Energy Nexus 20 (2025) 100602

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Small-scale biodigesters in a tropical semi-arid region: Impacts on emissions and water, energy and food security

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ARTICLE INFO

Keywords:
Social technology
Family farming
Biogas
Biofertilizer
Life cycle assessment

ABSTRACT

Due to the growing search for natural resources to meet human needs, interest has arisen in developing technologies based on the Water-Energy-Food (WEF) nexus. The implementation of biodigesters on small farms is an initiative that aligns with global agendas and the WEF nexus concept. This research aimed to evaluate the integration of a small-scale biodigester prototype locally referred to as "*biodigestor sertanejo*," on the water, energy, food, and environmental security of smallholder farmers in the semi-arid region of northeastern (NE) Brazil. Primary data were obtained from semi-structured questionnaires. A physical-chemical analysis of the digestate as a biofertilizer was also carried out. The emissions from the biodigester were analyzed using the life cycle assessment method. The use of biodigesters to treat animal waste has positively impacted the lives of families by reducing the proliferation of diseases and the contamination of water resources. Replacing firewood with biogas for cooking also helped reduce the number of cases of respiratory diseases in families by 10.9 %. It was also found that domestic savings of around USD 201.3 per year resulted from the switch to biogas energy.

Another benefit was using the digestate from the biodigester as an organic fertilizer, which increased food production. Environmental analysis showed that using manure for biogas production emits fewer greenhouse gases than applying it directly to crops or leaving it in open fields. This work provides insights for better management of water and energy resources in a semi-arid region and can support public policies and investments. The results also demonstrate how this technology enhances food security for local populations, which could serve as an incentive to expand its use.

Introduction

Low-income rural populations living in Drylands worldwide face multiple, overlapping risks, including hydrological variability and water scarcity, dependence on biomass for cooking, inadequate sanitation, and exposure to heat and air pollution. These pressures are interconnected through the Water–Energy–Food (WEF) nexus, where actions to secure one resource affect the others. Nevertheless, evaluations often isolate

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https://doi.org/10.1016/j.nexus.2025.100602
Received 20 December 2023; Received in revised form 5 November 2025; Accepted 18 November 2025

sectors, overlooking safety implications for women, children, and the elderly, who are most involved in cooking, fuel collection, and waste handling.

In regions with low economic development and high social inequality, such as the semi-arid Northeast (NE) of Brazil, there is growing interest in technologies that balance water, energy, and food sovereignty The application of these technologies is a crucial step toward reducing poverty, promoting economic growth, and improving living standards on a global scale [1]. Family farming represents about 77 % of agricultural establishments in Brazil and occupies around 23 % of cultivated areas [2]. In the Brazilian semi-arid region, family farms support >3.26 million people and are essential for local food supply, reinforcing the need to ensure their sustainability [3].

According to Barron-Gafford et al. [4], arid and semi-arid areas face the most severe challenges in guaranteeing water, energy, and food security, which are expected to intensify under future climate scenarios. These regions will likely suffer even more water limitations due to expected future climate scenarios [5]. Social technologies, developed from low-cost materials, to promote inclusion and social well-being [6,8], are promising alternatives in this context. Among them, the "*biodigestor sertanejo*" - a small-scale biodigester (SSB) with a volume of 15 m^3 - uses cattle manure and plant residues to produce biogas for cooking. This process reduces dependence on firewood and liquefied petroleum gas (LPG), thereby decreasing deforestation and greenhouse gas emissions. Approximately 50 % of all primary energy consumed in Northeast Brazil comes from firewood and gas (LPG) [7,9], and after the COVID-19 pandemic and the Russia-Ukraine War, LPG prices have increased substantially, further burdening low-income families [7].

The by-product of biodigestion, a nutrient-rich effluent or biofertilizer, is widely used in vegetable gardens to improve soil fertility and family nutrition while generating additional income. The treatment of residual biomass in biodigesters also contributes to environmental sanitation, reducing water pollution and risks of environmental accidents [10,11].

