an organic loading rate (OLR) of 15 kg COD m^{-3} d^{-1} were considered [36]. The reactor was designed (Equation (1)) to manage the total coffee residues generated in the season, and a 20% headspace was assumed.

$$V_r = \frac{Q \cdot S}{OLR} \tag{1}$$

where V_r is the useful volume of the reactor (m^3), Q is the volumetric flow rate fed to the reactor (m^3 d^{-1}), S is the concentration of substrate (kg COD m^{-3}), and OLR is the organic loading rate (kg COD m^{-3} d^{-1}).

The CH_4 production (BMP) from the AD reactor was calculated from the stoichiometry of the CH_4 formation reaction from 1 g of COD (0.35 NLCH_4 gCOD^{-1}) [37,38], also considering an average COD removal efficiency of 85%, represented by the biochemical methane potential (BMP). The operating temperature was set at 20 °C, consistent with the ambient temperature of the study region. The residues were assumed to be diluted with water at the entrance of the reactor, water that would be recycled during the entire reactor operation.

A COD/N ratio of 200/1 was assumed at the reactor inlet in order to prevent inhibition of the AD process by excess ammonia [38]. Thus, the amounts of substrates fed to the reactor during the coffee off-season (glycerin and cattle manure) were determined according to Equations (2) and (3).

$$COD_r = COD_{s1} + COD_{s2} \tag{2}$$

$$\dot{m}_i = S_i \cdot Q \tag{3}$$

where COD_r is the chemical oxygen demand of the reactor, COD_{s1} is the chemical oxygen demand of substrate 1, and COD_{s2} is the chemical oxygen demand of substrate 2; $\dot{m}_i$ is the mass flow rate for each substrate (kg d^{-1}), S_i is the mass concentration of each substrate (kg m^{-3}), and Q is the volumetric flow rate at the reactor inlet (m^3 d^{-1}).

2.3. Energetic Assessment Scenarios

Three scenarios of biogas (75% CH_4) uses were assessed based on the estimated CH_4 production per year (in the season, coffee residues—mucilage and wash water—were utilized, while during the off-season, glycerin and manure were employed) from the coffee farm biogas plant: thermal energy (S1), electricity (S2), and biomethane (S3). The input data are shown in Table 2. In all scenarios, the use of digestate to replace synthetic fertilizer was considered.

- Scenario (S1): based on the replacement of eucalyptus firewood—which is currently used for the grain drying stage—by the thermal energy (Equation (4)) generated from the biogas burning.

$$TE = Q_{biogas} \cdot LHV_{biogas} \cdot \eta_{TE} \quad (4)$$

where TE is the thermal energy (MJ year^{-1}), Q_{biogas} is the volumetric flow of biogas (m^3 year^{-1}), LHV_{biogas} is the lower heating value of biogas, and η_{TE} is the conversion efficiency for thermal energy.

- Scenario (S2): considered the electricity generation (Equation (5)) to supply household consumption and the coffee processing process by using an Internal Combustion Engine (ICE).

$$EE = Q_{biogas} \cdot LHV_{biogas} \cdot \eta_{EE} \quad (5)$$

where EE is the electric energy (kWh year^{-1}) and η_{EE} is the conversion efficiency for internal combustion engines.

- Scenario (S3): considered the replacement of LPG and diesel used in the coffee processing process and the agricultural operations in the farm by biomethane (Equation (6)) (purified biogas).

$$P_{CH_4} = BMP \cdot COD_{rem} \cdot \eta_{rem} \quad (6)$$

where P_{CH_4} is the biomethane production (m^3 d^{-1}), BMP is the theoretical biomethane potential (m^3 CH_4 kg COD^{-1}), COD_{rem} is the removal of COD (kg COD d^{-1}) and η_{rem} is the removal efficiency. Figure 2 shows the coffee farm biogas plant scheme, indicating the substrates fed to the reactor in the coffee season and off-season, respectively, as well as the three scenarios related to the biogas applications. For all scenarios, cleaning the biogas to remove moisture and sulfur should be considered, mainly to prevent damaging the equipment used in energy conversion, whether thermal or electric.

Table 2. Input data for the scenarios assessment considering thermal and electric energy and biomethane production in the coffee farm biogas plant.

Parameter	Value	Unit	Reference
Methane LHV	35.9	MJ m^{-3}	Henríquez [39]
Methane density	1.2	kg m^{-3}	Al Seadi et al. [40]
Biogas LHV (75% CH_4)	28	MJ m^{-3}	IEA [41]
Firewood LHV	13.0	MJ kg^{-1}	Cardoso Sobrinho et al. [42]
TE conversion efficiency	82.5	%	Hakawati et al. [43]
ICE Efficiency	35	%	Hakawati et al. [43]
Diesel LHV	42.5	MJ kg^{-1}	Ying et al. [44]
LPG LHV	46.44	MJ kg^{-1}	ANP [45]

LHV: lower heating value; TE: thermal energy; ICE: internal combustion engine; LPG: liquefied petroleum gas.

