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Economic and Environmental Feasibility of Cogeneration from Food Waste: A Case Study in São Paulo City

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Abstract: This paper presents a case study conducted at a food supply centre in a shopping centre in São Paulo city, Brazil. A waste digester was developed based on specifications provided by GE for the generator, and the cost of electricity production from food waste generated in the region was subsequently assessed. Results show that 1,368,750 m^3 biogas was produced for the year, which provided a reduction of 14% of electricity consumption and is equivalent to USD 854 thousand per year. The amount of carbon credits is equivalent to 10,775 metric tons of CO_2 and 51,840 tons of organic waste humus per year. The energy produced by biogas from food waste had a unit cost of 0.10 USD/kWh. At the end of the project, a profit of USD 3.087 million was achieved, which is equivalent to an ROI of 433%. There is a reduction in energy costs by USD 854 thousand per year and a payback of 1.01 years. These indicate that biogas production from food waste is economically viable.

Keywords: ecologic cost accounting; renewable energy; biogas; sustainable development; greenhouse gas mitigation

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1. Introduction

The significance of energy within society is indisputable, and its utilization facilitates the production of goods and the delivery of services that sustain the prevailing quality of life and foster technological advancement [1]. As environmental awareness has risen alongside the increasing demand for energy, there has been a prioritization of developing novel renewable sources for power generation [2]. The push for decarbonization in the global electricity grid has elevated the importance of renewable energy sources in diminishing reliance on fossil fuel-based generation [3]. The use of waste for cogeneration enhances energy efficiency, promotes a circular economy, and reduces environmental footprint [4].

Organic waste as a resource for energy generation has been explored in the literature and has proven to be an environmentally friendly alternative. Pereira and Silva [5] investigated the energetic valorisation of the biowaste fraction from municipal waste to produce biogas from an anaerobic digestion process and electricity. The results indicated a production of 272,221 m^3 of biogas for use as fuel in a cogeneration unit to transform chemical energy into electrical and thermal energy. Furthermore, the self-consumption of the cogeneration unit is 25% of the total electricity produced and 29% of the total thermal energy produced. Drofenik et al. [6] presented the conceptual design of a technological solution for efficiently converting food waste into heat and power. The study found that more than half of food waste originates from homes. A compact plant was devised to transform this waste into biogas, combined with a combined heat and power (CHP) unit and heat pump to double heat output. At micro-CHP capacity, 3330 households could contribute, replacing 5% of natural gas for water heating, with a 7.2-year payback at 80 EUR/MWh. Municipalities with over 40,000 residents see payback in under three years, with the heat cost at approximately 25 EUR/MWh with subsidies. Sidek et al. [7] developed an integrated anaerobic digestion model for biogas production from food waste, predicting the heat and power produced.

Shimako et al. [8] conducted a study to evaluate the environmental impacts of various energy production systems, encompassing both conventional and novel sources. Their findings indicate that heat generated from biogas stands out as the sole product exhibiting satisfactory environmental performance compared to conventional production methods. These findings align with the research conducted by Tufvesson et al. [9], which demonstrated that biogas derived from a range of sources, including cultivated crops, industrial residues, and various types of waste, leads to a reduction in greenhouse gas emissions when compared to fossil fuels. Moreover, Fusi et al. [10] conducted life cycle analyses, revealing that electricity generated from biogas is environmentally superior to grid electricity in seven out of eleven assessed impact categories.

While the current utilization of renewable energy remains limited, there exists a political impetus to augment its utilization in forthcoming years through the advancement of solar and wind energies, as well as the enhancement of electricity production from biogas, particularly notable in Germany and Italy [11]. Riva et al. [12] conducted a multiple case study in Italy to assess the feasibility of utilizing various organic matrices—energy crops (EC), manure, agro-industrial, and organic fractions of municipal solid waste (OFMSW)—for biogas production. They scrutinized the costs associated with biogas production and the energy output in each scenario, arriving at the following conclusions: (1) depending on the source material for biogas production, expenses such as the maintenance of production facilities (in the case of OFMSW), depreciation costs of facilities (in the case of agro-industrial residues), or supply costs (in the case of EC) could escalate the overall energy production costs; (2) The breakeven point for electric energy tariffs, calculated across various scenarios, ranged from 120 to 170 EUR per MWh.

Biogas production from solid waste is gaining traction in Europe [11]. It can be derived from agricultural waste, including animal and human dung [13], microalgae [8], or anaerobic waste from water treatment plants [14]. In the case of biogas production from microalgae, Cardeña et al. [15] observed a significant increase in methane production when ozone was applied to the microalgae culture, attributed to the detrimental effect of O_3 on algal cell wall structure and integrity, thereby enhancing CH_4 fermentation. Additionally, Santos et al. [14] noted that cities with populations exceeding 300,000 could potentially harness energy equivalent to nearly 0.25% of the residual fuels utilized for energy generation within these urban areas.

Castrillón et al. [16] investigated biogas production from manure and determined that a blend of manure and crude glycerin could yield a greater volume of gas compared to the mixtures of manure with fruit and vegetable waste or pure manure. This blend was further enriched through ultrasound application in a pre-treatment process to enhance methane yields. Viewing manure as a resource rather than waste prompts the need for more experimental data to offer precise recommendations regarding the suitability of horse manure for anaerobic digestion [17]. However, not all researchers tout the benefits of anaerobic processes for energy generation; Insam et al. [18] caution that the residues from this process may have adverse climate effects, albeit inconclusive. Bougnom et al. [19] highlight that these residues can exert a dual positive effect on selected soil chemical parameters as well as total forage yield.

Akbulut et al. [20] developed a family-sized anaerobic digestion biogas plant, which proved both technically and economically viable. Investigating the anaerobic digestion of dairy cow manure, sheep dung, and energy maize using a 15 m^3 anaerobic digester installed on a farm, they demonstrated a lower payback time of 4.0 years, with the potential for further reduction with higher biogas volumes. This strategy reduces electricity costs on rural properties and enhances cattle-raising competitiveness while concurrently mitigating pollution and decreasing natural resource utilization [21,22].

Jonge et al. [23] assert that anaerobic digestion of food waste is an increasingly favoured technology within waste management and energy recovery. With food waste constituting the organic fraction of municipal solid waste (OFMSW), its biodegradable nature and high nitrogen content render it suitable for anaerobic digestion to produce energy and stabilize the waste for subsequent use as fertilizer. Notably, the global production of municipal solid waste, which reached 2.01 billion tons in 2016, with an organic fraction ranging from 32 to 50%, is projected to escalate to 3.4 billion tons by 2050 [24].

Oliveira and Rosa [25] suggest that proper treatment of the 20 million tons of solid waste generated in Brazilian cities could yield almost 50 TWh of electricity, akin to incineration. Barros et al. [26] indicate that in cities with populations exceeding 200,000, initiatives utilizing landfill gas plants for energy generation become economically attractive. Minas Gerais, one of Brazil's leading dairy cow and cheese producers, has explored biogas production through the anaerobic digestion of whey [27]. Nevertheless, such endeavours remain limited in Brazil, primarily due to the absence of supportive public policies favouring the development of gas-powered generators over conventional engine adaptations, which yield low energy generation and render the process inefficient and unviable [28].

Therefore, waste-to-energy strategies have been explored for organic waste disposal, offering partial substitution of fossil resources and mitigating environmental impact. Among these strategies, anaerobic digestion stands out as an eco-friendly technology for converting solid or liquid organic wastes into biogas, which can be converted into useful energy such as electricity or heat [29]. Small-scale digesters deployed in rural households and farms across various Asian, African, and Latin American countries have demonstrated several environmental benefits, notably reducing air emissions from traditional fuel combustion for cooking, such as liquefied petroleum gas and firewood, and diminishing synthetic fertilizer usage [30–32].

A commercial generator tailored for biogas has facilitated the transformation of biological waste into electrical energy. With their high specificity and efficiency in gas-to-energy conversion, these generators hold promise for addressing energy shortages in Brazilian rural regions, enhancing farm economic viability, and mitigating environmental impacts from waste [33].

