methane

Article

Techno-Economic Assessment of On-Site Production of Biomethane, Bioenergy, and Fertilizer from Small-Scale Anaerobic Digestion of Jabuticaba By-Product

William Gustavo Sganzerla *, Rafael Gabriel da Rosa, Tiago Linhares Cruz Tabosa Barroso, Luiz Eduardo Nochi Castro and Tânia Forster-Carneiro *

School of Food Engineering (FEA), University of Campinas (UNICAMP), Campinas 13083-862, SP, Brazil
* Correspondence: sganzerla.william@gmail.com (W.G.S.); taniafc@unicamp.br (T.F.-C.)

Abstract: Bioenergy recovery from biomass by-products is a promising approach for the circular bioeconomy transition. However, the management of agri-food by-products in stand-alone treatment facilities is a challenge for the low-capacity food processing industry. In this study, the techno-economic assessment of a small-scale anaerobic digestion process was evaluated for the management of jabuticaba by-product and the production of biomethane, electricity, heat, and fertilizer. The process was simulated for a treatment capacity of 782.2 m^3 y^{-1} jabuticaba peel, considering the experimental methane production of 42.31 L CH_4 kg^{-1} TVS. The results of the scaled-up simulated process demonstrated the production of biomethane (13,960.17 m^3 y^{-1}), electricity (61.76 MWh y^{-1}), heat (197.62 GJ y^{-1}), and fertilizer (211.47 t y^{-1}). Economic analysis revealed that the process for biomethane recovery from biogas is not profitable, with a net margin of −19.58% and an internal rate of return of −1.77%. However, biogas application in a heat and power unit can improve project feasibility, with a net margin of 33.03%, an internal rate of return of 13.14%, and a payback of 5.03 years. In conclusion, the application of small-scale anaerobic digestion can prevent the wrongful open-air disposal of jabuticaba by-products, with the generation of renewable energy and biofertilizer supporting the green economy toward the transition to a circular economy.

Keywords: biogas; process design; process simulation; heat and power unit; co-generation; electricity; heat; circular economy; biorefinery

Citation: Sganzerla, W.G.; da Rosa, R.G.; Barroso, T.L.C.T.; Castro, L.E.N.; Forster-Carneiro, T. Techno-Economic Assessment of On-Site Production of Biomethane, Bioenergy, and Fertilizer from Small-Scale Anaerobic Digestion of Jabuticaba By-Product. *Methane* **2023**, 2, 113–128. https://doi.org/10.3390/methane2020009

Academic Editor: Patrick Da Costa

Received: 3 March 2023
Revised: 18 March 2023
Accepted: 27 March 2023
Published: 28 March 2023

1. Introduction

The production of renewable energy based on sustainable techniques has been a challenge for the reduction of greenhouse gases and climate change [1]. Recently, there are governmental incentives to reduce the use of non-renewable energy sources, especially petroleum-based energy, which has expanded the research trends on the production of renewable energy based on biomass, wind, solar, geothermal, oceanic, and hydroelectric sources [2]. However, knowledge advancement of renewable energy production revealed that, in some cases, there are several implementation problems [3], including the demand for large areas, the limitation and dependence on adverse climate conditions, environmental damage in areas of occupation, and high implementation costs [4]. Currently, incentives for renewable energy can be observed in Europe, where the consequences of sanctions applied in the conflict between Ukraine and Russia decreased the supply of natural gas [5,6]. From an environmental perspective, the decrease in the use of natural gas can be an advantage, especially because natural gas emits greenhouse gases and causes disturbances in the ecosystem [7]. However, alternatives for renewable energy production should be better investigated for long-term energy supply [8].

A promising alternative for the consolidation of renewable energy is applying anaerobic digestion (AD) technology [9,10], which can be a sustainable process to produce biogas.

The development of biogas networks is flexible and can be applied with different biodegradable substrates [11], being very promising for allowing both the reuse of organic waste and conversion into bioenergy and biofertilizers [12]. In the case of the agri-food industry, the main factor that encourages AD implementation is the on-site recovery of bioenergy that enables the possibility of self-energy supply for industrial activities, reducing expenses and logistics by correctly treating by-products with energy recovery [13]. For instance, the implementation of AD was evaluated for the treatment of soybean molasses and glycerin, with an estimated electric energy generation of 8.6 GWh y^{-1} based on an initial investment of USD 7.6 million and a financial return of USD 2.2 million annually [14].

The main products generated from AD are biogas and digestate [15]. The biogas produced from AD can be converted into biomethane and bioenergy [16], while the digestate can be upgraded into fertilizer [17]. Biogas has undesirable impurities in its composition, such as carbon dioxide, water vapor, hydrogen sulfide, siloxanes, nitrogen, ammonia, oxygen, and volatile organic compounds [18]. The presence of these interferents causes corrosion in engines and other components during energy conversion, which reduces fuel quality [19,20]. One of the alternatives to overcome this scenario is biogas cleaning and purification. In the case of biomethane production, purification with water, adsorption, membrane technology, or biological methods have been the most applied techniques [21]. However, the biogas purification process is expensive and should be better investigated for application in industrial-scale biogas plants [22]. Moreover, bioenergy recovery from biogas can be applied in two main routes: (i) simultaneous biogas conversion into electricity and heat in a heat and power unit (co-generation process) or (ii) biogas conversion into electricity in a generator, without the recovery of heat [23]. The implementation of a heat and power unit or a generator for bioenergy recovery should be better investigated, especially because the heat and power unit has a higher implementation cost and presents the advantage of producing two energy products (electricity and heat) [24]. In addition, the digestate after AD can be used as a biofertilizer, closing the life cycle within the circular economy concept [25]. The digestate after AD is rich in macro- and micronutrients, such as phosphorus, nitrogen, potassium, and sulfur, depending on the feedstock used [26]. The main advantage of biofertilizer recovered from digestate is the possible replacement of chemical fertilizers that cause soil and groundwater pollution [27].

One of the alternatives that should be explored is the implementation of small-scale AD processes with on-site energy recovery, which can be applied in low-processing industries that generate low amounts of organic waste [28]. In many agri-food industries, the amount of solid and liquid waste generated is significant; however, it is insufficient for application in medium- and large-scale AD plants [29,30]. In the case of the jabuticaba (*Myrciaria cauliflora*) processing industry in Brazil, the peel is considered the most pollutant by-product, and AD can be applied for waste management and bioenergy recovery, generating local energy and mitigating greenhouse gases [31]. However, for AD implementation, economic analysis should be investigated to demonstrate the main parameters that affect project profitability [29].

Based on the abovementioned factors, this study investigated the techno-economic assessment of a small-scale AD process for the management of jabuticaba by-product and the production of biomethane, electricity, heat, and fertilizer. For this, a previous laboratory-scale study was conducted to elucidate biogas production from a semi-continuous AD process. The previous experimental laboratory-scale data were applied for the simulation study, the processing design of the small-scale AD process, and economic analysis (cost discrimination, profitability indicators, and sensitivity analysis). Hence, this study provides a technical point of view for the future implementation of AD technology in the jabuticaba processing industry, subsidizing decision-making processes towards the adoption of the waste management process.

2. Results and Discussion

2.1. Recovery of Biomethane, Bioenergy, and Fertilizer

The experimental biogas production and composition are presented in Figure 1 considering semi-continuous AD in a laboratory-scale reactor of 4.3 L. Experimental biogas production at the laboratory scale and other parameters were established by da Rosa et al. [31]. The results demonstrate that the AD reactor oscillated the methane content during the 50 d, which is expected for the digestion of lignocellulosic biomass. Stabilization occurred after approximately 20 d, when the methane content increased and reached 50%. After 50 d of semi-continuous AD, the accumulated biogas and biomethane volumes reached 49.6 and 14.93 L, respectively. The experimental methane yield obtained at the end of the process was 42.31 L kg^{-1} TVS (total volatile solids). This experimental methane yield was used as a basis for the scale-up and economic analysis.