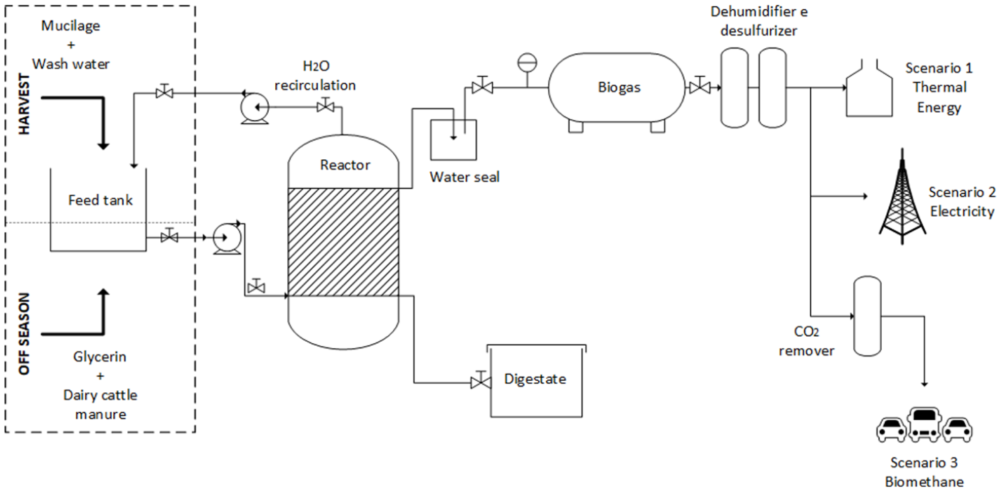

Figure 2. Scheme of the coffee farm biogas plant, considering the AD operation during the coffee season and off-season, and the biogas using assessed scenarios.

2.4. Economic Assessment Scenarios

The economic assessment was carried out for the three proposed scenarios in order to verify the project feasibility according to the biogas uses. The equipment investment values for the biogas plant implementation are shown in Table 3. The values were updated for the reference period of June/2023 using the Consumer Price Index (*CPI*) (Equation (7)) with a conversion rate of USD 0.20 per Brazilian Real (BRL).

$$Value_t = Value_0 \cdot \frac{CPI_t}{CPI_0} \tag{7}$$

Table 3. Input values for the implementation of the coffee biogas plant.

Phase	Equipment	Detail	Units	Value (USD) *	Reference
Biogas Generation (S1, S2, S3)	Feed tank	HDPE material (435 m^3)	1	12,525	Daniel [46]
	Structured fixed-bed reactor	Reinforced concrete material (579 m^3)	1	339,291	Fuess et al. [47]
	Support material	Polyurethane	23.1 m^3	5388	Fuess et al. [47]
	Digestate tank	HDPE material (1 m^3)	1	280	Daniel [46]
	Pump	Centrifugal	2	3884	Souza [48]
	Pump	Dosing	1	1509	Fuess et al. [47]
	Valves	Guillotine	7	663	Daniel [46]
	Gasometer (biogas tank)	PVC material (2800 m^3)	1	37,246	Daniel [46]
	Water seal	Stainless steel material	1	2415	Fuess et al. [47]
	Gas meter	-	1	137	Daniel [46]
Biogas cleaning (S1, S2, S3)	Dehumidifier + Desulfurizer	Molecular sieve	1	580	Daniel [46]
EE Generation (S2)	Compressor	10 bar	1	405	Daniel [46]
	Internal Combustion Engine—ICE	Efficiency between 25 and 35%	1	4801	Daniel [46]
Biogas purification (S3)	PSA purification	Compression, PSA purification, and supply	1	76,330	Daniel [46]

* Values were taken from Daniel [46], Fuess et al. [47], and Souza [48] and recalculated considering a scale factor of 0.65 [49]. The values were updated for the reference period of June 2023 with a conversion rate of USD 0.20 per BRL.

Table 4 presents the parameters and assumptions applied for the economic indicators calculation: net present value (NPV), internal rate of return (IRR), and discounted payback. Moreover, Table 4 presents the percentages of sales tax, income tax, and social contributions (IRPJ and CSLL in Portuguese). To obtain the NPV, IRR, and discounted payback, the free and discounted cash flows were calculated based on the parameters described in Table 4.

Table 4. Parameters considered in the economic evaluation.

Parameter	Value	Unit	Reference
Plant lifespan	25	year	Fuess et al. [47]
Investment in civil works and equipment	20 [a]	%	Assumed value
Working capital	10 [b]	%	Fuess et al. [47]
Minimum acceptable rate of return (MARR)	14	%	Souza [48]
Operation and maintenance	3 [c]	%	Fuess et al. [47]
sales tax	18	%	Assumed value
IRPJ + CSLL	34 [d]	%	Dias et al. [50]
Depreciation rate (linear, 10 years)	10	%	Fuess et al. [47]

[a] Additional investment costs for civil works and equipment (percentage of the initial investment in equipment). [b] Percentage of fixed investment. [c] Annual operation and maintenance cost (percentage of the fixed investment, including transport logistics). [d] Percentage of net income. IRPJ: Imposto de Renda de Pessoa Jurídica (Corporate income tax); CSLL: Contribuição Social sobre o Lucro Líquido (Social Contribution on Net Income).

Table 5 presents the specific saved costs in each scenario, according to the biogas uses. The energy surplus of each scenario was assumed to be sold either as electricity or biomethane. It is important to note that biomethane has not yet been priced, being valued by allocation according to the price of the replaced fuel.

Table 5. Input values adopted for the saved costs calculation according to the scenarios.

Scenario	Item	Value	Unit	Reference
S1—Thermal energy generation	Firewood to be replaced	11.20	USD/m^3	Simioni et al. [51]
	EE for sale (surplus)	0.08	USD/kWh	MME [52]
S2—Electricity generation	Network EE (household economy)	0.16	USD/kWh	MME [53]
	Network EE (process economy)	0.14	USD/kWh	MME [53]
	EE for sale (surplus)	0.08	USD/kWh	MME [52]
S3—Biomethane	LPG to be replaced	1.20	USD/kg	MME [53]
	Diesel to be replaced	0.75	USD/L	MME [53]
	CNG for sale (surplus)	0.67	USD/m^3	ANP [54]
	CBio *	6.47	USD/CBio	ANP [55]
All scenarios	Synthetic fertilizer to be replaced	20,64	USD/bag	CONAB [56]

* CBio: decarbonization credits traded on the stock exchange in accordance with the Biofuels National Policy, RenovaBio [57]. EE: electric energy; LPG: liquefied petroleum gas; CNG: compressed natural gas.