Household biodigesters are often promoted in drylands as social technologies that convert animal manure into clean cooking fuel and biofertilizer. However, most assessments prioritize technical yield or climate metrics, paying limited attention to safety outcomes related to indoor air quality, pathogen exposure, and operational reliability. To address these gaps, a framework that integrates WEF-safety and Life Cycle Assessment (LCA) is necessary to identify both co-benefits and trade-offs in resource-stressed environments. The WEF Nexus highlights the interdependencies among water, energy, and food systems, emphasizing integrated management to optimize resource use and promote sustainable development [12].

In this context, the SSB technology helps reduce dependence on firewood and LPG [9] while producing effluent suitable for fertigation in food production systems within a semi-arid ecosystem. Bioenergy presents complex links with water and food security, which can be either positive or negative, and therefore need to be evaluated using the WEF Nexus perspective to enhance sustainability [13]. Despite being relatively widespread in NE Brazil, the SSB technology has been little studied regarding its relationship with water, energy, and food security, or its environmental impacts compared to conventional energy sources. The application of LCA provides a robust method to analyze these impacts and identify sustainable alternatives under climate stress conditions [12].

This work is original in coupling a safety-oriented WEF Nexus assessment with process-based LCA to evaluate household biodigesters in an understudied semi-arid smallholder setting. Interviews with farmers, physicochemical analysis, and greenhouse gas (GHG) emissions measurements were conducted to assess the system of environmental performance and potential for climate mitigation. This integrated approach provides a comprehensive understanding of the role of SSB in the Brazilian semi-arid region, which may be helpful to the discussion of the potential of this technology in other regions of the world with similar socioeconomic and environmental characteristics.

Materials and methods

Data collection

A semi-structured survey (Supplementary Material - Section 1) was applied between March and August 2022 in farms where SSB of the "*biodigestor sertanejo*" type had been built between 2008 and 2015.

The "*biodigestor sertanejo*" (Fig. 1) is a technology adapted from the Indian biodigester model. It consists of three parts: the Loading Box, the Fermentation Tank, which also houses the biogas storage chamber, and the Discharge Box [9]. According to the authors, in the Loading Box, the homogeneous mixture of animal excrement (cattle, pigs, goats, and/or poultry) and water, supplies the Fermentation Tank where the biogas is produced and stored. A liquid product, the digestate, resulting from the fermentation process, is disposed of in the Discharge Tank and used as a biofertilizer. The first supply is around 6800 kg of the mixture, comprising 3400 L of water and 3400 kg of manure, and it takes about 30 days to start producing biogas. After this period, the biodigester is fed about 1 kg of manure to 1 L of water per day, depending on how often the biogas is used [14].

All farms were assisted by the NGO Diaconia, which, in partnership with other social organizations, provided the funds to construct the biodigesters. The farms were spread over seven municipalities in the microregion of Sertão do Pajeú, in the semi-arid portion of Pernambuco, Brazil (Fig. 2).

Of the 174 visited smallholder households, 109 were included in the analytical sample. Exclusions ($n = 65$) followed pre-specified criteria: (i) the biodigester was abandoned or its structure removed, preventing meaningful measurement of biogas/digestate use ($n = 15$); (ii) no consent/unavailable respondent after two call-backs ($n = 5$); (iii) missing core variables after field QC (e.g., fuel expenditures, herd size, digestate application) ($n = 20$); (iv) duplicate or unresolved contradictory records flagged during audits ($n = 20$); and (v) ineligible after screening (e.g., non-resident or no livestock) ($n = 5$). The survey was built to address questions related to the operation of the biodigesters, the agricultural activities on the farms, socioeconomic issues, and the perception of the families about the interconnection of the biodigester with the WEF nexus. We also analyzed whether the biodigesters were active or inactive and, if so, why they were not working.

Direct observations were also made regarding the conditions of the biodigesters on the farms of the families interviewed. The composition of the biogas (percentages of CH_4, CO_2, and H_2S) was also measured on 13 farms where the biodigesters were active and being fed with cattle manure (10 farms), only by pig manure (2 farms), and both types (1 farm) using the GEM 5000 m from Landtec.