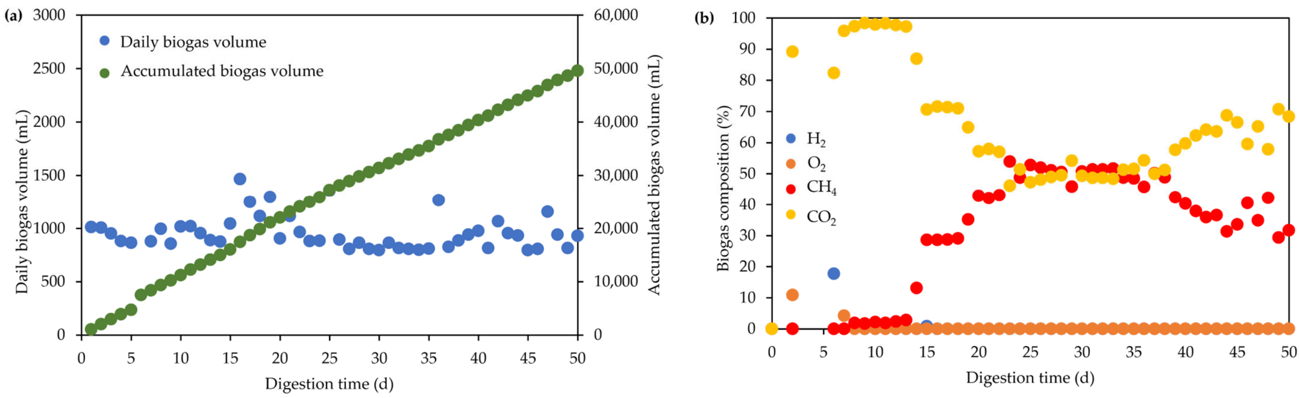

Figure 1. Experimental biogas produced from a laboratory-scale AD reactor operated with jabuticaba by-product for 50 d in semi-continuous mode. (**a**) Daily and accumulated biogas volume. (**b**) Biogas composition. Adapted from da Rosa et al. [31] with permission from Elsevier.

Figure 2 presents the flow diagram for the small-scale AD of jabuticaba agro-industrial by-product and the recovery of biomethane, electricity, heat, and fertilizer. The results obtained for the simulated scenarios are presented in Table 1 considering the established results obtained by da Rosa et al. [31]. Evaluating the scale-up AD process, Scenario 1 considered the recovery of biomethane through the purification of biogas and injection into the gas network to replace the use of natural gas. In this case, the production of biomethane reached 13,960.17 m^3 y^{-1} in the scaled-up simulated process. For Scenario 2, the biogas produced was converted into electricity (61.76 MWh y^{-1}) and heat (197.62 GJ y^{-1}) considering the application of biogas in a combined heat and power unit. In Scenario 3, the biogas was upgraded into electricity (61.76 MWh y^{-1}) in a generator without heat recovery. In all the scenarios studied, fertilizer production from the digestate was considered (211.47 t y^{-1}). By evaluating the data obtained, the process that was designed can be an advantage for the jabuticaba processing industry, where the by-products can be converted into biomethane, electricity, heat, and fertilizer, thus presenting value-added products to reduce energy consumption and recover natural and sustainable fertilizer for agricultural application. In addition, other important advantages of using bioenergy produced by the AD process are the environmental, social, and health benefits due to the burning of a cleaner fuel, which can reduce deforestation by replacing the use of wood while also creating new sources of energy and fertilizer generation [32,33].

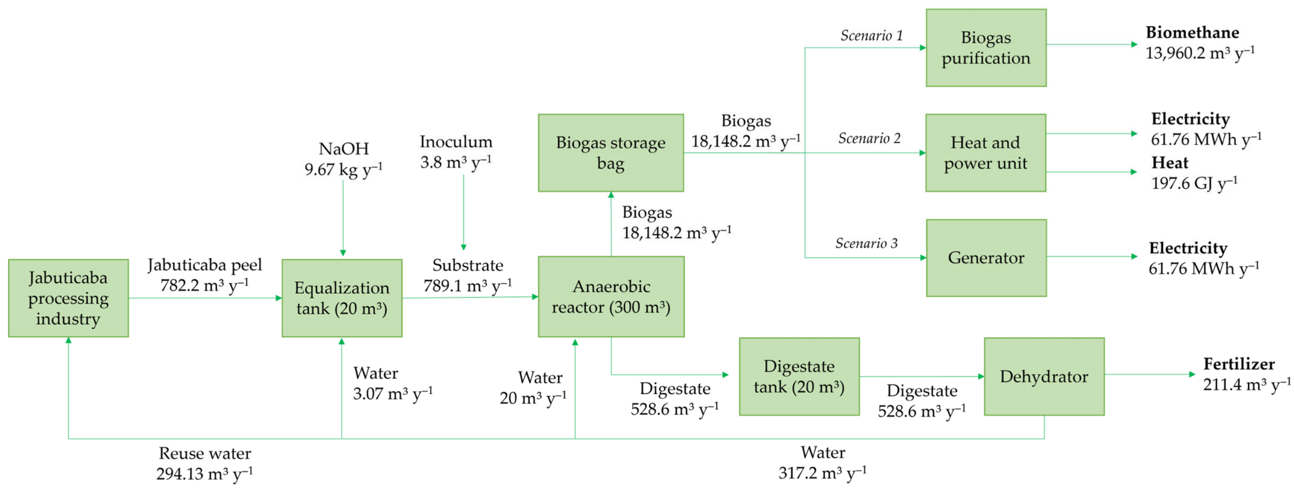

Figure 2. Process flow diagram for biomethane, electricity, heat, and fertilizer production from the small-scale AD of jabuticaba by-product.

Table 1. Production of biomethane, electricity, thermal energy, and fertilizer from the small-scale AD of jabuticaba by-product.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
Biomethane	$m^3\ y^{-1}$	13,960.18	–	–
Electricity	MWh y^{-1}	–	61.76	61.76
Heat	GJ y^{-1}	–	197.62	–
Fertilizer	t y^{-1}	211.47	211.47	211.47

2.2. Economic Analysis

It is important to evaluate the small-scale AD of food industry by-products, and economic analysis provides important insights for verifying project feasibility for further implementation [34,35]. Process simulation can be a positive approach to identifying obstacles in the implementation of the project, which can avoid difficulties during the implementation process associated with project execution [36]. In this simulation, the annual feedstock demand (jabuticaba by-product) for the AD process was equivalent for the three scenarios. The scaled-up process was simulated with a flow of jabuticaba by-product equal to 782.2 $m^3\ y^{-1}$. For AD, it is necessary to control the pH of the reactor, and in this case, 9.67 kg NaOH y^{-1} was necessary. Operational labor was considered the same for the studied scenarios. The amount of water in the process can be considered reused water, which is produced in the AD process, decreasing the costs for the company. For the simulated process, it was estimated that 294.13 $m^3\ y^{-1}$ of water could be reused in the AD process. The annual sales of biomethane, electricity, heat, and fertilizer can be observed in Table 2. Scenario 2 presented the highest revenues (12,192.30 USD y^{-1}), followed by Scenario 3 (10,565.89 USD y^{-1}) and Scenario 1 (5211.29 USD y^{-1}).