For each scenario, a sensitivity analysis of NPV, IRR, and discounted payback was carried out concerning the variation of investment costs, EE prices for consumption and sale, prices of fuels such as diesel, LPG, and CNG, and Cbio prices. The analysis was performed considering variation levels of 20% for each case.

3. Results

Considering the management of 100% of mucilage and washing water during the coffee season, the CH_4 production would reach 2080 m^3 d^{-1} (Table 6), corresponding to 297 L-CH_4 kg^{-1}-COD_{rem}. The difference in the substrate flow rate was due to the higher amounts of washing water used in the coffee bean processing. The washing water AD treatment from coffee processing was reported by Selvamurugan et al. [58] and Puebla et al. [59] as 261 L-CH_4 kg^{-1}-$COD_{removed}$ and 146 L-CH_4 kg^{-1}-COD_{rem}, respectively, lower values than those estimated in this work. The substrate's co-digestion (washing water and mucilage) adopted in the current work resulted in the highest CH_4 productivity.

Table 6. Substrate feeding flows and CH_4 production in season and in the off-season.

Parameter	Value	Unit
Reactor		
Total volume	579	m^3
Operating time	360	day
Methane production	2080	m^3 d^{-1}
Season flows		
Mucilage	1.8	m^3 d^{-1}
Washing water	133	m^3 d^{-1}
Off-season flows		
Cattle manure	1950	kg d^{-1}
Glycerin	5123	kg d^{-1}

Based on the reactor sizing during the coffee season, the same reactor volume was set up for the off-season, resulting in the mass flow of glycerin and cattle manure, as depicted in Table 6. These values ensure the operation of the reactor throughout the year. Given the calculated size and daily methane flow, and combining season and off-season production, it is possible to generate 250 thousand m^3 of biogas per year.

It is important to note that only the reactor mass balance was considered, disregarding the substrate's rheology. This would require a deeper study to assess the substrate's viscosity, especially glycerin, which could present some problems such as clogging or difficulties in agitation. According to Yang et al. [60], it is feasible to use an anaerobic fixed bed reactor for the CH_4 production under thermophilic conditions with a yield of 450 L-CH_4 kg^{-1}-glycerin using an OLR at 0.7 kg COD m^{-3} d^{-1}.

Figure 3 shows the energy balance of the coffee farm biogas plant for the assessed scenarios, based on the CH_4 potential from the AD reactor operating during the year (coffee season and off-season) and considering the respective biogas applications. Table 7 presents the results of each economic indicator analyzed, initial investment, NPV, IRR, and discounted payback, for each proposed scenario. Figure 4 shows the investment cost for each component in all scenarios. Figure 5 presents a sensitivity analysis for NPV, considering that fluctuations in certain costs could potentially render the scenarios economically better or not. Figure 6 presents the same sensitivity analysis as in Figure 5, but this time for the IRR indicator.

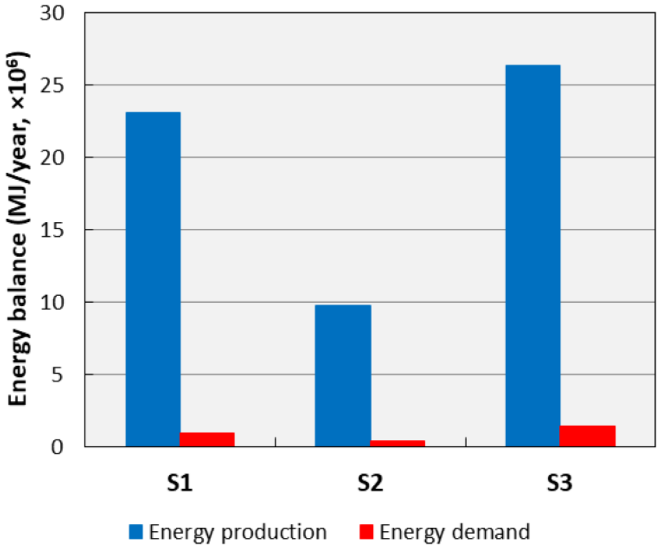

Figure 3. Energy balance according to the biogas uses in each Scenario—S1: demand for firewood and TE (thermal energy) production from biogas; S2: electric energy demand from the grid and EE (electric energy) production from biogas; S3: demand for CNG and LPG and biomethane production.