This paper presents a case study conducted in a food supply centre in São Paulo, where the volume of waste generated is substantial and contributes significantly to environmental damage, mainly through emissions from food waste. As advocated by some researchers, an environmentally sound solution for this waste lies in biogas generation and subsequent energy conversion. Thus, this study demonstrates the economic viability of electricity generation from food waste employing a commercial biogas-adapted generator. The case study was developed in one of the shopping centres of Latin America's largest shopping centre chain. These shopping malls generate a lot of organic food waste; thus, this study served as a model for the network's other shopping centres.

Energy from Biogas

The exploration of alternative energy sources dates back to at least the 1990s. However, recent focus on this subject has intensified, notably due to the implementation of the Kyoto Protocol [34,35]. The Kyoto Protocol introduced "Clean Development Mechanisms" that obligate member nations to quantify and mitigate the emissions of greenhouse gases contributing to global warming [36].

Biogas, a naturally occurring gas derived from the anaerobic fermentation of organic materials such as animal waste, crop residues, and various industrial and residential wastes, has gained attention. Biogas typically consists of 27 to 45% carbon dioxide and 55 to 70% methane [37], although exact compositions vary depending on the specific waste being decomposed. Table 1 presents examples of concentration ranges for different biogas constituents [2,38].

Anaerobic digestion stands out as a prominent waste-to-energy technology, converting biodegradable waste into energy-rich biogas. Recent investigations highlight the significant potential of kitchen waste as a feedstock for energy production, with anaerobic digestion emerging as a promising technique compared to alternatives such as incineration, pyrolysis, gasification, landfilling, and composting [39].

The process of transforming waste into biogas through anaerobic digestion occurs within an enclosed environment where bacteria convert organic matter into hydrocarbon gas [40]. This environment, known as a digester, can be categorized into two main types: batch and continuous systems.

Table 1. Values of greenhouse gas concentrations in the biogas.

Gas	Symbol	Biogas Concentration (%)
Methane	CH_4	50–80
Carbon dioxide	CO_2	20–40
Hydrogen	H_2	1.0–3.0
Nitrogen	N_2	0.5–3.0
Sulphide and others	H_2S, CO, NH_3	1.0–5.0
Biogas energy conversion (kWh)		1.43

Source: Adapted from Chaves et al. [38] and Souza et al. [41].

The batch digester is a straightforward digester system with minimal operational requirements. It consists of a fermentation chamber constructed of masonry and a portable gas tank fabricated from sheet metal. To produce biogas, the chamber is filled with waste, which undergoes fermentation for a period of fifteen to twenty days. Biogas production continues for at least twenty days, after which the digester needs to be emptied and cleaned [42].

The continuous digester operates uninterruptedly, with waste being introduced through vessels or pumps at predetermined intervals to facilitate movement and prevent blockage of the inlet hose. There are various models of continuous digesters, with the "Indian" and "Chinese" types being the most commonly used [42]. This study adopted an Indian continuous biodigester because the Chinese biodigester is recommended for smaller volumes. The Indian digester model was originated in Mumbai, India, around 1900. Indian digesters are characterized by a cylindrical fermentation chamber divided into two halves, allowing waste to undergo two stages of fermentation. Additionally, these digesters feature a worker responsible for operating a gas-meter bell, as well as access points for feeding and waste removal [28].

Anaerobic fermentation is inherently intricate, involving the decomposition and transformation of various organic substrates (e.g., carbohydrates, proteins, and lipids) found in raw materials through diverse pathways and at different rates, yielding a broad spectrum of intermediates and end products [43–45]. The digester can receive diverse organic wastes; however, the biogas production yield varies depending on the materials utilized and other factors, such as process temperature, moisture content, and aeration [2,46]. Biogas, besides being a renewable energy source, is recognized as a potential economic asset, as it utilizes agricultural waste from a region to produce energy. Moreover, the byproducts of biogas fermentation can serve as valuable fertilizer [47]. Furthermore, biogas can be harnessed to generate alternative forms of energy, thus, substituting conventional sources [2].

Economic development has spurred a significant demand for energy; however, the depletion of natural resources has prompted society to explore alternative avenues for generating renewable energy. Renewable sources enhance energy efficiency and mitigate environmental harm, exemplified by the production of biogas from organic waste. Recognizing the imperative for renewable energy, General Electric (GE) has engineered a biogas-adapted generator capable of converting waste into energy. This commercially available biogas generator offers a cost-effective solution for sustainable energy production. Its efficacy has been demonstrated across various countries, including India, Austria, and China. Brazil, with its vast and varied climate, is a fitting candidate for showcasing the economic feasibility of generating electricity from food waste using the aforementioned generator.

2. Methods

2.1. Plant Installation Design

This study falls within the realm of exploratory research, as defined by Sahu [48], aimed at developing a deeper understanding of a specific issue. Employing a methodological approach grounded in case study analysis allows for an in-depth examination of the subject matter [48]. Source materials for this study were gathered from various scholarly journals, brochures, and technical information accessible on websites.

The research was conducted in a shopping centre located in São Paulo, which is the largest shopping mall in Brazil and Latin America and the third largest globally, with an area of 423,000 m^2, and owns the shopping centre chain in Brazil. The impetus for this project stemmed from the necessity to address the substantial organic waste generated daily, approximately 150 tons, from food spoilage at the São Paulo supply centre.

In addressing this issue, the project proposed the implementation of a continuous Indian biodigester with a 4000 m^3 capacity for the digestion of food waste to subsequently utilize the resultant biogas in a generator to sustain continuous energy production. A commercial generator equipped with biogas, specifically the J920 motor manufactured by General Electric (New York, NY, USA), was selected for its capacity to achieve high levels of electrical efficiency, capable of delivering up to 9.5 MW per unit [49]. The project's impact is 1% on the shopping centre area, which is considered minimal and within Brazilian environmental standards.

The deployment of the commercial generator adapted for biogas (see Figure 1) has been observed across numerous countries, totalling approximately 560 systems. Collectively, these systems possess a power generation capacity of around 2.8 million megawatt-hours of electricity per year, sufficient to meet the needs of 800,000 European households [49]. The process of energy cogeneration with the commercial generator adapted for biogas involves several sequential steps, as illustrated in Figure 2.

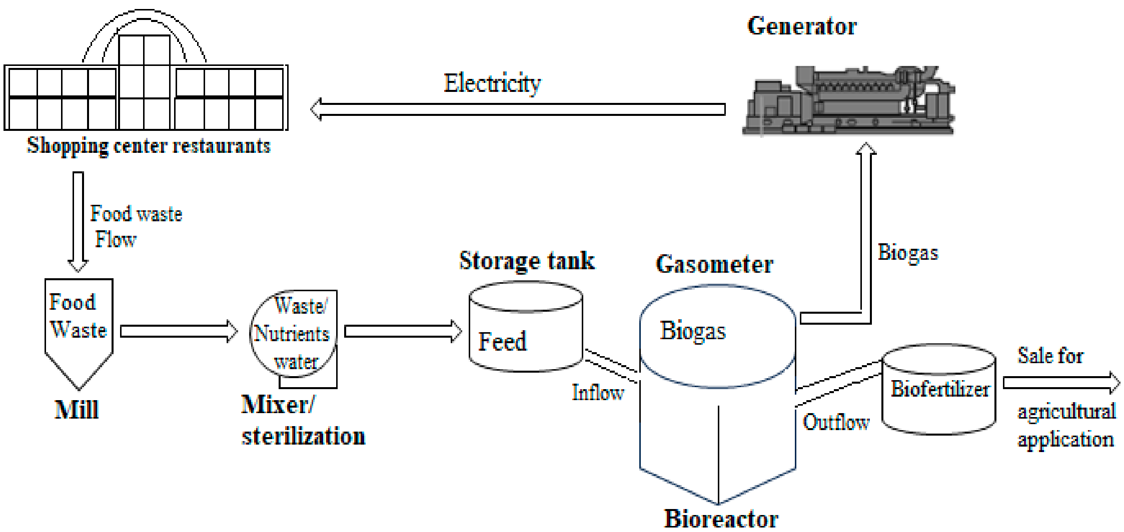

Figure 1. Scheme of the biogas production process from food waste.