The 174 interviews were used solely to estimate the number of active biodigesters, the duration of inactivity, and the reasons for ceasing operations among the sample of farmers, based on the total number of rural properties in Pernambuco with a biodigester installed by Diaconia in Pernambuco State. For the other data, we treated the 109 interviews that were fully answered as the sampling unit. In both cases, was calculated with a confidence level of 95 % and a sampling error of 6 percentage points.

Impact assessment

Based on the data from the interviews, the impacts of the "*biodigestor sertanejo*" on the lives of family farmers regarding water, energy, and food security were analyzed. Besides that, a Life Cycle Assessment method was performed to measure the impact of the construction and operation of the biodigester on the balance of GHG emissions [15].

2.2.1. Nexus impact (water–energy– food)

Fig. 3 shows the configuration in which this paper structured its

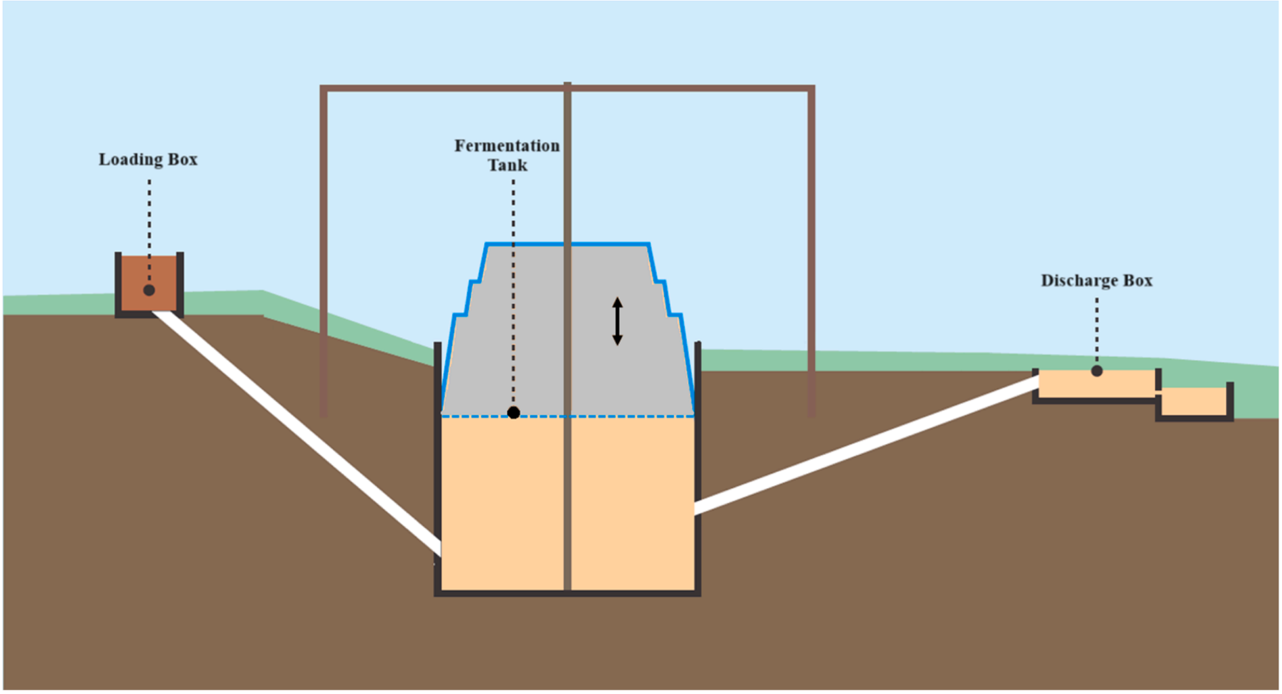

Fig. 1. **-** Parts of the *"biodigestor sertanejo"*.
Source: Adapted from Diaconia [14].