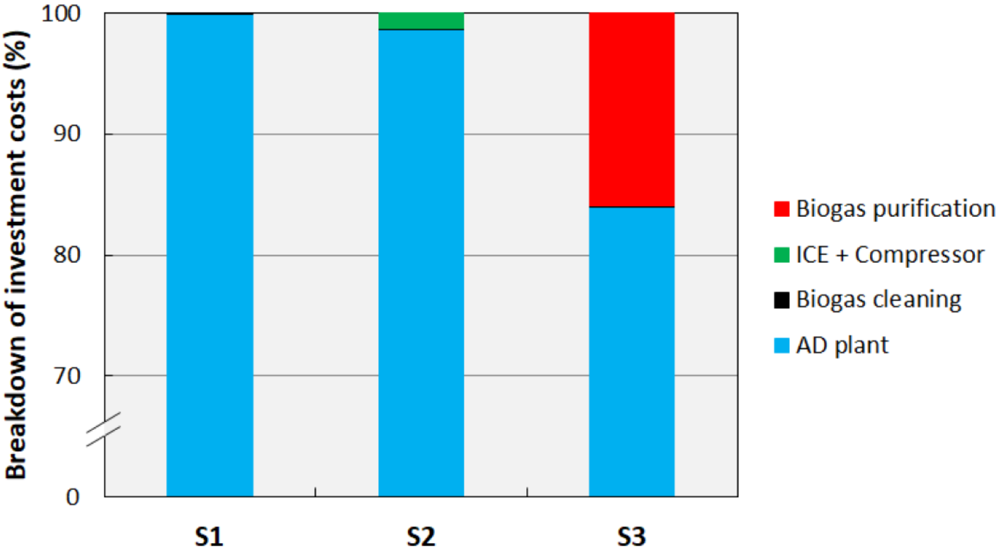

Figure 4. Investment cost by each component.

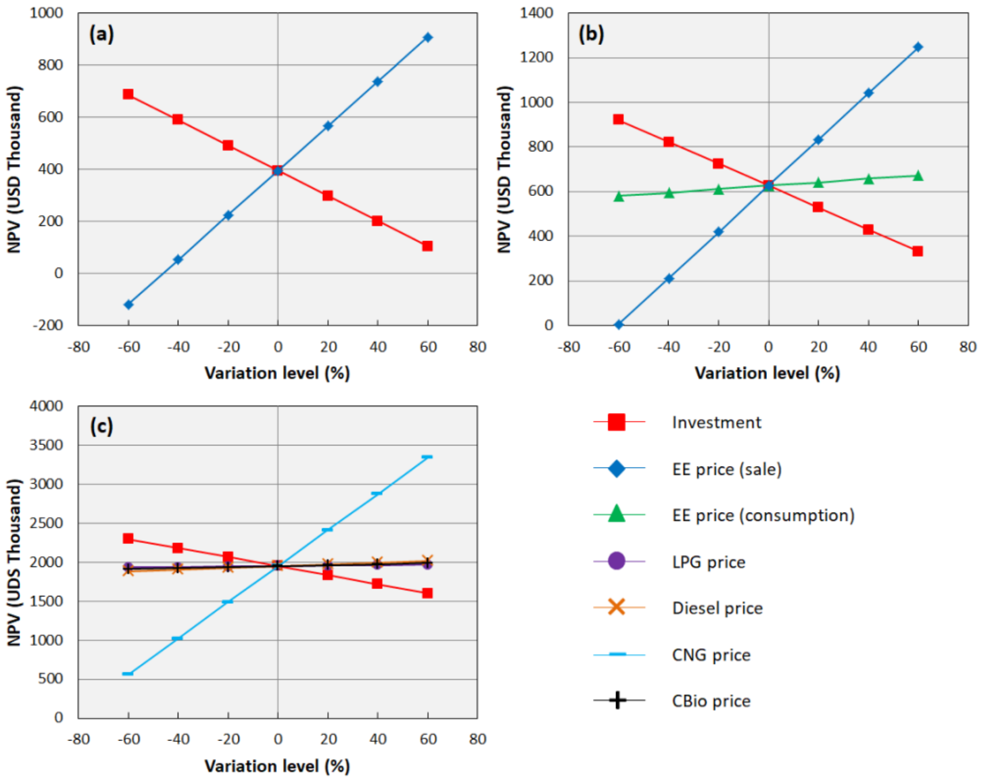

Figure 5. Sensitivity analysis of the net present value (NPV): (**a**) S1: variation of investment costs and EE sale; (**b**) S2: variation of investment costs, EE consumption, EE sale; (**c**) S3: variation of investment costs, consumption prices, Diesel, LPG, and CNG prices, CBio prices.