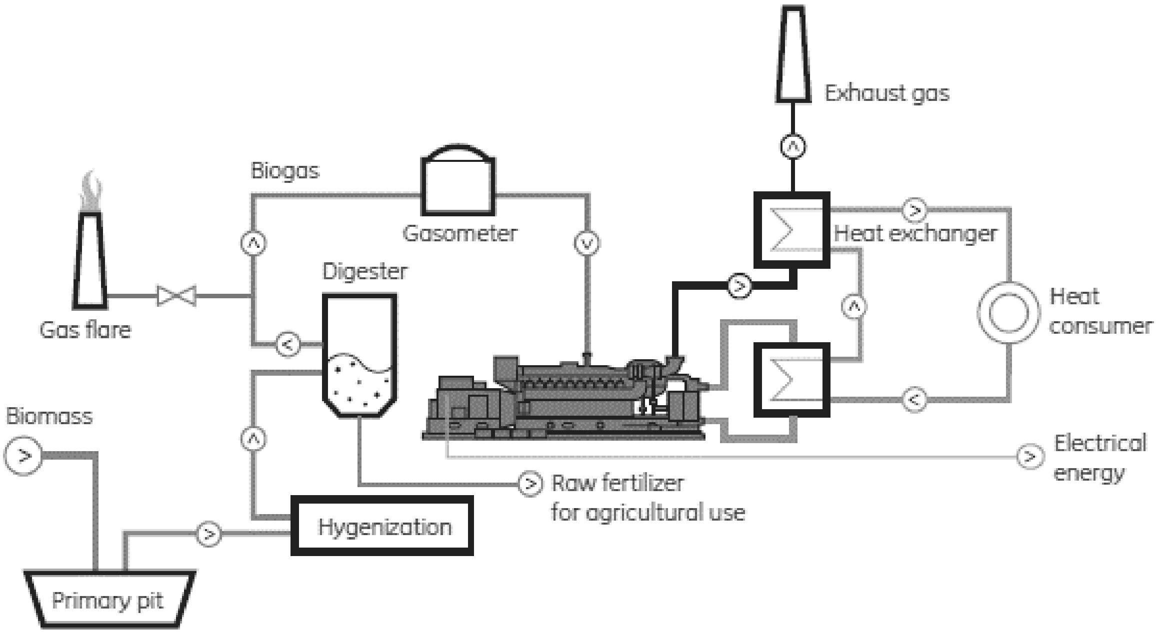

Figure 2. Biogas cogeneration process. Source: General Electric [49].

Initially, organic waste undergoes collection and storage in the primary pit. Subsequently, these wastes undergo sterilization to inhibit the proliferation of harmful microorganisms. The organic material undergoes fermentation within the digester, yielding biogas, which is then stored in a gas meter to ensure a continuous gas supply to the commercial biogas generator. Mechanical energy from the engine is harnessed to drive a generator, facilitating electricity production [49].

The selection of the biodigester's location is pivotal for the feasibility of the bioenergy plant installation project. By considering the location, biomass transport costs can be minimized while simultaneously addressing environmental concerns and complying with legal requirements [50].

The food waste was derived from leftovers from the shopping centre's in-house restaurants, which were crushed and mixed with inorganic nutrients and water. A proportion of 30% of total solids was used on a wet basis and 9% on a dry basis diluted in chlorinated water. Inorganic nutrients were added at the concentrations of 1 g/L of $NH_4H_2PO_4$ and 0.1 g/L of $MgSO_4$, and the pH was corrected from 6.5 to 7.0 with Na_2CO_3. All fermentative musts were sterilized by heating at 60 °C for 15 min before being inserted into the bioreactor [34]. Microorganisms selected from a sewage treatment plant were inserted into the bioreactor and fermented anaerobically until the waste was completely degraded. Gas emissions, temperature and pH were monitored to determine the optimal conditions for biogas production. The solid and liquid residues after fermentation were sold as humus for agricultural applications [29]. The biogas was stored and loaded to a power generator. Figure 2 shows a simplified scheme of biogas production in an anaerobic bioreactor installed in a shopping centre.

2.2. Economic and Environmental Assessment

The economic evaluation of electricity generation through biogas was performed by employing an adaptation of the approach outlined in the studies of Calza et al. [28], Benvenga et al. [34], Jyothilakshmi and Praskash [51], Passarini et al. [52], and Souza et al. [41]. This method encompasses factors such as capital investment, maintenance expenses, and other pertinent variables. Activity-based costing (ABC costing method) was the accounting method used in this work. The allocation of activity costs to products is carried out using a specific apportionment criterion for each activity (cost drivers) [34,52].

A structured procedure was used to assess the feasibility of investments based on the cash flow (CF) method. That makes an accounting balance in each period of the project, allowing the profits to be obtained by subtracting the costs and expenses of the revenues associated with the products. The ABC strategies were used to develop the balance sheets, considering that the prices of products were motivated by the costs associated with the production and the profit desired by the company (Miranda et al., 2018; Silva Filho et al., 2018) [53,54]. Computational techniques (Excel Solver for Windows) were used to simulate the cash flow of the biogas production project for a period of 10 years. Then, all the sensitivity analysis was carried out to determine the return on investment (ROI), net present value (NPV), and payback. It was also used to determine the amount of carbon credits [34,52].

The electricity cost derived from biogas is denoted as Ce [US$/kWh], as defined by Equation (1):

$$Ce = \frac{(ACMG + OME)}{EP} \tag{1}$$

ACMG is the annual cost of investment in the motor-generator and biodigester set [USD/year]; OME is the operation and maintenance expenses per year [USD/year]; and EP is the electricity production from the biogas plant [kWh/year].

$$ACMG = \frac{(ICMG \times CRF + OME)}{10} \tag{2}$$

in which ICMG is the initial cost of the motor-generator plus biodigester set [USD] and the investment time is ten years in Brazil (adopted by authors).

CRF is the capital recovery factor, which is obtained using Equation (3):

$$CRF = \frac{i(1+n)^n}{(1+n)^n - 1} \tag{3}$$

In this case, i is the interest rate and n is the number of years needed to return the investment. The investment was USD 7130 million, at a financial rate of 7.15% for ten years, acquired from the National Economic Development Bank (BNDES).

OME is the operation and maintenance expenses during the year, calculated by Equation (4):

$$OME = ICMG \times 4\% \tag{4}$$

The authors adopted 4%.

The variable EP in Equation (1) means the production of electricity by the biogas plant and is calculated using Equation (5):

$$EP = P \times T \tag{5}$$

In this case, P is the rated plant power output [kW], and T is the operation time of the plant [hours/year].

The payback can be calculated by Equation (6) as follows:

$$Payback = \frac{((ACMG + OME) \times 10)}{(EP \times P_{energy})} \tag{6}$$

in which P_{energy} is the sell price of produced energy = 0.2629 USD/kWh.

The calculation of byproduct saving considered the save from the sale of food waste humus per year (SM), and the the save from the sale of carbon credits per year (CC), see Equations (7) and (8), respectively:

$$SM = Food\ waste\ Weight \times Sale\ Price \tag{7}$$

$$CC = \frac{PGWE \times V_{methane} \times Density_{methane}}{1000} \quad (8)$$

where PGWE is the warming potential of the greenhouse gas (unit less).

The conversion of the energy consumed (or surplus of energy) to carbon credits would be performed using the Official Carbon Credits Calculator developed by the Brazilian GHG Protocol certified by the LRQA Business Assurance [52].

The case study was conducted at a food supply centre in a shopping centre of São Paulo city, boasting 423,000 square meters of constructed area and averaging 50 kWh/m^2 in energy consumption, equivalent to 21.15 GWh per month. Food waste samples were gathered from restaurants within the mall's food courts. These samples were collected on various dates, combined to preserve their proportions, and subsequently crushed using a multiprocessor.

3. Results and Discussion

The temperatures during the biodigestion process were closely monitored and exhibited variability, ranging from 18.5 °C to 26.8 °C, with an average of 21.4 °C. According to Avaci et al. [55], methanogenic bacteria become active when the temperature inside the biodigesters exceeds 10 °C. Optimal temperatures for accelerating anaerobic biodigestion typically fall within the range of 35 °C to 40 °C.