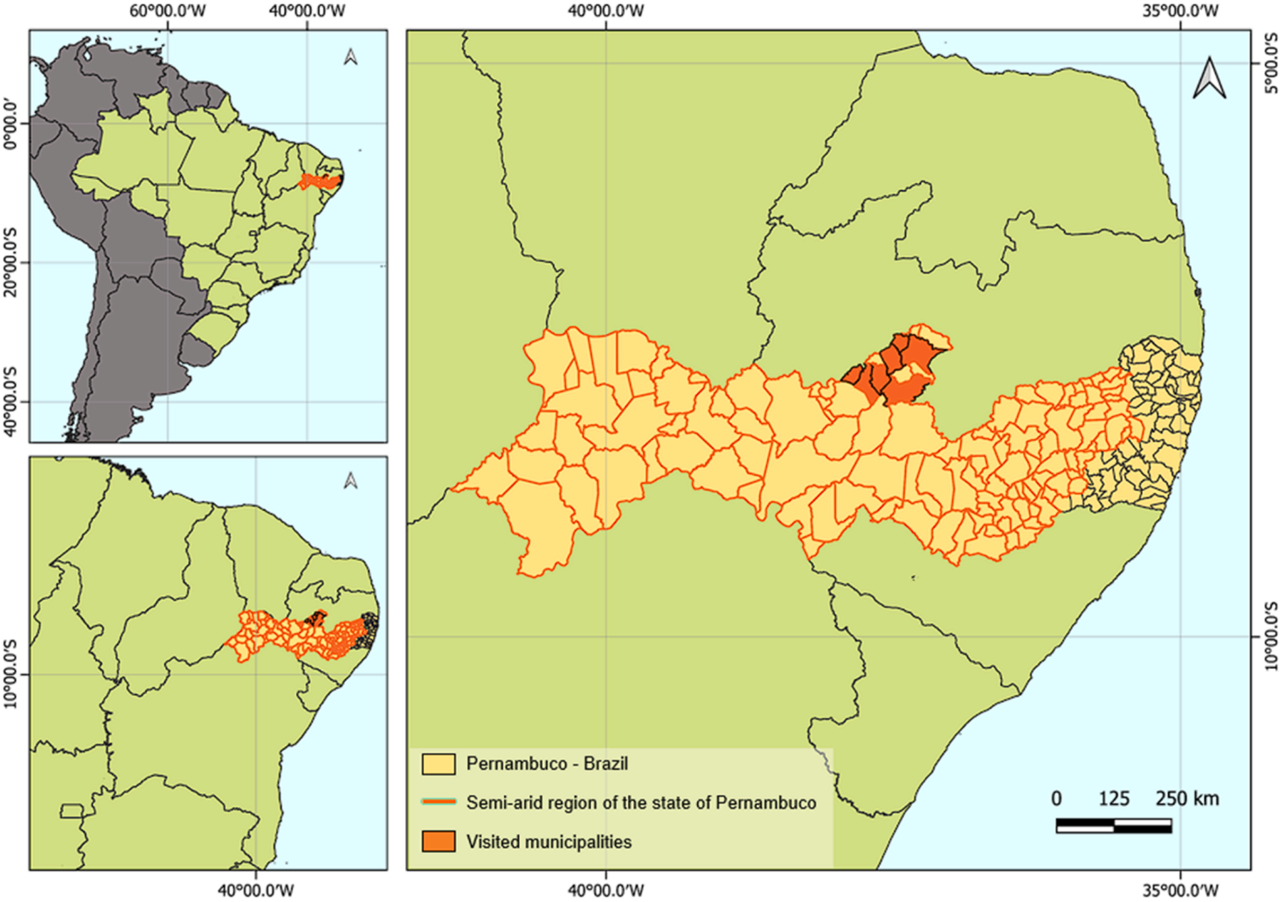

Fig. 2. Location of municipalities visited in the semi-arid region of Pernambuco, Brazil.