Table 2. Annual sales of biomethane, electricity, thermal energy, and fertilizer from the small-scale AD of jabuticaba by-product.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
Biomethane	USD y^{-1}	3908.85	–	–
Electricity	USD y^{-1}	–	9263.45	9263.45
Heat	USD y^{-1}	–	1626.42	–
Fertilizer	USD y^{-1}	1302.44	1302.44	1302.44
Total revenues	USD y^{-1}	5211.29	12,192.30	10,565.89

2.2.1. Cost Discrimination

Table 3 presents the significant costs of the process, and Figure 3 shows cost discrimination over the cost of manufacturing (COM). The sum of fixed capital investment (FCI), cost of operational labor (COL), cost of utilities (CUT), cost of waste treatment (CWT), and cost of raw material (CRM) represents the total annual cost for carrying out the AD of jabuticaba by-product. In general, the results showed that the management of jabuticaba by-product with the simulated small-scale AD process can be considered a low-cost process for properly disposing waste from industrial processing [37]. The total cost was higher for Scenario 2 (9034.76 USD y^{-1}), especially because this scenario presented high FCI (4990.80 USD y^{-1}). In addition, FCI had the highest cost in all scenarios, representing 50.88% for Scenario 1, 55.24% for Scenario 2, and 53.55% for Scenario 3. High FCI may be associated with the high implementation cost of the biogas purification equipment, the heat and power unit, and the power generator. CRM (162.94 USD y^{-1}) and COL (2160.00 USD y^{-1}) were the same for all scenarios since the processes were simulated with the same flow of jabuticaba by-product; consequently, the same amount of water, inoculum, and NaOH for pH neutralization is necessary in the process. CUT was higher for Scenario 1 (1605.59 USD y^{-1}), while Scenario 2 and Scenario 3 required lower expenditures (1285.52 USD y^{-1}), which can be associated with the electricity demand for operating the process of biogas purification in Scenario 1, a cost that is not necessary in the other scenarios. In this study, CWT was considered the same for all three scenarios (435.50 USD y^{-1}) since the same amount of digestate was upgraded into fertilizer. CWT consisted of the cost associated with the construction process for upgrading the digestate into fertilizer. Cost discrimination over the COM was FCI > COL > CUT > CWT > CRM. FCI represented up to 55% of total costs, followed by COL (23.91–24.81%) and CUT (14.23–18.07%). CWT and CRM represented the lowest contribution, lower than 5% in all scenarios. According to Fernando-Foncillas and Varrone [38], installation and labor costs represent more than 50% of the operating costs in the AD process. Vinardell et al. [39] demonstrated that the waste treatment and disposal fee represented the highest cost contribution, showing a notable impact on the net cost. Finally, Sillero et al. [40] found that the highest costs of the AD process were FCI and the CUT.

Table 3. Major costs of the small-scale AD of jabuticaba by-product.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
Fixed capital investment	USD y^{-1}	4520.80	4990.80	4661.80
Cost of operational labor	USD y^{-1}	2160.00	2160.00	2160.00
Cost of utilities	USD y^{-1}	1605.59	1285.52	1285.52
Cost of water treatment	USD y^{-1}	435.50	435.50	435.50
Cost of raw material	USD y^{-1}	162.94	162.94	162.94
Total	USD y^{-1}	8884.83	9034.76	8705.76

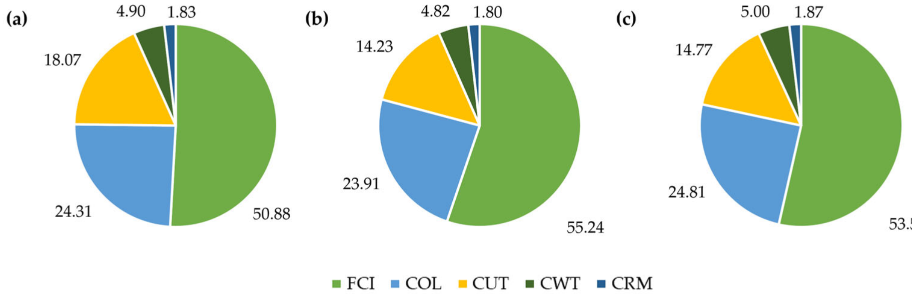

Figure 3. Contribution of each cost discriminated over the cost of manufacturing for the small-scale AD of jabuticaba by-product. (**a**) Scenario 1; (**b**) Scenario 2; (**c**) Scenario 3.

2.2.2. Cost of Manufacturing

Measurement of the COM is one of the main parameters used to determine project feasibility [41]. Table 4 presents the COM of biomethane, electricity, thermal energy, and fertilizer for the scenarios studied. In Scenario 1, the COM of biomethane and fertilizer was 0.72 USD m^{-3} and 47.20 USD t^{-1}, respectively. For Scenario 2, the COM of electricity (157.58 USD MWh^{-1}), heat (0.049 USD MJ^{-1}), and fertilizer (46.02 USD t^{-1}) production were determined. In addition, Scenario 3 showed a marginal increase in the COM of electricity (155.96 USD MWh^{-1}) compared to Scenario 2 (157.58 USD MWh^{-1}). The COM of fertilizer in Scenario 3 was 45.54 USD t^{-1}, similar to the other scenarios. In previous studies, Sillero et al. [40] demonstrated that the economic analysis of a temperature-phase anaerobic co-digestion of sewage sludge, wine vinasse, and poultry manure revealed that the COM of electricity (84.99 USD MWh^{-1}), heat (0.019 USD MJ^{-1}), and fertilizer (30.91 USD t^{-1}) was lower than that in the present study, which can be associated with the scale of the anaerobic reactor. In addition, Sganzerla et al. [42] demonstrated that the lowest COM was obtained for the AD process operated with a higher processing capacity. Although the COM for biomethane, electricity, heat, and fertilizer was higher compared to the literature, the cost benefits of the small-scale AD of jabuticaba by-product should be observed, as well as the annual sales and profitability indicators. In addition, this study is the first approach in determining the economic assessment of small-scale AD of jabuticaba by-product, and future optimization can be better elucidated to increase the methane yield of this process, which will consequently improve bioenergy recovery.

Table 4. Cost of manufacturing for biomethane, electricity, thermal energy, and fertilizer from the small-scale AD of jabuticaba by-product.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
Biomethane	USD m^{-3}	0.72	–	–
Electricity	USD MWh^{-1}	–	157.58	155.96
Heat	USD MJ^{-1}	–	0.049	–
Fertilizer	USD t^{-1}	47.20	46.02	45.54

2.2.3. Profitability Analysis

Figure 4 shows cash flow and Table 5 presents the results of profitability indicators for the scenarios studied. Cash flow was assessed by deducting depreciation, interest rates, and income taxes over the investment period [43]. The results obtained demonstrated that the current assets were negative in the first four years, indicating an increase according to yearly revenues. Regarding the profitability indicators, Scenario 1 presented the lowest gross margin (24.61%) when compared with Scenario 2 (67.78%) and Scenario 3 (62.82%). This fact demonstrates that the direct costs of the project are expensive when compared with the revenues. This fact was confirmed in the net margin, which measures the profit generated after revenue. The process of producing biomethane is not profitable since it presents a negative net margin. In addition, the highest return on investment (ROI) (18.52%) and internal rate of return (IRR) (13.14%) were obtained for Scenario 2, demonstrating that, for small-scale AD processes, the application of a heat and power unit to upgrade biogas into electricity and heat is the best option. Scenario 2 resulted in the lowest payback (5.03 years) and the highest net present value (NPV) (USD 49,953.98) after 10 years of operation.