Initially, from the first to the fifth day of the experiment, there was a thermal fluctuation of 0.88 °C. Subsequently, between the 6th and 18th days, the fluctuation decreased to 0.73 °C. In the final period, spanning from the 19th to the 22nd day, the thermal variation increased to 3.37 °C. Notably, a temperature fluctuation of 3 °C is adequate for inducing mortality in a significant portion of the digesting bacteria. Furthermore, if the daily temperature fluctuation reaches 5 °C, it renders the biodigestion process unfeasible [56]. The temperature within the biodigester and the daily thermal fluctuations are shown in Figure 3.

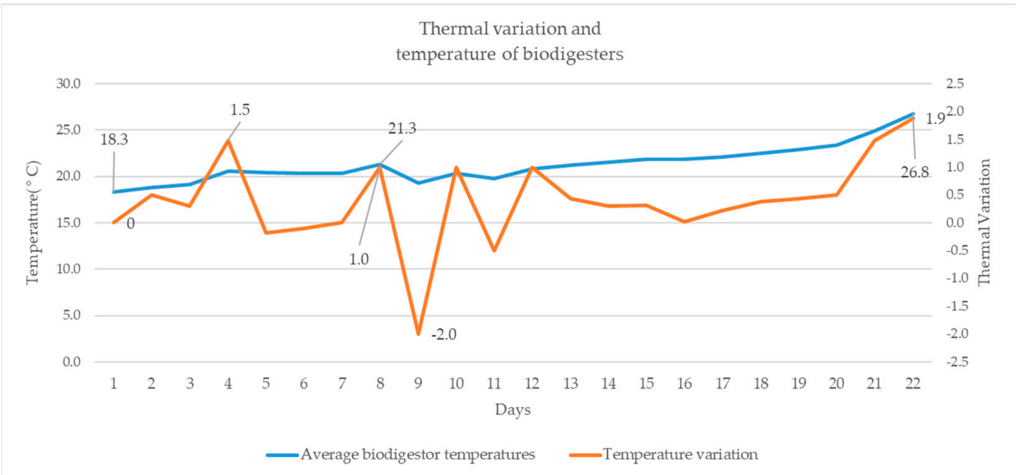

Figure 3. Internal temperature and thermal variation in biodigesters. Source: The author.

The mean temperature of the biodigesters was correlated with the average daily biogas production across the assessed treatments. Experiments E1 and E2 yielded biogas. On average, biogas production persisted for 13 days in E1, starting approximately 5 days after the initiation of the experiment. In E2, the average duration of biogas production was 11 days, with production starting around 5 days after the experiment's commencement. Biogas production data in experiments E1 and E2 are shown in Figure 4.

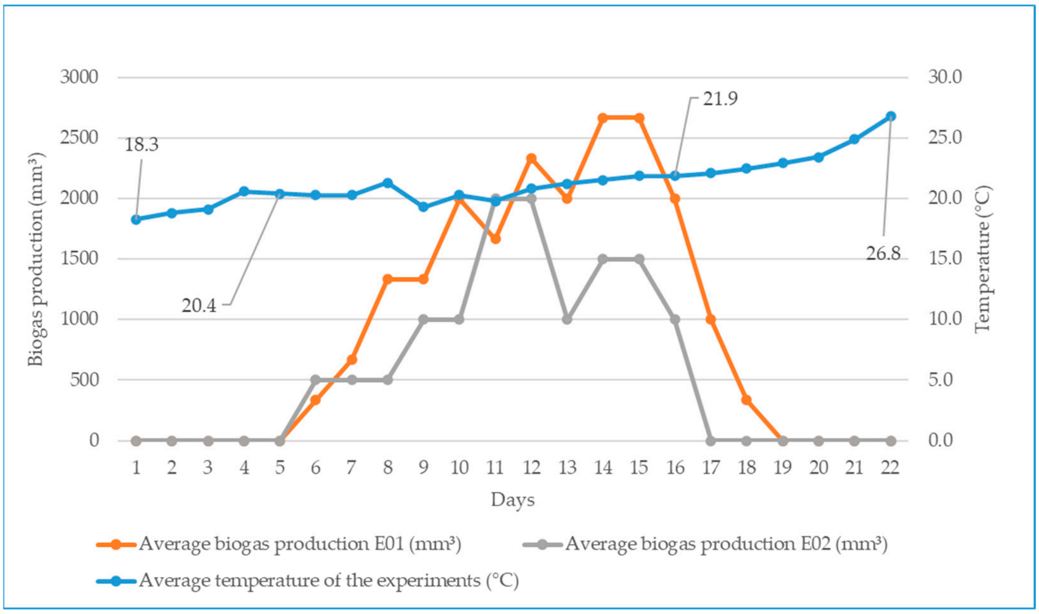

Figure 4. Biogas production and temperature in E1 and E2. Source: The author.

Gyalpo [57] was found in an experiment involving the anaerobic digestion of pig-derived residual solid organic matter, where biogas production persisted for 68 days at a temperature of 25 °C. However, the biogas production extended to 131 days after the temperature was set at 45 °C. The average temperature of the biodigesters in experiments E1 and E2 was initially 18.3 °C. This deviation from the temperatures reported in relevant literature suggests a delayed onset of anaerobic digestion, resulting in a reduced duration of biogas production. Figure 5 depicts the average daily biogas production growth curve for the assessed treatments (E1 and E2). Following the onset of fermentation, biogas production remained consistent. Continuous biomass supply to the biodigester would sustain biogas production at rates of 20,333 mL and 12,500 mL, respectively, for the two treatments.

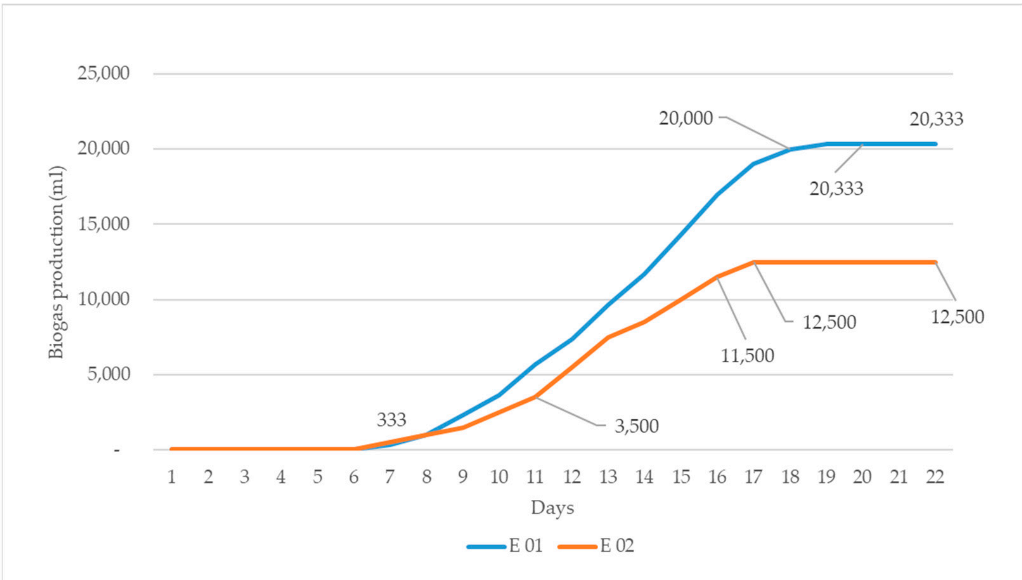

Figure 5. Average Biogas Growth Curve of E1 and E2. Source: The Author.

Comparison between the average production volumes of experiments E1 and E2 yielded 20,333 mL and 12,500 mL, respectively. These findings were juxtaposed with the work of Alkanok et al. [58], considering identical substrates (fruit, vegetable, and flower waste) and mixed waste for biogas production. While the production yields of Alkanok et al. [58] were slightly lower, at 6000 mL and 6800 mL, their biogas generation commenced more rapidly than in experiments E1 and E2, as depicted in Figure 6.