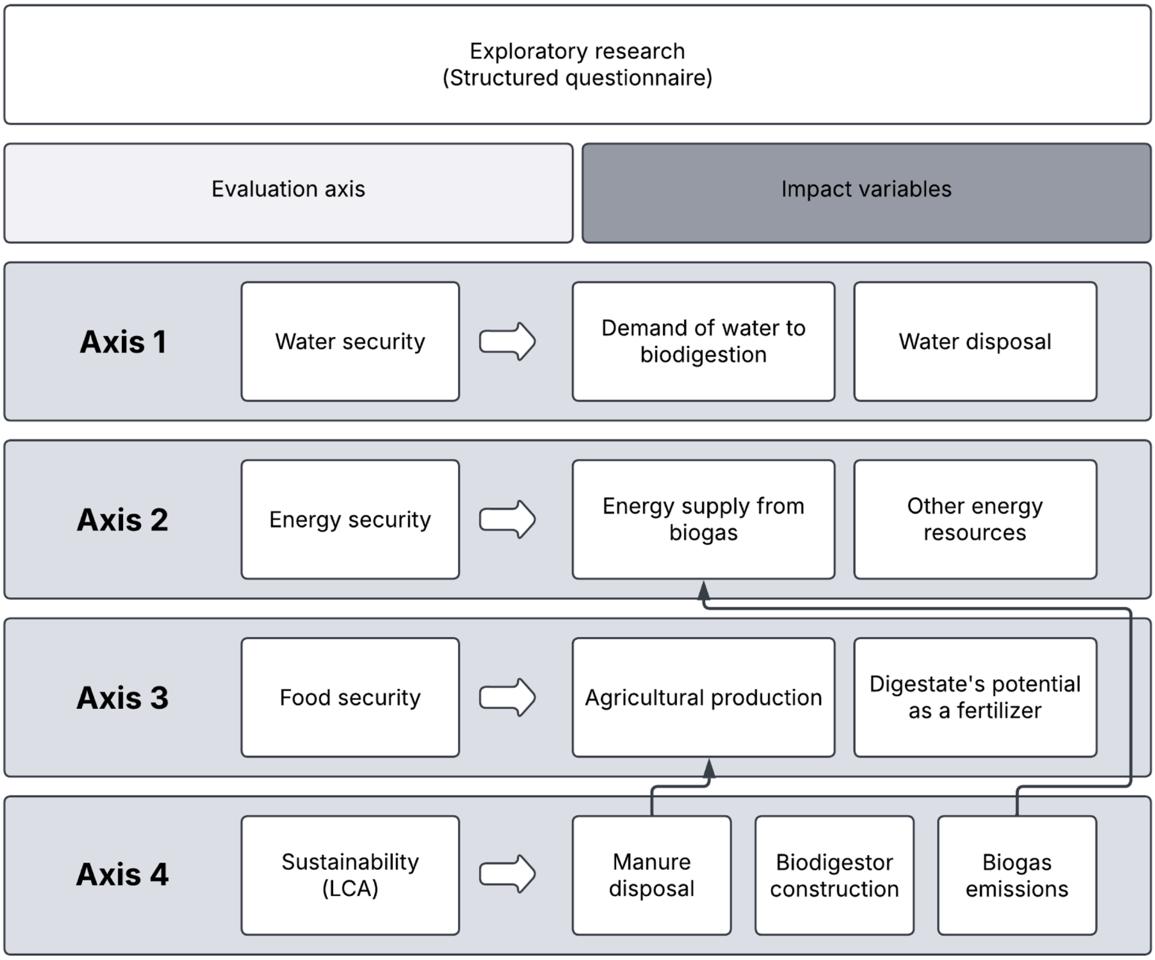

Fig. 3. Conceptual structure of the study and interrelationships between the nexus and sustainability assessment axes.

research. Regarding the impact on water security (Axis 1), we discussed the use of water in the management of the biodigester, the availability of water on the properties and in the region, the benefits of promoting sanitation, and the need for studies on the use of wastewater in the biodigestion process.