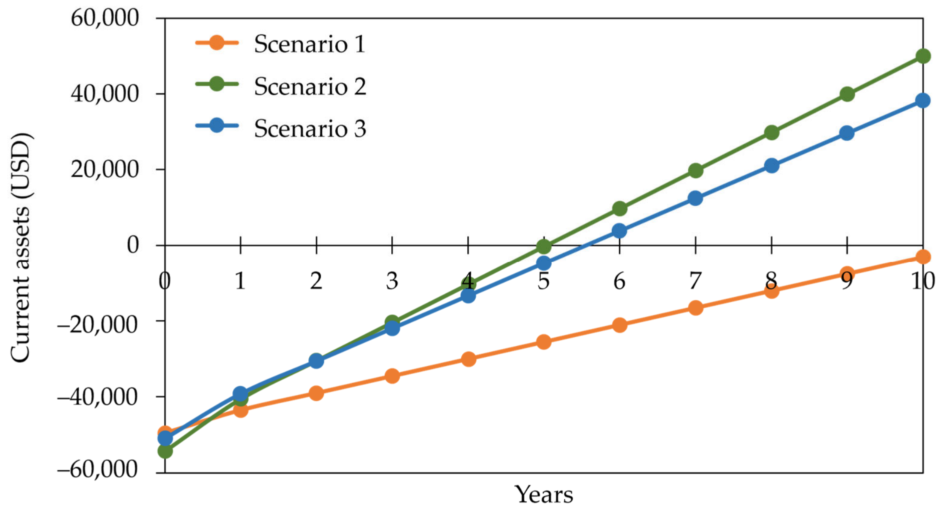

Figure 4. Cash flow (current assets, USD) for the scenarios studied.

Table 5. Profitability indicators for biomethane, electricity, thermal energy, and fertilizer production from the small-scale AD of jabuticaba by-product.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
Gross margin	%	24.61	67.78	62.82
Net margin	%	−19.58	33.03	27.82
Return on investment	%	9.05	18.53	16.88
Internal rate of return	%	−1.77	13.14	10.85
Payback	y	10.7	5.03	5.56
Net present value	USD	−3139.66	49,953.98	38,218.75

2.2.4. Sensitivity Analysis

Sensitivity analysis ensures robustness and the best cost-effectiveness for the systems to be installed [44]. Sensitivity analysis was carried out for all scenarios to verify the influence of the market price of biomethane, electricity, heat, and fertilizer and the influence of costs (FCI, CRM, COL, and CUT) on NPV and IRR. The sensitivity analysis results (±30%) can be seen in Figure 5. CRM did not show significant differences in the scenarios studied in terms of price variation. The other indicators (CUT, COL, and FCI) were more sensitive, with COL and FCI being the most affected in all scenarios, both being strongly affected by a sensitivity of ±30%. Scenario 2 was the most beneficial, where the FCI decrease to 30% promoted an IRR of almost 20%. Checking the project's profitability in different market conditions is a decisive factor in the practical implementation of the project [40]. Variations in the market price of biomethane, electricity, heat, and fertilizer are expected. For Scenario 1, a positive variation of 30% in the market price of biomethane promoted an increase in NPV of almost USD 5000, and a decrease of 30% would cause a reduction of more than USD 10,000. For Scenario 2 and Scenario 3, electricity market price was the most affected parameter, where the increase of 30% in Scenario 2 and Scenario 3 increased IRR by 17%. Sensitivity analysis becomes a tool of great importance for the implementation of processes as sales prices suffer several variations throughout the year. With the performance of sensitivity analysis, the chances of a project being successful are increased.

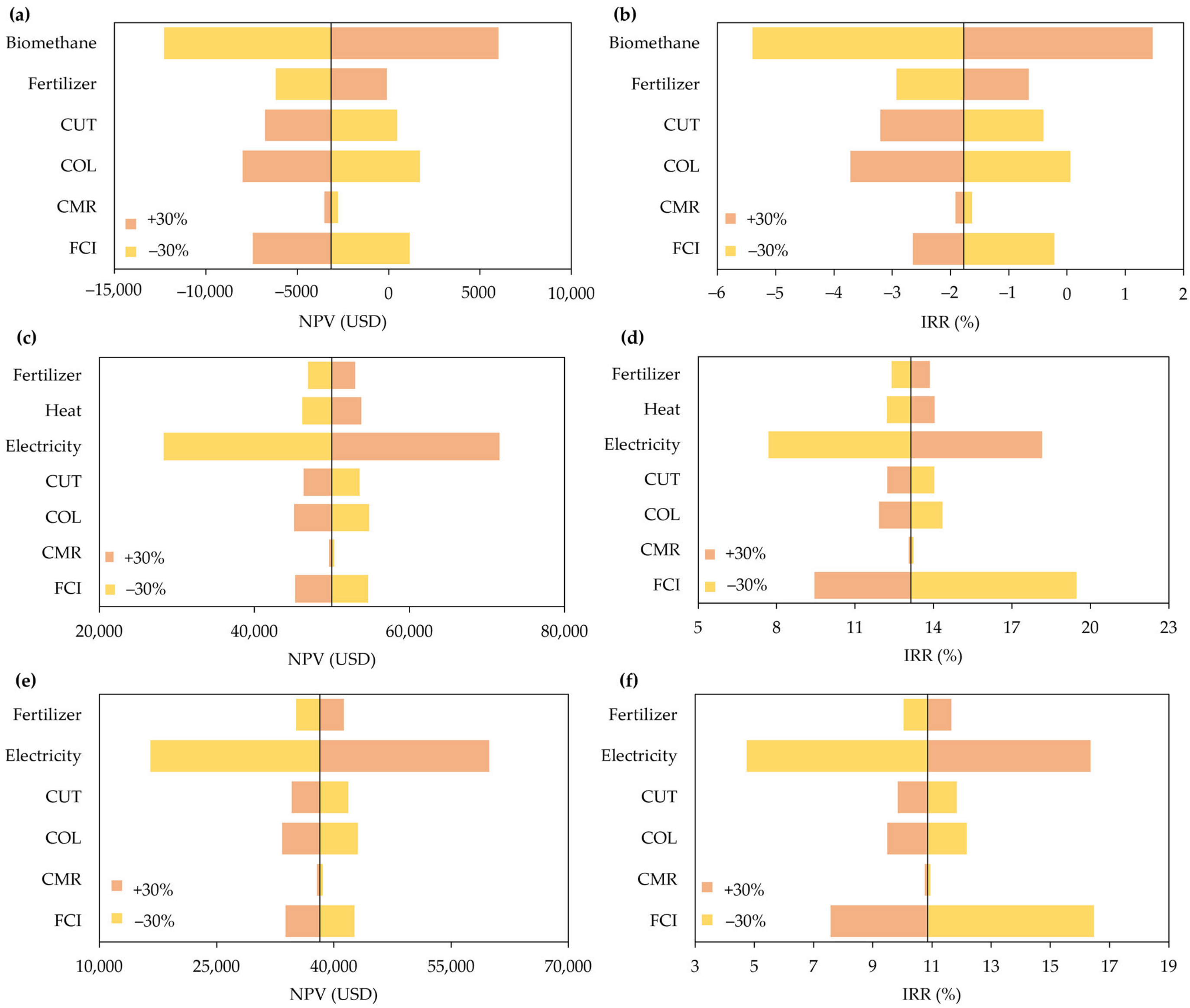

Figure 5. Sensitivity analysis of the influence of the costs (FCI, CRM, COL, and CUT) and market price of biomethane, electricity, heat, and fertilizer on profitability indicators (NPV and IRR). (**a**) Scenario 1, NPV; (**b**) Scenario 1, IRR; (**c**) Scenario 2, NPV; (**d**) Scenario 2, IRR; (**e**) Scenario 3, NPV; and (**f**) Scenario 3, IRR.