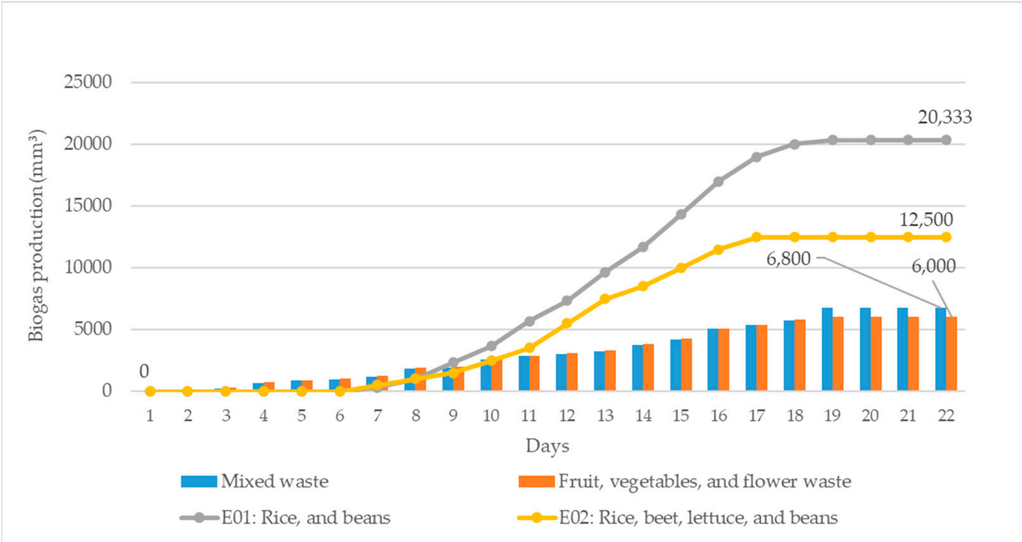

Figure 6. Variation in biogas production into bioreactors.

In a similar study, Kuczman et al. [59] evaluated the energy recovery potential from food wastes and proposed a method to establish anaerobic digestion processes using solely food waste. This was achieved using a prototype anaerobic digester with a total volume of 408 L, comprising 15% total solids, maintained at a temperature of 29.4 °C, and equipped with an agitation system. Operating under steady-state conditions for 51 days with a hydraulic retention time of 103 days, the system achieved a 90% reduction in volatile solids and an 82% reduction in chemical oxygen demand. Methane production rates were observed at 0.51 $L.g^{-1}$ CODc and 0.44 $L.g^{-1}$ VSc, and a volumetric yield of 0.32 $L.L^{-}1rd-^{1}$, representing 59% of the biogas composition.

In another study, Granzotto et al. [60] investigated the treatment of organic residues from a university restaurant. Employing a 200-L semi-pilot scale anaerobic digester monitored over 240 days, the system operated at mesophilic temperatures with varying hydraulic retention times (30 and 60 days). Substrate and digestate pH levels ranged from 4.8 to 6.3 and 6.2 to 7.3, respectively. The study observed average removal rates of 95% for chemical oxygen demand, 95% for biochemical oxygen demand, 53% for total solids, 93% for sedimentable solids, and 77% for volatile solids. The biogas yield was determined at 0.22 $m^3 \cdot kg^{-1}$ vs. or 0.067 $m^3 \cdot kg^{-1}$ of the substrate, with an average methane content of 60%.

Table 2 presents the results of the two experiments, displaying the following parameters: the total biogas production in millilitres from 500 g of biomass in each experiment, yielding 20,333 mL and 12,500 mL, respectively, or 40,666 mL/kg (0.136 m^3/kg dry matter) and 25,000 mL/kg (0.083 m^3/kg dry matter). Additionally, it includes the average duration of biogas production in days, the average daily rate of biogas production in mL/day, the minimum and maximum amounts of biogas produced in a single day, the standard deviation indicating the dispersion of the dataset, and the projected total productivity if the experiments were conducted with 1000 g of biomass. Based on this data, it is calculated that 333.33 metric tons of food waste over 20 days would sustain the daily production of 1 cubic meter of biogas. The produced biogas had 60% methane. Food waste has been proven to generate more biogas per mass and has a shorter residence time than organic animal or vegetable waste. This makes these wastes much more viable for biogas production than others and is an abundant option in large cities.

Table 2. Results obtained from the experiments carried out.

Description	E1	E2	Units
Total average	20,333	12,500	mL/day
Average time	13	12	day
Average production rate	1564	1042	mL/day
Average minimum rate	333	500	mL/day
Maximum average rate	2667	2000	mL/day
Standard deviation mean	809	552	mL/day
Total average productivity	40,666	25,000	mL/kg
Daily average productivity	3128	2083	mL/kg

The experiments experienced a loss in total mass, as shown in Table 3. Additionally, the production of biogas and pH levels at the onset and conclusion of the experiments are noteworthy. Experiment E2 exhibited an average mass loss of 15.40 kg (10.26%), whereas E1 demonstrated a greater reduction with an average loss of 22.30 kg (14.86%). Consequently, E1 yielded a smaller quantity of biofertilizer compared to E2. This discrepancy can be attributed to E2's more efficient conversion of organic matter into biogas, resulting in a more pronounced reduction in mass.

Table 3. Loss of matter and pH.

Experiments	Initial Mass [kg]	Final Mass [kg]	Loss of Matter [kg]	pH	
				Initial	Final
E1	500	477.70	22.30	6.6	6.8
E2	500	484.60	15.40	6.6	7.0

Regarding pH levels at the beginning and end of the experiments, all treatments commenced with a pH of 6.6. Treatments E1 and E2 experienced an increase in pH by the end. The optimal pH range, as per existing literature, typically falls between 6.0 and 8.0 [61]. The initial stages of anaerobic biodigestion can lead to the accumulation of organic acids, causing a decrease in pH. However, methanogenic bacteria facilitate the conversion of acids into gaseous byproducts, thereby restoring pH levels close to neutrality. This mechanism ensures the smooth progression of the biodigestion process [62].

The biogas production in E1 reached 20,333 mL/kg (0136 m^3/kg dry matter), while in E2, it was 12,500 mL/kg (0.083 m^3/kg dry matter). These findings underscore the impact of temperature variation on methanogenic bacteria behaviour, directly affecting biogas production outcomes. Notably, biogas productivity is contingent upon substrate, co-substrate, and inoculum characteristics. Laboratory-scale testing proves crucial for addressing operational challenges in full-scale plants, thereby enhancing system performance, stability, and process control [63]. The experiments conducted on a laboratory scale facilitated economic analyses to support a proposal for implementing a motor generator for biogas electricity production.

3.1. Economic Analysis

The São Paulo supply centre consistently produces an average of 150 tons of organic waste per day, totalling 4,500,000 kg of organic waste per month. Considering an experiment where, on average, 0.025 m^3/kg of biogas was generated, requiring 1 kg of biomass over 30 days, and utilizing a daily waste capacity of 150,000 kg of organic waste, the resultant biogas production amounts to 3750 m^3 per day. Over 30 days, this capacity yields approximately 112,500 m^3 of biogas per month.

The motor generator utilized in this study achieves an electrical power output of 1.8 MW, equivalent to roughly 109,091 kWh per month. According to Silva et al. [64], one m^3 of biogas is equivalent to 4.95 kWh of energy. Thus, the motor generator's biogas consumption reaches approximately 3636 m^3 per day. With an assumed consumption rate of 364 m^3/hour, the biogas digester must possess a daily volume of 4000 m^3.

Silva et al. [64] determined the size and cost of the digester investment in this study. They propose a digester with dimensions of $20 \times 20 \times 10$ m^3, equating to a volume of 4000 m^3, at an approximate cost of USD 23,809.52. Considering the motor generator's biogas consumption rate, the proposed digester volume sufficiently meets the demand with an added safety margin.

The estimated value of the motor generator is approximately USD 674,171.00. Simulating equipment financing, with an interest rate of 7%, provided by the federal government for agricultural activities and an amortization period of 5 years, yields a calculated Fixed Repayment Charge of 0.142.