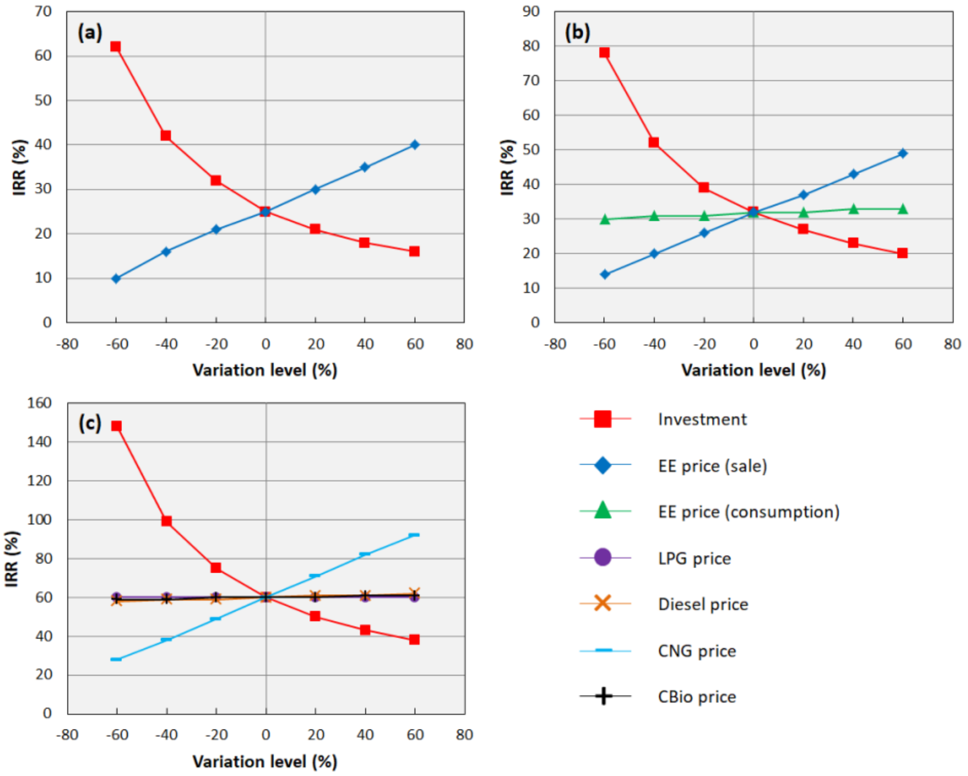

Figure 6. Sensitivity analysis of the internal rate of return (IRR): (**a**) S1: variation of investment costs and EE sale; (**b**) S2: variation of investment costs, EE consumption, EE sale; (**c**) S3: variation of investment costs, consumption prices, Diesel, LPG, and CNG prices, CBio prices.

Table 7. Economic performance of scenarios.

Economic Indicator	S1	S2	S3
Initial investment	USD 525,093	USD 531,861	USD 624,322
NPV	USD 395,014	USD 626,577	USD 1,950,517
IRR	25%	32%	60%
Discounted payback	6 years and 2 months	4 years and 6 months	2 years and 1 month

NPV: net present value; IRR: internal rate of return.

4. Discussion

4.1. Energy Assessment

The results showed (Figure 3) that the total energy provided by the biogas uses would far exceed the specific energy demand for all the scenarios. For S1, the thermal energy generated by the biogas burning could supply the dryers used in the last stage of coffee processing during the season: 3.2 MJ kg^{-1}-green coffee is demanded for this process [61], resulting in the demand of 960,000 MJ per year for the grain drying stage in the current study. This value represents only 4% of the total thermal energy generated from biogas, and thus, a surplus of 22,099,755 MJ would be available for other uses. In practical terms, the energy generated could supply a farm's production chain with a capacity that is roughly 23 times larger than the one under study. Apart from the considerable biogas production amount, the energy equivalence between the boiler's furnace fuels (in terms of LHV) indicated that the grains drying stage could be more efficient with biogas: LHV_{biogas} is 2.3-fold higher than $LHV_{firewood}$. Additionally, the replacement of eucalyptus firewood with biogas could contribute to preventing deforestation [62] on occasions when logging may occur illegally.

In the case of S2, the electric energy generated from biogas could annually supply 30 residences in the coffee farm workers' colony, considering the average energy consumption in Brazilian households (reference year: 2020) of 173 kWh $month^{-1}$ [63]. Additionally, the coffee farm's beneficiation process's electrical requirements could also be fully met. Similar to S1, a surplus electricity of 96% could still be sold in order to generate additional revenue in the current scenario. Compared with other agroindustrial sectors, Ferraz Junior et al. [64] reported average values for electricity generated from biogas in a sugarcane plant, reaching 0.015 MWh per sugarcane ton, being lower than the value obtained in this study with 0.6 MWh per green coffee ton.

Scenario S3 showed that the potential exists to refine the produced biogas into biomethane, which can serve as a domestic cooking gas in the colony's residences or as a fuel source for the farm's fleet of harvesters and trucks, thereby addressing the third scenario encompassing LPG and diesel replacement. The average fuel consumption at the coffee farm stands at 16.25 kg LPG $Household^{-1}$ $Month^{-1}$ [65], with the total demand required by the 30 households being 271,674 MJ $year^{-1}$. With the results of the present study, it is possible to generate 47,266 kg LPG $Month^{-1}$, sufficient to supply approximately 2908 households, if the gas was solely used to supply households. Diesel consumption arises from the operation of agricultural machinery and transportation activities during the coffee harvest, amounting to 0.094 kg per kilogram of green coffee [66], equivalent to a total demand of 1,198,500 MJ $year^{-1}$. As depicted in Figure 3, the biomethane generated through this process could meet the diesel demand (1,198,500 MJ annually), resulting in a surplus that can meet the energy needs of the 30 households annually. Taking into account both the use of gas for households and the fleet's needs, a total of 1,470,174 MJ per year would be utilized, yielding a surplus of 24,870,355 MJ per year (94% biomethane energy surplus) that can be injected into the natural gas grid. Comparing the LHV of different fuels is crucial for assessing their energy efficiency. The LHV of LPG and diesel are 46.4 MJ kg^{-1} and 42.2 MJ kg^{-1} [45], respectively, being higher than the LHV of biomethane which has a value of 30 MJ kg^{-1}. This suggests that biomethane is not as energy efficient, but it generates a lower environmental impact by compensating for this energy difference. Moraes et al. [67] indicated the potential to replace 40% of the diesel used in agricultural machinery in the sugarcane agroindustry and, according to Ferraz Junior et al. [64], the potential for biogas production by sugarcane plants and landfills in the State of São Paulo can replace up to half of the diesel consumed in the state. These data corroborate the importance of replacing fossil fuels such as diesel in Brazil with biomethane.