3. Materials and Methods

3.1. Previous Laboratory-Scale Experiments

The laboratory-scale AD reactor was set up and operated in a semi-continuous mode to manage the jabuticaba by-product [31]. Table 6 summarizes the operating parameters and experimental results for the laboratory-scale AD reactor and the production of biomethane, electricity, heat, and fertilizer. The laboratory-scale reactor had a total volume of 4.3 L, with a working volume of 3.32 L for the substrate and 0.98 L for the headspace. The biogas produced was collected in a Tedlar bag, which was used to measure methane composition. The AD process was operated under mesophilic (36 °C) and methanogenic (pH between 7 and 8.5) conditions with a hydraulic retention time (HRT) of 33.2 d, organic loading rate (OLR) of 4.32 g_{COD} L^{-1} d^{-1}, and volatile solids loading rate (VSR) of 1.47 g_{TVS} L^{-1} d^{-1}. For this, the feed of the laboratory-scale process was composed of 69.58 g substrate d^{-1} (14.58 g jabuticaba by-product and 55 mL water). Stirring was applied for 10 min d^{-1} (5 min before sampling and 5 min after NaOH addition) at approximately 350 rpm. The process was operated in semi-continuous mode for 50 d. The experimental results revealed a production of 49.6 L of biogas, which was composed of approximately 30% methane. The methane volume was 14.93 L and the accumulated methane yield was 42.31 L CH_4 kg^{-1} TVS. Finally, the productivity of methane was 4.29 L CH_4 kg^{-1} substrate considering the initial mass to start the process and the mass of feed in the process.

Table 6. Summary of the operating parameters and experimental results for the laboratory-scale AD reactor and the production of biomethane, electricity, thermal energy, and fertilizer.

Parameters	Unit	Results
Start-up of laboratory-scale AD reactor		
Reactor volume	L	4.3
Headspace	L	0.98
Volume of substrate	L	3.32
Initial mass of substrate	kg	2.08
Initial mass of jabuticaba by-product	kg	0.5
Initial mass of inoculum	kg	0.87
Initial volume of water	L	0.71
Feed		
Mass of jabuticaba by-product	kg d^{-1}	0.014
Volume of water	L d^{-1}	0.055
Mass of substrate	kg d^{-1}	0.069
Operational parameters		
HRT	d	33.2
OLR	g_{COD} L^{-1} d^{-1}	4.32
VSR	g_{TVS} L^{-1} d^{-1}	1.47
Temperature	°C	36
pH	–	7–8.5
Operation time	d	50
Production of biogas, methane, bioenergy, and fertilizer		
Accumulated methane volume	L	14.93
Accumulated biogas volume	L	49.6
Methane yield	L CH_4 kg^{-1} TVS	42.31
Daily methane volume	L CH_4 d^{-1}	0.29
Methane productivity	m^3 CH_4 t^{-1}	4.29
Electricity	MWh t^{-1}	0.019
Heat	MJ t^{-1}	60.75
Fertilizer	m^3 t^{-1}	0.26

3.2. Process Design Simulation and Scenarios

Based on previous laboratory-scale experiments, a simulated process was conducted to elucidate the industrial application of AD for biomethane, bioenergy, and fertilizer production from the management of jabuticaba by-product. The process was designed and simulated considering a small-scale AD process with a treatment capacity of 9 m^3 d^{-1}. This flow was adopted since the jabuticaba processing industry is considered a low-capacity industry in Brazil. The simulated process consisted of the collection and homogenization of jabuticaba peel (782.2 m^3 y^{-1}) in an equalization tank, with the addition of water and NaOH to control the pH of the process. In the start-up of the AD reactor, the substrate was composed of jabuticaba peel (72.14 m^3), inoculum (126.09 m^3), and water (101.77 m^3). The inoculum is necessary only once since the process operates in continuous mode. Hence, the total flow of the substrate in the process is 789.1 m^3 y^{-1}. The volume of the AD reactor was calculated according to Equation (1).

$$\text{Reactor volume }(m^3) = \text{HRT }(d) \times Q\,(m^3\,d^{-1}) \quad (1)$$

where HRT is the hydraulic retention time based on the laboratory-scale experiments (33.2 d) and Q is the flow of substrate considering the treatment capacity of the simulated process (9 $m^3\,d^{-1}$).

After AD, the biogas produced was stored in a bag for further conversion into biomethane or bioenergy. For the recovery of biomethane, a purification system was adopted to remove carbon dioxide, hydrogen sulfide, water vapor, and other impurities. The assumptions adopted for biogas purification were based on the literature [45]. In addition, the biogas produced can be upgraded into bioenergy (electricity and heat). In a common generator, biogas is converted into electricity, while a heat and power unit can be used for the combined conversion of biogas into electricity and heat. The potential for electricity and heat was estimated according to Equations (2) and (3).

$$\text{Electricity} = V_{biogas} \times LCV_{CH_4} \times C_m \times \eta_e \times CF \quad (2)$$

$$\text{Heat} = V_{biogas} \times LCV_{CH_4} \times C_m \times \eta_h \quad (3)$$

where V_{biogas} is the volume of biogas produced in the AD process (m^3), LCV_{CH_4} is the lower calorific value of methane (35.59 MJ m^{-3}), C_m is methane composition (%), η_e is engine efficiency for electricity (assumed as 40%), η_h is engine efficiency for heat (assumed as 50%), and CF is the conversion factor from MJ to MWh (1 MWh = 3600 MJ). The values for engine efficiency were obtained from commercial heat and power units available in the market [46].

The digestate obtained was stored in a tank and submitted to a dehydrator to separate the water and concentrate the nutrients. For this, it was considered a mass biodegradation of 33% after AD and a mass reduction of 60% in the dehydration process operated with a maximum dehydration rate of approximately 3 $m^3\,d^{-1}$. The final moisture content of the fertilizer was assumed to be 70% [47]. The water generated after dehydration was considered as reuse water, which means that it can be applied in the AD process or used in the industry for cleaning. The assumptions adopted for the digestate upgrade into fertilizer were based on the literature [40].

Hence, based on the process designed, the following scenarios were studied in the small-scale AD process: Scenario 1, recovery of biomethane via biogas purification and injection into the gas grid to replace the use of natural gas; Scenario 2, recovery of bioenergy (electricity and heat) using biogas in a combined heat and power unit; and Scenario 3, recovery of electricity using biogas in a generator. In all scenarios, the use of digestate as fertilizer was considered. These scenarios were adopted to estimate the better application of biogas in the small-scale AD process of jabuticaba by-product.

3.3. Economic Assessment

3.3.1. General Assumption

Previous studies addressed a conceptual model for economic analysis of the AD process [40,42,48]. Economic analysis was conducted to compare the costs and benefits of the simulated scenarios. Capital investment, operating costs, COM, revenues, profitability indicators, and sensibility analysis were considered. Table 7 summarizes the general parameters used for the economic analysis. In general, the values were considered based on Brazilian economic indicators.

Table 7. Assumptions adopted for the economic analysis.