About the impact on energy security (Axis 2), data was provided on the energy and economic impact on families with active and inactive biodigesters, the other energy sources used by families, and a brief discussion on the energy potential and environmental impact of biogas and other fuel sources for cooking food.

Regarding the impact on food security (Axis 3), the data collected in the interviews on the agricultural production of rural families, the reasons for the inactivation of biodigesters, and the use of digestate as a biofertilizer in agriculture were evaluated. A physical-chemical and microbiological analysis of the digestate was also carried out to identify the potential impact of biodigestate on agriculture, the method of which is explained in the following section.

In addition, the sustainability analysis was carried out through a Life Cycle Assessment (LCA) (Axis 4) of the entire biogas production chain based on the quantification of GHG emissions, including (i) manure disposal, which is linked to food security, (ii) the manufacture of the biodigester, and (iii) emissions from combustion compared to other fuels, which is linked to energy security.

2.3. Sampling protocol and physicochemical and microbiological analysis of digestate

Digestate samples were collected simultaneously from four rural biodigesters in the Pajeú region (Pernambuco, Brazil), all operating under identical feeding regimes. Sampling was conducted at a standardized location, the digestate outlet tank following the anaerobic reactor, ensuring that all samples originated from the same operational point across properties. Prior to sampling, the digestate in each outlet tank was mechanically homogenized to ensure representative sampling. A volume of 1 L was collected from each property on a single day, immediately transferred to sterile containers, and transported under refrigeration at 4 °C to preserve their physical, chemical, and biological integrity in accordance with Standard Methods for the Examination of Water and Wastewater (SMWW) [16].

Physiological and microbiological analysis of the digestate was also carried out to analyze the impact on food security (Axis 3). Digestate samples were collected from rural properties in the Pajeú region (Pernambuco, Brazil) and transported under refrigeration at 4 °C to preserve their physical, chemical, and biological integrity. All physicochemical and microbiological analyses were conducted in triplicate to ensure data reliability and reproducibility.

The following parameters were determined according to the SMWW [16]: pH (potentiometry), electrical conductivity (conductometry), Chemical Oxygen Demand (COD), Total Solids (TS), Volatile Solids (VS) and Total Kjeldahl Nitrogen (TKN). Total Organic Carbon (TOC) was estimated indirectly from COD using Eq. (1) based on Carmo and Silva [17]:

$$TOC\left(mg\ L^{-1}\right) = 0.425 * COD\left(mg\ L^{-1}\right) - 2.064 \tag{1}$$

Multi-elemental analysis was performed by inductively coupled plasma optical emission spectrometry (ICP-OES) (Model 5100, Agilent

Technologies, USA) following procedures adapted from Silva et al. [18, 19]. The elements quantified were Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, V and Zn. The results were compared with the safety thresholds established by the Brazilian Ministry of Agriculture and Livestock [20] and European [21] regulations for organic fertilizers.

The microbiological safety of the digestate was evaluated using the ReadyCult® Coliforms 100 (MERCK) chromogenic test. This is a qualitative method for detecting total coliforms and *Escherichia coli*. Aliquots of the samples were transferred to sterile containers containing the reagent, following the manufacturer's instructions, and then incubated at 35–37 °C for 24 h. Total coliforms were indicated by a blue-green coloration, while *E. coli* detection was confirmed by fluorescence under UV light. Samples that exhibited no color change and no fluorescence were interpreted as negative for both groups, indicating an absence of detectable microorganisms above the method's detection limit. The method has been validated to detect bacterial loads in the range of 10–100 CFU per 100 mL using reference strains (e.g., *E. coli* ATCC 11,775), ensuring high sensitivity and specificity for environmental monitoring according to ISO 9308–2 and EPA 1604.