Considering all the scenarios, it is apparent that the farm's total energy demand could be met with surplus energy to be traded. This opens up the possibility of integrated simultaneous generation of thermal energy, electric energy, or biomethane tailored to the primary requirements of the coffee processing and the farm itself. Although the energy assessments were considered for the entire year, it should be noted that S1 and S3 hold particular appeal during the harvest period when coffee beans are being dried and machinery consumes more diesel. S2, on the other hand, remains attractive year-round, as electricity consumption in the colony's households is constant. In all scenarios, a valuable byproduct produced is the digestate. It is worthwhile to contemplate substituting synthetic fertilizers with the digestate obtained from the AD process during the off-season, particularly because this period corresponds to the primary fertilization season. Coffee farm soil needs 250 kg ha^{-1} year^{-1} of N [68], and crop needs depend on productivity during the season, with some crops requiring a higher nitrogen addition compared to others. For the calculations, the value of nitrogen generated during the entire off-season period was considered, supplying approximately 4% of the demand for synthetic fertilizers. It is worth mentioning that along with N, the digestate has several other important nutrients for the soil that can be used.

The importance of biogas and its energy versatility in all scenarios is highlighted, especially when purifying biogas to obtain biomethane. There is an additional process that requires an investment, but that makes the biofuel acceptable according to the regulations required in Brazil, and that can have a greater return on its sale.

4.2. Economic Assessment

According to the results (Table 7), all scenarios presented a positive NPV and IRR higher than the minimum acceptable rate of return MARR 14%, which makes scenarios feasible for this work. S3, despite having the highest initial investment due to the added biogas purification step compared to the other scenarios, exhibited a positive NPV and IRR of 60%, signifying the project's feasibility as well. It is crucial to underscore that the viability of the third scenario hinges solely on biomethane sales, with the study factoring in the installation of a biomethane microstation for distribution.

When examining the allocation of resources within the initial investment for each scenario (as depicted in Figure 4), it becomes evident that the anaerobic digestion plant represents the largest share in all scenarios. This can be attributed to the reactor type selected and the prevailing technology costs. Brazil's heavy reliance on imported technologies contributes to these elevated expenses, which may render certain projects financially unviable.

For S1 and S2 (Figure 5), it is evident that variations in initial investment, mainly the biodigester installations, and in the electricity price had a huge impact on economic viability. For instance, in S1, if the electricity price is 40% lower than initially proposed, the NPV turns negative. In the case of S3, if the prices of CBIo, diesel, and LPG change, few alterations will be observed in relation to the NPV. However, CNG has a significant impact on the NPV if its value is reduced, probably resulting in a negative NPV. This suggests that in this scenario, it may not be as viable to use biomethane and instead opt for CNG, particularly when its consumption cost is lower. In the case of CBio, there are interesting incentives for renewable energy projects, but in this work, such credits did not greatly influence the economic results.

The same logic observed for NPV applies to IRR as well (Figure 6). In S1, it is evident that an increase in the value of EE sales leads to an increase in IRR, and when the initial investment costs decrease, IRR also increases. This pattern is repeated in S2, and it is notable in S3 that IRR increases with a reduction in initial investment values, which include the reactor price. The third scenario shows a lower sensitivity to changes in CNG prices and almost nothing to changes in diesel, LPG, and CBio prices. Comparing the two sensitivity analyses confirms the importance of the costs of the technology for AD, being the main factor contributing to the viability of projects that seek energy self-sustainability and promote the decarbonization goals in Brazil.

4.3. Brazil's Biogas Potential: Investment Opportunities and Growth Prospects

It was demonstrated through sensitivity analyses that if certain factors are varied, particularly related to the initial investment in biogas plant construction and, more significantly, the value of the reactors, these scenarios become more economically attractive, with a strong emphasis on the application of gas as biomethane or LPG (always emphasizing the consideration of the distance from the anaerobic digestion plant to the gas pipeline). In this context, Brazil has been working with various political and economic incentives to enhance the structural quality of biogas plants, leading to pricing structuring possibilities and consequent economic viability. Brazil is stimulating the implementation of new projects for biogas and biomethane. According to ABIOGAS [69], the target for 2030 is the production of 30 million m^3 CH_4 with an investment of USD 950 million per year, considering a reduction of at least 30% of CH_4 emissions in Brazil signed at COP26. The Climate Fund (Fundo Clima), linked to the Ministry of the Environment (MMA), is currently the main tool that BNDES has to finance the biogas sector, most of which are for electricity distribution with a minimum financing amount of USD 1.9 million, reaching a maximum of USD 15.2 million [69]. MMA also launched in March 2022 the Zero Methane Program, which focuses on energy use and fuel from waste or organic products as sources of biogas and biomethane [70]. Small and big rural and urban projects are pushed through the program, allowing rural producers and landfill managers to become suppliers of fuel and renewable energy, among other excellent environmentally strategic prospects. Specific lines of credit and financing from public and private financial agents can provide good chances for the growth of actions and activities, including, for instance, biogas production in coffee processing farms.

Currently, Brazilian companies are increasing their proposals with renewable energy to enter the Brazilian Emission Reduction Market (MBRE), determined to invest in the biogas or biomethane market. This market showed a 15%-growth in the last year, with 45 plants connected to the grid; in addition, ethanol can replace 48% of the gasoline consumed in the country. Cities such as São Paulo and Rio de Janeiro currently lead the production of biomethane in Brazil, with installed production capacities close to 200,000 m^3 day^{-1} [69].

Among some examples in operation in Brazil is the attractive biogas plant for renewable energy located in Guariba, São Paulo. The project had an investment of USD 29.07 million and 153,100 m^2 of built area. The plant treats more than 5 million tons of sugarcane per year. Vinasse is used as a substrate for the harvest period and the filter cake for the off-season, producing biogas on a commercial scale of 138,000 MWh per year, of which 96,000 MWh were traded in a bioenergy auction in 2016 [71].