Parameters	Unit	Value	Reference
	Selling prices		
Biomethane	USD m^{-3}	0.28	[42]
Electricity	USD MWh^{-1}	150	[47]
Heat	USD MJ^{-1}	0.00823	[42]
Fertilizer	USD t^{-1}	6.15	[42]
	Buying prices		
Jabuticaba by-product	USD m^{-3}	0.20	[1]
Water	USD m^{-3}	0.35	[48]
NaOH	USD kg^{-1}	0.53	[48]
Electricity	USD MWh^{-1}	150	[47]
Operational labor cost	USD h^{-1}	3	[42]
	Economic inputs		
Project lifetime	y	25	[1]
Annual depreciation rate	%	8	[1]
Annual tax rate	%	25	[1]
Attractiveness rate	%	15	[1]
Inflation rate	%	5	[1]
Time of plant operation	d y^{-1}	320	[1]
Financing (external capital)	%	50	[1]
Bank financing period	y	10	[1]
Annual interest rate	%	10	[1]

[1] Values considering the current economic indicators of Brazil for 2022.

3.3.2. Itemized Cost Estimation and Cost of Manufacturing

The itemized costs were estimated by evaluating the FCI, CRM, COL, CUT, and CWT. FCI was related to the implementation of the small-scale AD process. Equipment installation costs (Table 8) were collected from current market prices. The CRM of jabuticaba peel was estimated on-site at 0.2 USD m^{-3}. The CRM for water and NaOH was estimated as 0.2 USD m^{-3} and 0.53 USD kg^{-1}, respectively [48]. COL was assumed as 3 USD h^{-1} worked and a demand of 1 worker at 2 h d^{-1} [42]. The CUT considered in this study included electricity (0.15 USD kWh^{-1}) and heat (0.0082 USD MJ^{-1}) for the process, both of which were estimated considering current Brazilian market prices. CWT was established as the capital necessary for implementing the process for digestate upgrade into fertilizer.

Table 8. Cost of equipment and FCI for implementation of the small-scale AD process.

Description	Unit Cost (USD)	Scenario 1	Scenario 2	Scenario 3
Pump	130	390	390	390
Biogas pump	30	30	30	30
Temperature probe	28	28	28	28
Pressure probe	55	55	55	55
pH probe	60	60	60	60
Biogas flow meter	100	100	100	100
Tank	725	1450	1450	1450
Anaerobic reactor	35,000	35,000	35,000	35,000
Biogas storage bag	250	250	250	250
Solid—Liquid dehydrator	3500	3500	3500	3500
Biogas purification	8000	8000	–	–
Heat and power unit	12,700	–	12,700	–
Power generator	9410	–	–	9410
Pipe	100	100	100	100
Landscaping	600	600	600	600
Total FCI (USD)		49,563	54,263	50,973.00

COM was calculated as the sum of the main process components (FCI, COL, CUT, CWT, and CRM) according to Equation (4) [49].

$$COM = (0.304 \times FCI) + (2.73 \times COL) + [1.23 \times (CUT + CWT + CRM)] \quad (4)$$

where COM is the cost of manufacturing, FCI is fixed capital investment, COL is the cost of operational labor, CUT is the cost of utilities, CWT is the cost of waste treatment, and CRM is the cost of raw material.

3.3.3. Profitability Analysis

Profitability analysis was determined by evaluating the gross margin, net margin, IRR, ROI, payback, and NPV. The gross margin was calculated by the difference between revenue and the cost of goods sold, while net margin is the gross margin considering operating expenses. NPV is the difference between the present value of cash inflows and outflows over a period, calculated according to Equation (5). IRR is the discount rate that equals the NPV to zero and can be calculated using Equation (6).

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} - I_0 \quad (5)$$

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+IRR)^t} \quad (6)$$

where FC_t is the cash flow in period t, t is the period in which the money will be invested, n is the useful life of the project, i is the cost of capital, and I_0 is the initial investment.

ROI is used for capital budgeting and to evaluate the performance of an investment project. ROI was calculated according to Equation (7).

$$ROI\ (\%) = \frac{\text{Annual net profit}}{\text{Total capital investment}} \quad (7)$$

Payback is the period in years required to recover the original investment, calculated according to Equation (8).

$$\text{Payback}\ (y) = \frac{\text{Total capital investment}}{\text{Annual net profit}} \quad (8)$$

3.3.4. Sensitivity Analysis

Sensitivity analysis was assessed to evaluate the relevance of the input parameters on the economic performance of the scenarios studied. The profitability variables modeled in the cash flow were NPV and IRR. A tornado diagram was made with a variation of ±30% to better comprehend the effect of FCI, CRM, COL, CUT, and the market price of biomethane, electricity, heat, and fertilizer over the IRR and NPV of the process.

4. Limitations and Future Prospects

The small-scale AD process with on-site production of biomethane, electricity, heat, and fertilizer was demonstrated as a suitable alternative for the management of jabuticaba by-products. However, some limitations should be highlighted to provide robust conclusions and future prospects for process implementation. The first limitation is associated with the demand for automated processes with real-time control of operational parameters and methane measurement. This can support the stable operational performance of the process and lead to a consequent decrease in the amount of operational labor required. In addition, an increase in methane content during continuous operation can be achieved by applying process control and optimization, which will affect the project's feasibility. In this study, laboratory-scale results were obtained in a standard stirred tank reactor. However, the design and optimization of novel reactors with different configurations can be an alternative means of improving biomass degradability and biomethane production. AD is a biological process, and analysis of microbial community dynamics should be conducted to determine the interactions between the substrate, operational performance, and biogas production. Correlation between these variables is a promising approach to increasing methane content in biogas and a project's feasibility. Nonetheless, a decrease in the COM of biomethane is essential to compete with the low market price of natural gas. The production of biogas with low carbon dioxide content and a low amount of impurities (hydrogen sulfide, siloxanes, and water vapor) can increase the lifetime of the heat and power unit and decrease the cost of biogas purification into biomethane. Another essential aspect that should be considered is the supply and availability of jabuticaba by-products in Brazil over the years. The seasonal and regional production of jabuticaba can be a challenge for application of the AD process, and this should be overcome by the large-scale production and processing of jabuticaba. Finally, the avoided greenhouse gas emissions resulting from application of small-scale AD can be further considered to decrease the carbon footprint of the industrial sector, which is the main environmental benefit. This can be investigated in the future by a life cycle assessment of the process. For instance, the digestate generated after AD can be used as a sustainable fertilizer for agricultural applications, replacing mineral fertilizers in jabuticaba crops and closing the life cycle.

5. Conclusions

This study demonstrated the feasibility of small-scale AD in the on-site production of biomethane, bioenergy, and biofertilizer for the management of jabuticaba by-product. The project was simulated for the management of 782.2 m^3 jabuticaba peel y^{-1} in a continuous anaerobic reactor of 300 m^3. The fixed capital investment of the process ranged between USD 49,563 and 54,263, with annual operation costs of up to USD 9034.76. The annual production of biomethane (13,960.18 m^3 y^{-1}), electricity (61.76 MWh y^{-1}), heat (197.62 GJ y^{-1}), and fertilizer (211.47 t y^{-1}) demonstrated that the jabuticaba by-product can be converted into value-added products and bioenergy. Based on the revenues established, the most profitable scenario was obtained for the process with biogas upgrading in a heat and power unit, with a gross margin of 67.78%, net margin of 33.03%, ROI of 18.53%, IRR of 13.14%, payback of 5.03 y, and NPV of USD 49,953.98. Hence, the application of a heat and power unit for biogas upgrading into electricity and heat was demonstrated as a better option when compared with biogas purification for biomethane and biogas conversion into electricity in a common generator without heat recovery. This condition was achieved due to the high efficiency of the heat and power unit with co-generation of electricity and heat. In conclusion, the application of AD can prevent the wrongful open-air disposal of jabuticaba by-products, with the generation of renewable energy and biofertilizer supporting the green economy toward the transition to a circular economy.