Operational and maintenance expenses throughout the year, estimated at around 4% of the total investment, according to Souza et al. [41], amount to USD 269.67 annually. Additionally, the annual cost of the motor generator (CAG) is USD 134,888.31. The yearly cost of biogas (CAB) is USD 294.25. The electrical output achieved by the motor generator is 1.8 MW. Assuming the plant operates for 3650 h annually, equivalent to 10 h per day for 365 days, the total annual electricity production (EP) is estimated to be 6,570,000 kWh. Substituting the values of CAG, CAB, and EP into the equation yields a cost of 0.10 USD/kWh. The payback period is calculated to be within one year, with a return-on-investment rate (ROI) of 433% in ten years. Refer to Table 4 for detailed calculations.

Table 4. Data and results of economic analysis results.

Description	Unit	Values
Generator cost estimation	USD	674,171.00
Biodigester cost estimation	USD	23,809.52
Maintenance cost	USD	269.67
Electricity production	kWh/y	6,570,000.00
Unitary energy cost	USD/kWh	0.10
Biomass used	kg/month	4,500,000
Investment	USD	713,000.00
Financial rate	%, a.y.	7.15
Instalments	USD/y	102,220.20
Net present value (NPV)	USD	3,087,820.53
Return on investment (ROI)	%	433%
Payback	Year	1.01

The electricity price from the grid is USD 0.13 per kWh in São Paulo. The energy unitary cost from the motor generation is USD 0.10 per kWh. The energy produced by biogas from food waste had a unit cost of USD 0.10, which is 23% lower than the amount charged in Brazil and 8.3% lower than in the European Union. Given that the shopping centre has an annual average consumption of 45,583,852 kWh, and the motor generator produces 6,570,000 kWh annually, this electricity production accounts for 14% of the shopping centre's total demand in this study. At the end of the project, a profit of USD 3.087 million was achieved, which is equivalent to an ROI of 433%. There is a reduction in energy costs by USD 854 thousand per year, and the project is paid in 1.01 years. These results indicate that the project is very viable and economically safe.

$$\text{Annual cost reduction} = 6{,}570{,}000 \times (0.13) = 854{,}100.00 \text{ USD/y}$$

For context, a typical residence in São Paulo, consisting of two bedrooms, a living room, a laundry area, a kitchen, and one bathroom, consumes approximately 150 kWh per month. With an annual energy production of 6,570,000 kWh, this could power approximately 3650 homes annually. Furthermore, this production results in a reduced volume of methane emissions, generating carbon credits (CC)

3.2. Environmental Analysis

The environmental analysis considered the calculation of carbon credit and humus. When methane gas undergoes combustion to produce CO_2, the Potential Global Warming Equivalent (PGWE) value is determined by the difference between the initial PGWE gas value (21) and the resulting PGWE value (1), yielding a PGWE of 20 [53]. Present negotiations for carbon credit prices average at USD 10.00. Substituting these values into Equation (9) and accounting for the fact that methane constitutes 60% of the methane content in biogas, according to Miranda et al. [54], and assuming an annual biogas production of 1,368,750 m^3, the calculated methane equivalent is approximately 821,250 m^3, corresponding to an emission of 10,775 tons of CO_2 per year.

$$CC = \frac{PGWE \times V_{methane} \times Density_{methane}}{1000} \tag{9}$$

$$CC = \frac{20 \times 821,250 \times 0.656}{1000} = 10,775$$

Considering the mean market value of carbon credits (CC) at USD 10.00 per unit [65], with each CC equivalent to 10,775 metric tons of CO_2, a total gain of USD 107,748 can be achieved, alongside an enhanced corporate image within the market.

Another environmental benefit was the humus generation from biodigester residues. This study assumes the humus market price of 12.00 USD/ton, as reported by Farezin et al. [66]. The disposal of organic waste is 150 tons daily, which means 54,000 tons annually. Considering a 4% loss of organic matter within the biodigester, the annual organic waste available for humus production decreases to 51,840 tons. Multiplying this quantity by the humus price of 12.00 USD/ton yields an estimated yearly gain of approximately USD 622,080. These sources of sustainable by-products can double the project's revenue, but as there are many uncertainties in their markets (possibility of sale, demand for products, price variation, etc.), they are not considered in cost accounting.

With the implementation of biogas generator technology, the shopping centre gains numerous advantages:

- Mitigates organic waste accumulation (e.g., food waste) and waste disposal;
- Converts waste into renewable energy;
- Decreases greenhouse gas emissions;
- Recycles organic materials utilized into fertilizer, characterized by high quality and minimal odour;
- Reduces its internal costs with energy.

Additionally, there are reductions in the generation of organic solid waste from the shopping centre by 54,000 tons, in energy consumption by 6500 MWh, and in GHG emissions of 54,000 t of CO_2 per year.

4. Conclusions

The company stopped generating 54 thousand tons of food waste to produce 1,368,750 m^3 biogas and 51,840 tons of organic waste humus, and 10,775 metric tons of carbon credits per year were produced, mitigating the generation of food waste and 14% of energy consumption.

The energy produced by biogas from food waste had a unit cost of 0.10 USD/kWh. At the end of the project, a profit of USD 3.087 million was achieved, which is equivalent to an ROI of 433%. There is a reduction in energy costs by USD 854 thousand per year and a payback of 1.01 per year. These indicate that biogas production from food waste is economically viable.

Furthermore, the adoption of this technology presents other advantages. The reuse of thermal energy dissipated by the equipment and the utilization of humus as a protein-rich fertilizer offers additional gains. These figures underscore the multifaceted benefits of integrating the motor generator technology into waste management practices, highlighting its potential as a sustainable energy solution.

While this study demonstrates promising outcomes, it is important to acknowledge its limitations and suggestions for future research. One limitation lies in the specificity of the case study conducted in São Paulo, which may not be directly applicable to other regions with different waste management infrastructures or energy demands. Future studies could explore the scalability and adaptability of this technology in diverse geographical contexts, as well as delve deeper into the environmental impacts and potential challenges associated with large-scale implementation. Additionally, investigations into optimizing the efficiency and cost-effectiveness of the biogas generation process, along with exploring innovative methods for maximizing the utilization of by-products such as humus, can further enhance this approach's sustainability and economic viability.

Thus, this research lays a foundation for future endeavours aimed at harnessing the potential of food waste as a renewable energy resource while emphasizing the need for continuous innovation and exploration in this field. In addition, this model of waste reuse can certainly be implemented on a large scale around the world, especially in regions with clusters of restaurants.

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References

1. Bianco, G.; Bonvini, B.; Bracco, S.; Delfino, F.; Laiolo, P.; Piazza, G. Key performance indicators for an energy community based on sustainable technologies. *Sustainability* **2021**, *13*, 8789. [CrossRef]
2. Azman, S.; Khadem, A.F.; Van Lier, J.B.; Zeeman, G.; Plugge, C.M. Presence and role of anaerobic hydrolytic microbes in conversion of lignocellulosic biomass for biogas production. *Crit. Rev. Environ. Sci. Technol.* **2015**, *45*, 2523–2564. [CrossRef]
3. de Souza Machado, A.C.C.; Filho, G.L.T.; de Abreu, T.M.; Facchini, F.; da Silva, R.F.; Pinto, L.F.R. Use of Balanced Scorecard (BSC) Performance Indicators for Small-Scale Hydropower Project Attractiveness Analysis. *Energies* **2023**, *16*, 6615. [CrossRef]
4. Pinto, L.F.R.; Tucci, H.N.P.; Mummolo, G.; Neto, G.C.d.O.; Facchini, F. Circular Economy Approach on Energy Cogeneration in Petroleum Refining. *Energies* **2022**, *15*, 1713. [CrossRef]
5. Pereira, F.; Silva, C. Energetic Valorization of Bio-Waste from Municipal SolidWaste in Porto Santo Island. *Clean Technol.* **2023**, *5*, 233–258. [CrossRef]
6. Drofenik, J.; Urbancl, D.; Goricanec, D.; Kravanja, Z.; Novak Pintaric, Z. Food Waste to Energy through Innovative Coupling of CHP and Heat Pump. *Energies* **2023**, *16*, 3344. [CrossRef]
7. Sidek, N.F.; Harun, N.; Liyana, F.N.; Zamri, M. Simulation of an Integrated Anaerobic Digestion and Combined Heat and Power System for Food Waste Utilization. *Chem. Eng. Technol.* **2022**, *45*, 1454–1460. [CrossRef]
8. Shimako, A.H.; Tiruta-Barna, L.; Pign, Y.; Benetto, E.; Gutiérrez, T.N.; Guiraud, P.; Ahmadi, A. Environmental assessment of bioenergy production from microalgae based systems. *J. Clean. Prod.* **2016**, *139*, 51–60. [CrossRef]
9. Tufvesson, L.M.; Lantz, M.; Börjesson, P. Environmental performance of biogas produced from industrial residues including competition with animal feed—Life-cycle calculations according to different methodologies and standards. *J. Clean. Prod.* **2013**, *53*, 214–223. [CrossRef]
10. Fusi, A.; Bacenetti, J.; Fiala, M.; Azapagic, A. Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion. *Front. Bioeng. Biotechnol.* **2016**, *4*, 26. [CrossRef]