On the other hand, the replacement of diesel with biomethane for use in buses in a pilot scale began with the initiative of the Haacke poultry farm in the state of Paraná. The farm produces large amounts of manure, generating a total of 960 m^3 of biomethane per day, capable of supplying a bus with a capacity of 120 passengers [72].

According to studies by EPE [73], taking as a reference a biomethane plant with a production of 25,000 Nm^3 day^{-1}, the estimated investment, operating, and maintenance costs between 2020 and 2030 (Capex) and considering the processing to obtain biomethane will be USD 3.61 billion, while the Opex will reach USD 2.66 billion. This means that later projects, such as the one proposed in this work, may be of interest to some companies associated with the sector, bringing investment and public–private partnerships, continuing to focus on clean energies, thus contributing to the reduction of dependence on fossil fuels.

Integrating the coffee sector through cooperatives that can divide the investment cost so that all residues from the farms can be processed together is another option to reduce implementation costs. Among the main advantages is the shared investment for the projects and the use of all the energy produced.

4.4. Coffee Farms Integration with Agroindustrial Eco-Park

The energy use assessment of biogas in coffee farms revealed the challenges in developing biogas plants with continuous and profitable production due to the short harvest period of the culture. This leads to seasonal waste generation, which can cause interruptions in the anaerobic reactor, resulting in low efficiency or perhaps rendering the process technically impractical. This analysis can be the starting point for a wider agroindustrial integration, emphasizing the importance of the application of agroenergy, which provides the possibility of the absolute use of biomass, adds value, reduces environmental liabilities, and increases social benefits [74,75]. This integration model consists of an industrial symbiosis focused on the Brazilian context: an Agroindustrial Eco-Park.

This innovative integration model comes from a more traditional and comprehensive concept known as an Eco-Industrial Park (EIP), which consists of delimited regions where groups of companies cooperate with local communities, sharing resources to reduce waste and pollution and increase environmental quality and economic gains, to stimulate sustainable development. This concept was first outlined in 1989 by Frosch and Gallopoulos [76], who envisioned an industrial ecosystem to optimize the flow of resources by the reuse of waste from one process as a raw material for another process. According to the United Nations Industrial Development Organization (UNIDO), the definition of EIPs was given as "a tract of land that is developed and subdivided into plots according to a comprehensive plan that makes provision for roads, transport and public utilities for the use of a group of firms and industrial business-oriented activities carried out in the park". EIPs are in the area of industrial ecology, based on the symbiosis between industries that traditionally would operate separately, but they engage in collectivity in this approach, aiming at a competitive advantage through the exchange of materials, energy, residues, and/or byproducts [77]. The key to industrial symbiosis lies in the collaboration and possibilities of synergism offered by geographical proximity [78].

Other successful examples of EIPs that have emerged are concentrated in developed countries such as Puerto Rico, USA [79], Rotterdam Harbor and Industrial Complex, The Netherlands [80], United Kingdom [81], Kwinana and Gladstone, Australia [82] and Guigang, China [83]. Although the Kalundborg prototype has encouraged the creation of more EIPs around the world, several challenges regarding the identification, evaluation, and implementation of potential symbioses have been confronted by many national EIP programs that could easily be overcome by adopting innovative strategies and working in collaboration [84].

Considering the Brazilian scenario, the extension of the EIP to the perspective of Agroindustrial Eco-Parks makes sense, as the agroindustry plays an important role in the country, accounting for ca. 28% of the Gross Domestic Product (GDP), more than 20% of all employment and almost 50% of exports, with China (37%) and the European Union (15%) as the major importers [85,86]. The importance of Brazilian agribusiness was felt during the period of the COVID-19 pandemic, with the country's economic growth (5.2%) close to the world growth forecast by the International Monetary Fund (IMF) for 2021 (5.9%) [86,87]. While several sectors of the Brazilian economy retracted, the "agrosector" grew by 0.6% in 2020 [86]. Brazil is a strategic global player, exporter, and producer of key agribusiness value chains such as sugarcane and ethanol, oilseed and grains complex, coffee, orange juice, and animal protein, which is the first or highly ranked in the international market. The leading role in the efficiency of this sector was due to investment in technology in the field, modernization of companies, governance gains, best ESG (environmental, social, and governance) practices, and, finally, better access to third-party capital. According to the latest agricultural census, agricultural establishments occupy 41% of the national territory: 72 million hectares from small producers and 52 million hectares from big agro-establishments [88]. The favorable environmental conditions and the availability of cultivable land allow Brazil to have a natural vocation for this sector, although some challenges still need to be overcome to reach full exploitation, such as infrastructure and logistics, deficient management skills, greenhouse gas (GHG) emissions, and energy efficiency of the system. Great opportunities can be seen in the biotechnology field to leverage growth shortly, following the adopted model of agricultural development based on science: a worldwide tendency to be valued as leading technology.

Bringing this concept to the present work, Figure 7 illustrates the potential exchange of residue, energy, and the recirculation of water by the most common industries around the coffee farm (in a radius of 30 km). In addition to the waste considered in this study, alternative waste integration options are also presented, taking into account the proximity of other agricultural activities in the vicinity of the coffee farm area under investigation. For this, an analysis of agricultural activities was carried out based on the study performed by the Secretary of State for Agriculture, Livestock and Supply of Minas Gerais (SEAPA) [89]. The agroindustrial sector that most moves the region is of animal origin (beef, swine, and poultry). Therefore, these agroindustries that present large amounts of residue were placed in the hypothetical Agroindustrial Eco-Park. Several residues are generated from poultry farming, with an annual slaughter of 104,300 birds in the region. Swine farming contributed around 1700 animals, and cattle farming has a maximum of 683,000 animals. The inadequate form of disposal of generated residues by these industries allows the presence of a high load of polluting nutrients in the environment [90].