2.4. Life cycle assessment

2.4.1. Definition of the objective and scope

A process-based life-cycle assessment focused on climate change (CO_2-eq) was conducted to compare household biodigestion with prevailing manure-management practices in semi-arid smallholder systems in Brazil, in accordance with ISO 14,040/44 [22,23]. The functional unit is one household-year of cattle-manure management via a "*biodigestor sertanejo*", encompassing biogas used for cooking and the agronomic reuse of digestate in rainfed crop systems; results are additionally reported per cubic meter of biogas. System boundaries are cradle-to-use for manure and energy services and gate-to-field for digestate, including on-farm collection and feeding of manure, anaerobic digestion, biogas combustion in household stoves (accounting for methane slip), short-term digestate storage, field application, and system-expansion credits for displaced cooking fuels.

Two counterfactual baselines represent prevalent practices in the Brazilian semi-arid: (B1) direct field deposition/application of fresh manure and (B2) open-pit storage followed by application. Biogenic CO_2 is documented but excluded from GWP, whereas CH_4 and N_2O are fully included. All manure is collected on-farm, and digestate is typically applied within the homestead plot using buckets or wheelbarrows, given the negligible distances and the absence of motorized hauling per application in the field. Digestate application in the field is explicitly modeled via direct and indirect soil N_2O, assuming same-day incorporation (as reported by households), which lowers volatilization and nitrification–denitrification potential relative to surface broadcasting.

Substitution credits are allocated when biogas replaces fuelwood and/or LPG, using observed replacement fractions from surveys or conservative partial substitution when data are unavailable. Black-carbon forcing is excluded in the base case due to characterization uncertainty. Hardware manufacturing is omitted in the base case (screening indicates a subcut-off contribution at the household scale) and is included in the sensitivity analysis.

Emissions are parameterized with the IPCC 2006 Guidelines and the 2019 Refinement [24] for warm-dry (semi-arid) conditions: CH_4 from unmanaged/open-pit manure applies climate-appropriate methane conversion factors (MCF) and species-specific maximum methane potential (B_0) where volatile-solids data are unavailable; post-digestion CH_4 uses a reduced MCF reflecting lower remaining VS; direct soil N_2O adopts $EF_1 = 1$ % of N applied (as N_2O—N) for organic amendments; and indirect N_2O uses default volatilization and leaching fractions (Frac_GASM, Frac_LEACH), with sensitivity bounds reflecting low leaching in the Caatinga and rapid incorporation.

Uncertainty is assessed with one-at-a-time tests for methane slip (0–5 %), digestate-storage MCF (±30 %), EF_1 (0.5–1.5 %), indirect N_2O fractions (±50 % around defaults), inclusion/exclusion of hardware manufacturing, and digestate transport (0 vs. 2-km motorcycle). Processes expected to contribute <1–5 % of GWP are excluded. Across these ranges, the sign of the climate benefit remains robust.

2.4.2. GHG emissions: manure disposal

Biogas production offers an alternative use for manure obtained on farms, which is produced regardless of the presence of a biodigester. For this reason, the Intergovernmental Panel on Climate Change (IPCC) guidelines were used to estimate the emissions associated with manure by comparing alternatives where it is used as fertilizer, as a substrate for biogas production, or left for natural degradation [24]. Eq. (2) was used to estimate the methane emission factors (EF) in kg CH_4 per year.

$$EFCH4 = VS[kgVSyr-1] \times B0[m3CH4kg-1VS] \times MCF[-] \times 0.67[kgm-3] \tag{2}$$

Where VS = volatile solids fed or excreted (kg VS yr^{-1}); $B0$= maximum methane potential (m^3 CH_4 kg^{-1} VS); MCF = methane conversion factor (dimensionless fraction; use MCF %/100); 0.67 kg m^{-3} = CH_4 density at 0 °C, 1 atm. Output $EFCH4$em kg CH_4 yr^{-1}.