Author Contributions: Conceptualization, W.G.S. and T.F.-C.; methodology, W.G.S. and R.G.d.R.; investigation, T.L.C.T.B., R.G.d.R. and L.E.N.C.; writing—original draft preparation, W.G.S., T.L.C.T.B., R.G.d.R. and L.E.N.C.; writing—review and editing, W.G.S. and T.F.-C.; supervision, T.F.-C.; project administration, T.F.-C.; funding acquisition, T.F.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Brazilian Science and Research Foundation (CNPq) (Productivity in Technological Development grant 302451/2021-8); Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil) (Finance code 001); and the São Paulo Research Foundation (FAPESP, Brazil) (grant numbers 2018/14938-4 for T.F.C.; 2019/26925-7 for W.G.S.; 2020/16248-5 for T.L.C.T.B.; and 2021/04096-9 for L.E.N.C.).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We acknowledge the Brazilian Science and Research Foundation (CNPq), Coordination for the Improvement of Higher Education Personnel (CAPES), and the São Paulo Research Foundation (FAPESP).

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

References

1. He, Y.; Li, X.; Huang, P.; Wang, J. Exploring the Road toward Environmental Sustainability: Natural Resources, Renewable Energy Consumption, Economic Growth, and Greenhouse Gas Emissions. *Sustainability* **2022**, *14*, 1579. [CrossRef]
2. Olabi, A.G.; Abdelkareem, M.A. Renewable Energy and Climate Change. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112111. [CrossRef]
3. Seetharaman; Moorthy, K.; Patwa, N.; Saravanan; Gupta, Y. Breaking Barriers in Deployment of Renewable Energy. *Heliyon* **2019**, *5*, e01166. [CrossRef]
4. Halkos, G.E.; Gkampoura, E.-C. Reviewing Usage, Potentials, and Limitations of Renewable Energy Sources. *Energies* **2020**, *13*, 2906. [CrossRef]
5. Cui, L.; Yue, S.; Nghiem, X.-H.; Duan, M. Exploring the Risk and Economic Vulnerability of Global Energy Supply Chain Interruption in the Context of Russo-Ukrainian War. *Resour. Policy* **2023**, *81*, 103373. [CrossRef]
6. Halecki, W.; Bedla, D. Global Wheat Production and Threats to Supply Chains in a Volatile Climate Change and Energy Crisis. *Resources* **2022**, *11*, 118. [CrossRef]
7. Abu, R.; Patchigolla, K.; Simms, N. A Review on Qualitative Assessment of Natural Gas Utilisation Options for Eliminating Routine Nigerian Gas Flaring. *Gases* **2023**, *3*, 1–24. [CrossRef]
8. Budak, G.; Chen, X.; Celik, S.; Ozturk, B. A Systematic Approach for Assessment of Renewable Energy Using Analytic Hierarchy Process. *Energy. Sustain. Soc.* **2019**, *9*, 37. [CrossRef]
9. Mizger-Ortega, J.; Vanegas Chamorro, M.; Celis-Quintero, M. Anaerobic Digestion in Biogas Production from Organic Matter: A Bibliometric Analysis from 2000 to 2021. *Int. J. Energy Econ. Policy* **2022**, *12*, 505–514. [CrossRef]
10. Sivakumar, P.; Bhagiyalakshmi, M.; Anbarasu, K. Anaerobic Treatment of Spoiled Milk from Milk Processing Industry for Energy Recovery—A Laboratory to Pilot Scale Study. *Fuel* **2012**, *96*, 482–486. [CrossRef]
11. Kunatsa, T.; Xia, X. A Review on Anaerobic Digestion with Focus on the Role of Biomass Co-Digestion, Modelling and Optimisation on Biogas Production and Enhancement. *Bioresour. Technol.* **2022**, *344*, 126311. [CrossRef]
12. Assis, T.I.; Gonçalves, R.F. Valorization of Food Waste by Anaerobic Digestion: A Bibliometric and Systematic Review Focusing on Optimization. *J. Environ. Manag.* **2022**, *320*, 115763. [CrossRef]
13. Rabbat, C.; Awad, S.; Villot, A.; Rollet, D.; Andrès, Y. Sustainability of Biomass-Based Insulation Materials in Buildings: Current Status in France, End-of-Life Projections and Energy Recovery Potentials. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111962. [CrossRef]
14. Paulinetti, A.P.; Augusto, I.M.G.; Batista, L.P.P.; Tavares, A.G.B.; Albanez, R.; Ratusznei, S.M.; Lovato, G.; Rodrigues, J.A.D. Anaerobic Digestion as a Core Process for Sustainable Energy Production in the Soybean Biorefinery: A Techno-economic Assessment. *Sustain. Horiz.* **2022**, *3*, 100024. [CrossRef]
15. Ampese, L.C.; Sganzerla, W.G.; Di Domenico Ziero, H.; Mudhoo, A.; Martins, G.; Forster-Carneiro, T. Research Progress, Trends, and Updates on Anaerobic Digestion Technology: A Bibliometric Analysis. *J. Clean. Prod.* **2022**, *331*, 130004. [CrossRef]
16. Kabeyi, M.J.B.; Olanrewaju, O.A. Technologies for Biogas to Electricity Conversion. *Energy Rep.* **2022**, *8*, 774–786. [CrossRef]
17. Czekała, W.; Jasiński, T.; Grzelak, M.; Witaszek, K.; Dach, J. Biogas Plant Operation: Digestate as the Valuable Product. *Energies* **2022**, *15*, 8275. [CrossRef]
18. Atelge, M.R.; Senol, H.; Djaafri, M.; Hansu, T.A.; Krisa, D.; Atabani, A.; Eskicioglu, C.; Muratçobanoğlu, H.; Unalan, S.; Kalloum, S.; et al. A Critical Overview of the State-of-the-Art Methods for Biogas Purification and Utilization Processes. *Sustainability* **2021**, *13*, 11515. [CrossRef]
19. Piechota, G. Biogas/Biomethane Quality and Requirements for Combined Heat and Power (CHP) Units/Gas Grids with a Special Focus on Siloxanes-a Short Review. *Sustain. Chem. Eng.* **2021**, *3*, 1–10. [CrossRef]
20. Rogala, Z.; Stanclik, M.; Łuszkiewicz, D.; Malecha, Z. Perspectives for the Use of Biogas and Biomethane in the Context of the Green Energy Transformation on the Example of an EU Country. *Energies* **2023**, *16*, 1911. [CrossRef]
21. Khan, M.U.; Lee, J.T.E.; Bashir, M.A.; Dissanayake, P.D.; Ok, Y.S.; Tong, Y.W.; Shariati, M.A.; Wu, S.; Ahring, B.K. Current Status of Biogas Upgrading for Direct Biomethane Use: A Review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111343. [CrossRef]
22. Korberg, A.D.; Skov, I.R.; Mathiesen, B.V. The Role of Biogas and Biogas-Derived Fuels in a 100% Renewable Energy System in Denmark. *Energy* **2020**, *199*, 117426. [CrossRef]
23. Cao, Y.; Dhahad, H.A.; Togun, H.; Abdollahi Haghghi, M.; Anqi, A.E.; Farouk, N.; Rosen, M.A. Seasonal Design and Multi-Objective Optimization of a Novel Biogas-Fueled Cogeneration Application. *Int. J. Hydrogen Energy* **2021**, *46*, 21822–21843. [CrossRef]