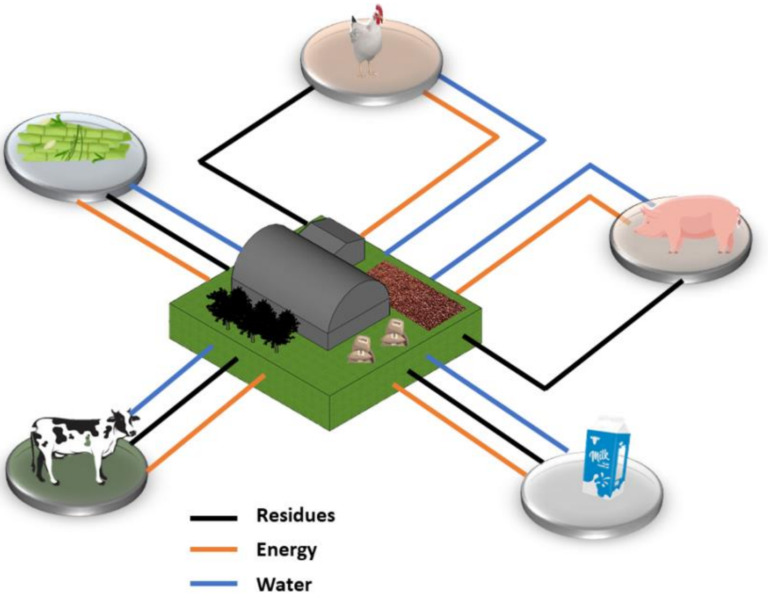

Figure 7. Schematic representation of a potential Eco-Park applying the coffee farm biogas unit as the hub of the agroindustrial integration.

In addition, in the study area, a dairy factory was found around the farm, which could supply residues such as anaerobic sludge and whey for energy generation: these residues are attractive due to their organic load and amount produced. According to the Ministry of Agriculture, Livestock and Supply, Brazil has the largest production of whey, with 2.7 million tons per year, and this substrate could be processed through AD [91]. On the other hand, the production of sugarcane is distributed throughout the Minas Gerais territory and is one of the main crops in the country with the greatest opportunities for the generation of renewable energy. This industry could exchange residues within the Agroindustrial Eco-Park, such as filter cake and vinasse, to speed up the biodigester process, taking advantage of the high processing of 64.8 thousand tons of sugarcane for the Minas Gerais sector [92]. Around 5860 million m^3 of biogas per year could be generated from the integration of these residues (Table 8), meaning an energy gain of 5859 million m^3 of biogas compared to the scenario proposed in this study (coffee, cattle manure, and glycerin).

Table 8. Biogas potential in the proposed Eco-Park.

Agroindustrial Sector	Biogas Production Factor *	Unit	Estimated Biogas [m^3]
Poultry	0.00194	m^3 animal^{-1}	202
Swine	1.52	m^3 animal^{-1}	2584
Cattle	8.73	m^3 animal^{-1}	5,962,590
Whey	0.8	m^3 m^{-3}-processed milk	76,000
Sugarcane—vinasse	17.68	m^3 m^{-3}-processed sugarcane	1,013,861,947
Sugarcane—filter cake	84.41	m^3 ton^{-1}-crushed sugarcane	4,840,502,655

* The biogas production factor values were taken from Instituto 17 [93].

Within the concept of the Agroindustrial Eco-Park and concerning the current study, the main idea proposed is to integrate the coffee farm with the soybean farm, which produces biodiesel, and cattle farms for the utilization of manure. However, since these regions are favorable for agroindustries, other agricultural sectors can be integrated into this business model. Furthermore, within this concept and considering new sector integrations to make scenarios S1 and S2 more favorable, the implementation of new waste materials such as vinasse, filter cake, and waste from wine and poultry could help increase CH_4 production, consequently offsetting the CAPEX expenses related to the construction of the biogas plant. This allows for the integration of different sectors through the treatment of their waste materials, generating value-added products for all to benefit from, such as electricity, biomethane, thermal energy, and digestate as fertilizer.

Finally, the prospects of an Agroindustrial Eco-Park with energy purposes would be viable to mitigate environmental degradation and improve the treatment of the large amount of residue generated. In addition, obtaining energy for use in some processing stages of each industry and the recirculation of water always aim at optimizing the use of resources. It is worth mentioning that other factors that interfere, such as the supply and demand of each product of interest, the logistics of collection and transport, and current environmental legislation, among others, should be evaluated, but that would be an option at a macro level to contribute to cost reduction and environmental sustainability.

5. Conclusions

This work highlights that producing biogas from coffee residues is highly advantageous for farms, as it can meet all energy demands. The utilization of residues from other agricultural activities, such as glycerin and animal manure, gave all scenarios proposed in this study both energy and economic advantages, signifying the potential for industrial symbiosis through biogas utilization and energy harnessing. The factor to highlight is the strong dependence on the electric energy price variation to bring economic feasibility. It is noteworthy that biomethane could bring profitability by selling it and contribute to the replacement of fossil fuels such as diesel and LPG. Finally, the Agroindustrial Eco-Park (AEP) proposal might be promising in the context of coffee farms as it would allow the integration of other surrounding agroindustries to exchange energy, residues (substrates), and water recirculation, applying the concept of a circular bioeconomy. Considering the hypothetical AEP proposed, a 5859 million m^3 per year increase in bioenergy production could be achieved with the integrated use of waste to biogas beyond the border of coffee, livestock, and biodiesel production units.

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