11. Torrijos, M. State of Development of Biogas Production in Europe. *Procedia Environ. Sci.* **2016**, *35*, 881–889. [CrossRef]
12. Riva, C.; Schievano, A.; D'Imporzano, G.; Adani, F. Production costs and operative margins in electric energy generation from biogas. Full-scale case studies in Italy. *Waste Manag.* **2014**, *34*, 1429–1435. [CrossRef] [PubMed]
13. Kumar, R.; Kumar, V.; Nagpure, A.S. Bio-energy potential of available livestock waste and surplus agriculture crop residue: An analysis of 602 rural districts of India. *Sci. Total Environ.* **2023**, *889*, 163974. [CrossRef]
14. Santos, I.F.S.; Barros, M.B.; Tiago Filho, G.L. Electricity generation from biogas of anaerobic wastewater treatment plants in Brazil: An assessment of feasibility and potential. *J. Clean. Prod.* **2016**, *126*, 504–514. [CrossRef]
15. Cardeña, R.; Moreno, G.; Bakonyi, P.; Buitrón, G. Enhancement of methane production from various microalgae cultures via novel ozonation pretreatment. *Chem. Eng. J.* **2017**, *307*, 948–954. [CrossRef]
16. Castrillón, L.; Fernández-Nava, Y.; Ormaechea, P.; Marañón, E. Optimization of biogas production from cattle manure by pre-treatment with ultrasound and co-digestion with crude glycerine. *Bioresour. Technol.* **2011**, *102*, 7845–7849. [CrossRef] [PubMed]
17. Hadin, A.; Eriksson, O. Horse manure as feedstock for anaerobic digestion. *Waste Manag.* **2016**, *56*, 506–518. [CrossRef]
18. Insam, H.; Gómez-Brandón, M.; Ascher, J. Manure-based biogas fermentation residues—Friend or foe of soil fertility? *Soil Biol. Biochem.* **2015**, *84*, 1–14. [CrossRef]
19. Bougnom, B.P.; Niederkofler, C.; Knapp, B.A.; Stimpfl, E.; Insam, H. Residues from renewable energy production: Their value for fertilizing pastures. *Biomass Bioenergy* **2012**, *39*, 290–295. [CrossRef]
20. Akbulut, A.; Kose, R.; Akbulut, A. Technical and Economic Assessments of Biogas Production in a Family Size Digester Utilizing Different Feedstock Rotations: Döğer Case Study. *Int. J. Green Energy* **2014**, *11*, 113–128. [CrossRef]
21. Guares, S.A.; Lima, J.D.; Oliveira, G.A. Techno-economic model to appraise the use of cattle manure in biodigesters in the generation of electrical energy and biofertilizer. *Biomass Bioenergy* **2021**, *150*, 106107. [CrossRef]
22. Dranka, G.G.; Cunha, J.; Lima, J.D.; Ferreira, P. Economic evaluation methodologies for renewable energy projects. *AIMS Energy* **2020**, *8*, 339–364. [CrossRef]
23. Jonge, N.; Davidson, A.; Jansen, J.C.; Nielsen, J.L. Characterisation of microbial communities for improved management of anaerobic digestion of food waste. *Waste Manag.* **2020**, *117*, 124–135. [CrossRef] [PubMed]
24. Kaza, S.; Yao, L.; Perinaz, B.-T.; Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; Urban Development Series; World Bank: Washington, DC, USA, 2018. [CrossRef]
25. Oliveira, L.B.; Rosa, L.P. Brazilian waste potential: Energy, environmental, social and economic benefits. *Energy Policy* **2003**, *31*, 1481–1491. [CrossRef]
26. Barros, R.M.; Tiago Filho, G.L.; Silva, T.R. The electric energy potential of landfill biogas in Brazil. *Energy Policy* **2014**, *65*, 150–164. [CrossRef]
27. Antonelli, J.; Lindino, C.A.; Azevedo, J.C.R.; Souza, S.N.M.; Cremonez, P.A.; Rossi, E. Biogas production by the anaerobic digestion of whey. *Revista Ciênc. Agrar.* **2016**, *39*, 463–467. [CrossRef]
28. Calza, L.F.; de Lima, C.B.; Nogueira, C.E.C.; Siqueira, J.A.C.; Santos, R.F. Cost assessment of biodigester implementation and biogas produced energy. *Eng. Agric.* **2015**, *35*, 990–997. [CrossRef]
29. Neto, J.G.; Ozorio, L.V.; Abreu, T.C.C.; Santos, B.F.; Pradelle, F. Modeling of biogas production from food, fruits and vegetables wastes using artificial neural network (ANN). *Fuel* **2021**, *285*, 119081. [CrossRef]
30. Mendieta, O.; Castro, L.; Escalante, H.; Garfi, M. Low-cost anaerobic digester to promote the circular bioeconomy in the non-centrifugal cane sugar sector: A life cycle assessment. *Bioresour. Technol.* **2021**, *326*, 124783. [CrossRef]
31. Lansche, J.; Müller, J. Life cycle assessment (LCA) of biogas versus dung combustion household cooking systems in developing countries—A case study in Ethiopia. *J. Clean. Prod.* **2017**, *165*, 828–835. [CrossRef]
32. Garfí, M.; Castro, L.; Montero, N.; Escalante, H.; Ferrer, I. Evaluating environmental benefits of low-cost biogas digesters in small-scale farms in Colombia: A life cycle assessment. *Bioresour. Technol.* **2019**, *274*, 541–548. [CrossRef] [PubMed]
33. Carvalho, B.V.; Melo e Sousa, A.P.; Soto, F.R.M. Evaluation of environmental management systems on swine farms. *Revista Ambiente Água* **2015**, *10*, 164–171. [CrossRef]
34. Benvenga, M.A.C.; Librantz, A.F.H.; Santana, J.C.C.; Tambourgi, E.B. Genetic algorithm applied to study of the economic viability of alcohol production from Cassava root from 2002 to 2013. *J. Clean. Prod.* **2016**, *113*, 483–494. [CrossRef]
35. Giraçol, J.; Passarini, K.C.; Silva Filho, S.C.; Calarge, F.A.; Tambourgi, E.B.; Santana, J.C.C. Reduction in ecological cost through biofuel production from cooking oils: An ecological solution for the city of Campinas, Brazil. *J. Clean. Prod.* **2011**, *19*, 1324–1329. [CrossRef]
36. Basseto, L.I.; Silva, C.L.; Rocha Junior, W.F. Mercado de carbono e instituições: Oportunidades na busca por um novo modelo de desenvolvimento. *Interciencia* **2012**, *37*, 8–13.
37. Goldemberg, J.; Coelho, S.T. Bioenergy: How much? *Environ. Res. Lett.* **2013**, *8*, 031005. [CrossRef]
38. Chaves, L.I.; da Silva, M.J.; de Souza, M.S.N.; Secco, D.; Rosa, H.A.; Nogueira, C.E.C.N.; Frigo, E.P. Small-scale power generation analysis: Downdraft gasifier coupled to engine generator set. *Renew. Sustain. Energy Rev.* **2016**, *58*, 491–498. [CrossRef]
39. Ajay, C.M.; Mohan, S.; Dinesha, P. Decentralized energy from portable biogas digesters using domestic kitchen waste: A review. *Waste Manag.* **2021**, *125*, 10–26. [CrossRef] [PubMed]
40. Ristinen, R.A.; Kraushaar, J.P. *Energy and the Environment*, 2nd ed.; Wiley: New York, NY, USA, 2005; p. 384.