24. Erixno, O.; Rahim, N.A.; Ramadhani, F.; Adzman, N.N. Energy Management of Renewable Energy-Based Combined Heat and Power Systems: A Review. *Sustain. Energy Technol. Assess.* **2022**, *51*, 101944. [CrossRef]
25. Sharma, B.; Suthar, S. Enriched Biogas and Biofertilizer Production from Eichhornia Weed Biomass in Cow Dung Biochar-Amended Anaerobic Digestion System. *Environ. Technol. Innov.* **2021**, *21*, 101201. [CrossRef]
26. Kitessa, W.M.; Fufa, F.; Abera, D. Biogas Production and Biofertilizer Estimation from Anaerobic Co-Digestion of Blends of Wastewater and Microalgae. *Int. J. Chem. Eng.* **2022**, *2022*, 3560068. [CrossRef]
27. Ezemagu, I.G.; Ejimofor, M.I.; Menkiti, M.C.; Diyoke, C. Biofertilizer Production via Composting of Digestate Obtained from Anaerobic Digestion of Post Biocoagulation Sludge Blended with Saw Dust: Physiochemical Characterization and Kinetic Study. *Environ. Chall.* **2021**, *5*, 100288. [CrossRef]
28. O'Connor, S.; Ehimen, E.; Pillai, S.C.; Black, A.; Tormey, D.; Bartlett, J. Biogas Production from Small-Scale Anaerobic Digestion Plants on European Farms. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110580. [CrossRef]
29. O'Connor, S.; Ehimen, E.; Pillai, S.C.; Lyons, G.; Bartlett, J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. *Energies* **2020**, *13*, 637. [CrossRef]
30. Theuerl, S.; Herrmann, C.; Heiermann, M.; Grundmann, P.; Landwehr, N.; Kreidenweis, U.; Prochnow, A. The Future Agricultural Biogas Plant in Germany: A Vision. *Energies* **2019**, *12*, 396. [CrossRef]
31. Da Rosa, R.G.; Sganzerla, W.G.; Barroso, T.L.C.T.; Castro, L.E.N.; Berni, M.D.; Forster-Carneiro, T. Sustainable Bioprocess Combining Subcritical Water Pretreatment Followed by Anaerobic Digestion for the Valorization of Jabuticaba (*Myrciaria cauliflora*) Agro-Industrial By-Product in Bioenergy and Biofertilizer. *Fuel* **2023**, *334*, 126698. [CrossRef]
32. Vasco-Correa, J.; Khanal, S.; Manandhar, A.; Shah, A. Anaerobic Digestion for Bioenergy Production: Global Status, Environmental and Techno-Economic Implications, and Government Policies. *Bioresour. Technol.* **2018**, *247*, 1015–1026. [CrossRef]
33. Farghali, M.; Osman, A.I.; Umetsu, K.; Rooney, D.W. Integration of Biogas Systems into a Carbon Zero and Hydrogen Economy: A Review. *Environ. Chem. Lett.* **2022**, *20*, 2853–2927. [CrossRef]
34. Mahmud, R.; Moni, S.M.; High, K.; Carbajales-Dale, M. Integration of Techno-Economic Analysis and Life Cycle Assessment for Sustainable Process Design—A Review. *J. Clean. Prod.* **2021**, *317*, 128247. [CrossRef]
35. Chai, S.Y.W.; Phang, F.J.F.; Yeo, L.S.; Ngu, L.H.; How, B.S. Future Era of Techno-Economic Analysis: Insights from Review. *Front. Sustain.* **2022**, *3*, 924047. [CrossRef]
36. Rajendran, K.; Murthy, G.S. Techno-Economic and Life Cycle Assessments of Anaerobic Digestion—A Review. *Biocatal. Agric. Biotechnol.* **2019**, *20*, 101207. [CrossRef]
37. Tan, J.B.; Jamali, N.S.; Tan, W.E.; Che Man, H.; Zainal Abidin, Z. Techno-Economic Assessment of On-Farm Anaerobic Digestion System Using Attached-Biofilm Reactor in the Dairy Industry. *Sustainability* **2021**, *13*, 2063. [CrossRef]
38. Fernando-Foncillas, C.; Varrone, C. Potential of the Sewage Sludge Valorization in Scandinavia by Co-Digestion with Other Organic Wastes: A Techno-Economic Assessment. *J. Clean. Prod.* **2021**, *324*, 129239. [CrossRef]
39. Vinardell, S.; Astals, S.; Koch, K.; Mata-Alvarez, J.; Dosta, J. Co-Digestion of Sewage Sludge and Food Waste in a Wastewater Treatment Plant Based on Mainstream Anaerobic Membrane Bioreactor Technology: A Techno-Economic Evaluation. *Bioresour. Technol.* **2021**, *330*, 124978. [CrossRef]
40. Sillero, L.; Sganzerla, W.G.; Carneiro, T.F.; Solera, R.; Perez, M. Techno-Economic Analysis of Single-Stage and Temperature-Phase Anaerobic Co-Digestion of Sewage Sludge, Wine Vinasse, and Poultry Manure. *J. Environ. Manag.* **2023**, *325*, 116419. [CrossRef]
41. Yi, L.; Ehmsen, S.; Glatt, M.; Aurich, J.C. Modeling and Software Implementation of Manufacturing Costs in Additive Manufacturing. *CIRP J. Manuf. Sci. Technol.* **2021**, *33*, 380–388. [CrossRef]
42. Sganzerla, W.G.; Buller, L.S.; Mussatto, S.I.; Forster-Carneiro, T. Techno-Economic Assessment of Bioenergy and Fertilizer Production by Anaerobic Digestion of Brewer's Spent Grains in a Biorefinery Concept. *J. Clean. Prod.* **2021**, *297*, 126600. [CrossRef]
43. Roosa, S.A.; Doty, S.; Turner, W.C. *Energy Management Handbook*, 9th ed.; River Publishers: New York, NY, USA, 2018; ISBN 9781003151364.
44. Ahmad, J.; Imran, M.; Khalid, A.; Iqbal, W.; Ashraf, S.R.; Adnan, M.; Ali, S.F.; Khokhar, K.S. Techno Economic Analysis of a Wind-Photovoltaic-Biomass Hybrid Renewable Energy System for Rural Electrification: A Case Study of Kallar Kahar. *Energy* **2018**, *148*, 208–234. [CrossRef]
45. Lawson, N.; Alvarado-Morales, M.; Tsapekos, P.; Angelidaki, I. Techno-Economic Assessment of Biological Biogas Upgrading Based on Danish Biogas Plants. *Energies* **2021**, *14*, 8252. [CrossRef]
46. CHP Brasil. Qualified Cogeneration. Available online: https://chpbrasil.com.br/en/solucoes/cogeracao-qualificada (accessed on 26 March 2023).
47. Li, Y.; Han, Y.; Zhang, Y.; Luo, W.; Li, G. Anaerobic Digestion of Different Agricultural Wastes: A Techno-Economic Assessment. *Bioresour. Technol.* **2020**, *315*, 123836. [CrossRef]

48. Tena, M.; Buller, L.S.; Sganzerla, W.G.; Berni, M.; Forster-Carneiro, T.; Solera, R.; Pérez, M. Techno-Economic Evaluation of Bioenergy Production from Anaerobic Digestion of by-Products from Ethanol Flex Plants. *Fuel* **2022**, *309*, 122171. [CrossRef]
49. Turton, R.; Bailie, R.C.; Whiting, W.B.; Shaeiwitz, J.A.; Bhattacharyya, D. *Analysis, Synthesis, and Design of Chemical Processes*, 3rd ed.; Prentice Hall of India: Delhi, India, 2012.