41. Souza, S.N.M.; Pereira, W.C.; Nogueira, C.E.C.; Pavan, A.A.; Sordi, A. Cost of electricity by hog raising biogas in group engine generators. *Acta Sci. Technol.* **2004**, *26*, 127–133. [CrossRef]
42. Borges Neto, M.R.; Carvalho, P.C.M.; Carioca, J.O.B.; Canafístula, F.J.F. Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas. *Energy Policy* **2010**, *38*, 4497–4506. [CrossRef]
43. Zhang, M.; Zhang, Y.; Zhenqwen, L.; Zhang, C.; Tan, Z.; Liu, X.; Wan, C.; Yang, X.; Lee, D.J. Anaerobic co-digestion of food waste/excess sludge: Substrates—Products transformation and role of NADH as an indicator. *J. Environ. Manag.* **2019**, *232*, 197–206. [CrossRef] [PubMed]
44. Kim, M.; Chowdhury, M.M.I.; Nakhla, G.; Keleman, M. Synergism of co-digestion of food wastes with municipal wastewater treatment biosolids. *Waste Manag.* **2017**, *61*, 473–483. [CrossRef] [PubMed]
45. Dalke, R.; Demro, D.; Khalid, Y.; Wu, H.; Dermitas, M.U. Current status of anaerobic digestion of food waste in the United States. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111554. [CrossRef]
46. Li, W.; Guo, J.B.; Cheng, H.C.; Wang, W.; Dong, R.J. Two-phase anaerobic digestion of municipal solid wastes enhanced by hydrothermal pretreatment: Viability, performance and microbial community evaluation. *Appl. Energy* **2017**, *189*, 613–622. [CrossRef]
47. Turdera, M.V.; Yura, D. Estudo da viabilidade de um biodigestor no município de dourados. In Proceedings of the 6th Encontro de Energia no Meio Rural, Campinas, Brazil, 6–8 June 2006. Available online: http://www.proceedings.scielo.br/scielo.php?script=sci_arttext&pid=MSC0000000022006000100062&lng=en&nrm=iso (accessed on 20 December 2023).
48. Sahu, P.K. Research Methodology: A Guide for Researchers. In *Agricultural Science, Social Science and Other Related Fields*; Springer: New Delhi, India, 2013; p. 432.
49. General Electric. Some Energy Lasts for Generations. Available online: https://www.jenbacher.com/en/energy-solutions/energy-sources/biogas (accessed on 18 October 2023).
50. Jesus, R.H.G.; Souza, J.T.; Piglieri, F.N.; Pierkarski, C.M.; Francisco, A.C. Biodigester location problems, its economic–environmental–social aspects and techniques: Areas yet to be explored. *Energy Rep.* **2021**, *7*, 3998–4008. [CrossRef]
51. Jyothilakshmi, R.; Praskash, S.V. Design, fabrication and experimentation of a small scale anaerobic biodigester for domestic biodegradable solid waste with energy recovery and sizing calculation. *Procedia Environ. Sci.* **2016**, *35*, 749–755. [CrossRef]
52. Passarini, K.C.; Pereira, M.A.; Farias, T.M.B.; Calarge, F.A.; Santana, C.C. Assessment of the viability and sustainability of an integrated waste management system for the city of Campinas (Brazil), by means of ecological cost accounting. *J. Clean. Prod.* **2014**, *65*, 479–488. [CrossRef]
53. Silva Filho, S.C.; Miranda, A.C.; Silva, T.A.F.; Calarge, F.A.; Souza, R.R.; Santana, J.C.C.; Tambourgi, E.B. Data on kinetic, energy and emission performance of biodiesel from waste frying oil. *Data Brief* **2018**, *18*, 1224–1228. [CrossRef] [PubMed]
54. Miranda, A.C.; Silva Filho, S.C.; Tambourgi, E.B.; Curvelo Santana, J.C.; Vanalle, R.M.; Guerhardt, F. Analysis of the costs and logistics of biodiesel production from used cooking oil in the metropolitan region of Campinas (Brazil). *Renew. Sustain. Energy Rev.* **2018**, *88*, 373–379. [CrossRef]
55. Avaci, A.B.; Souza, S.N.M.; Chaves, L.I.; Nogueira, E.C.; Niedzialkoski, R.K.; Secco, D. Avaliação econômico-financeira da microgeração de energia elétrica proveniente de biogás da suinocultura. *Rev. Bras. Eng. Agric. Ambient.* **2014**, *17*, 456–462. [CrossRef]
56. Guerra Sgorlon, J.; Rizk, M.C.; Bergamasco, R.; Granhen Tavares, C.R. Avaliação da DQO e da relação C/N obtidas no tratamento anaeróbio de resíduos fruti-hortículas. *Acta Sci. Technol.* **2011**, *33*, 421–424. [CrossRef]
57. Gyalpo, T. *Anaerobic Digestion of Canteen Waste at a Secondary School in Dar es Salaam, Tanzania*; Swiss Federal Institute of Aquatic Science and Technology (Eawag): Dübendorf, Switzerland, 2010.
58. Alkanok, G.; Demirel, B.; Onay, T.T. Determination of biogas generation potential as a renewable energy source from supermarket wastes. *Waste Manag.* **2014**, *34*, 134–140. [CrossRef] [PubMed]
59. Kuczman, O.; Gueri, M.V.D.; Souza, S.N.M.; Schirmer, W.N.; Alves, J.E.; Secco, D.; Buratto, W.G.; Ribeiro, C.B.; Hernandes, F.B. Food waste anaerobic digestion of a popular restaurant in Southern Brazil. *J. Clean. Prod.* **2018**, *196*, 382–389. [CrossRef]
60. Granzotto, F.; Aita, C.; Silveira, D.D.; Mayer, F.D.; Pujol, S.B.; Pinas, J.A.V.; Hoffmann, R. Use of anaerobic biodigestor in the treatment of organic waste from a university restaurant. *J. Environ. Chem. Eng.* **2021**, *9*, 105795. [CrossRef]
61. Ogejo, J.A.; Li, L. Enhancing biomethane production from flush dairy manure with turkey processing wastewater. *Appl. Energy* **2010**, *87*, 3171–3177. [CrossRef]
62. Silva, F.B.; Zaneti, I.C.; Silva, G.O. Implementação do reator artesanal para biodigestão anaeróbia de resíduos alimentares do restaurante universitário da UNB. In Proceedings of the 9th Fórum Internacional de Resíduos Sólidos, Porto Alegre, Brazil, 13–15 June 2018; Instituto Venturi: Porto Alegre, Brazil, 2018; pp. 1–9. Available online: https://www.institutoventuri.org.br/ojs/index.php/firs/article/view/763 (accessed on 20 December 2023).
63. Franca, L.S.; Bassin, J.P. The role of dry anaerobic digestion in the treatment of the organic fraction of municipal solid waste: A systematic review. *Biomass Bioenergy* **2020**, *143*, 105866. [CrossRef]
64. Silva, J.P.; Berwing, K.H.; Dettmers, A. Obtenção de biogás a partir de combinações de resíduos de arroz e esterco suíno. In Proceedings of the XX Congresso Brasileiro de Engenharia Química, Florianópolis, Brazil, 19–22 October 2017.

65. Wang, L.; Yang, C.; Xu, Z.; Yuan, G.; Tang, L.; Bai, Y.; Wang, X. Analysis of carbon electricity coupled market modeling method based on carbon credit trading mechanism. *Int. J. Electr. Power Energy Syst.* **2024**, *156*, 109707. [CrossRef]
66. Farezin, E.C.; Sarubbi, J.; Morais, J.L.R.; Junior, W.H.; Soto, F.R.M. Análise ambiental, sanitária e econômica de um sistema de tratamento de resíduos sólidos e efluentes em uma granja de suínos. *Veterinária e Zootec.* **2018**, *25*, 164–172. [CrossRef]