Manure samples were collected in the field within all farms studied. After laboratory tests to determine the volatile solids content, an average value of 83 % dry matter was reached. Similarly, dry matter was estimated at 18 % of the total mass. The other parameters were taken from the tables provided by the IPCC [24], which considers Bo equal to 0.13 $m^3CH_4/kgVS$, relative to low herd productivity, and the MCF value equal to 5 %, 1 %, and 0.47 %, respectively, for the biodigester, fertilizer, and natural degradation systems. Eq. (3), which includes all direct management emissions, and Eq. (4), which includes indirect emissions, were used to estimate N_2O gas emissions.

$$EN2_O, dir[kgN_2Oyr-1]= Napplied[kgNyr-1] \times EF1 - \times\frac{44}{28} \tag{3}$$

$$EN2O, ind[kgN2Oyr-1] = (Nvol \times EF4 + Nleach \times EF5) \times 2844 \tag{4}$$

Where the $N_{(T)}$ (kg N yr^{-1}) is the total nitrogen applied via digestate per household-year; $EF1$(–) is the direct emission factor for organic amendments (IPCC default 0.01); N_{vol} (kg N yr^{-1}) equals $Frac_{GASM}$(–) × $N_{applied}$, where $Frac_{GASM}$ is the fraction of applied N that volatilizes; $EF4$(–) is the emission factor for volatilized N converted to N_2O; N_{leach} (kg N yr^{-1}) equals $Frac_{leach}$ (–) × $N_{applied}$, where $Frac_{leach}$ is the fraction of applied N that leaches; $EF5$(–) is the emission factor for leached N converted to N_2O; the ratio 44/28 converts N_2O–N to N_2O by molecular weight; all nitrogen quantities are reported as N, and $EN2O, dir$and $EN2O, ind$ are expressed in kg N_2O yr^{-1}.

The value of approximately 3 % nitrogen in manure on a dry basis was obtained from the literature [25]. The other parameters were obtained from the IPCC [24], with EF_3 equal to 0.02 for non-treatment of manure, 0.01 for use as fertilizer, and zero for biodigestion; $N_{Volatization}$ is equal to 35 % of total nitrogen for anaerobic systems and 7 % for use as fertilizer. In the case of non-treatment, the value is 20 %. For all cases, EF_4 is equal to 0.01.

In addition, according to the IPCC guideline 2019 [24], N_2O emissions from anaerobic digestion are negligible based on the absence of oxidized forms of nitrogen entering these systems and their low nitrification and denitrification potential. For the analysis of CH_4 and N_2O emissions on an annual basis, the addition of 5 % fugitive emissions during anaerobic digestion was considered, according to IPCC data [26]. To convert the obtained values in kg CH_4 and kg N_2O to kg CO_2-eq, the IPCC 2021 GWP 100y method was used [27]. Based on these factors, we estimated CH_4 and N_2O emissions from manure under three circumstances: 1) Emissions from the decomposition of manure deposited in open fields and corrals; 2) Emissions derived from the use of manure as fertilizer in cropping fields; and 3) Fugitive emissions from the biodigesters.

2.4.3. *Manufacture of the biodigester*

The LCA of the materials for biodigester construction was developed using Simapro v. 9.5.0.1 (2023) and the Ecoinvent 3.8 database (2021). The functional unit selected was the construction of one biodigester. The geographical characterization utilized is defined in Section 2.1. The inventory of materials used is detailed in Table S1 (supplementary material).

Due to environmental concerns associated with climate change and global warming, the environmental impact assessment method selected was IPCC 2021 GWP 100y, which groups GHG emissions into a standard common metric (CO_2-eq) [27]. This method categorizes GHG emissions into three compartments: fossil emissions, biogenic emissions, and emissions associated with land transformation.

GHG emissions quantified in this study also called the carbon footprint, are one of the most widely used environmental indicators to assess the climate impacts associated with a process or product [28].

2.4.4. *GHG emissions - combustion*

In the last stage of the environmental impact assessment, we compared the emissions from residential use of LPG, firewood and biogas from the “*biodigestor sertanejo*”, (Axis 4). Although the physical and chemical characteristics of LPG and biogas vary depending on climate and geographic location, it was assumed that using the factors predefined by the IPCC would not generate a significant error.

The IPCC also provides standardized data for greenhouse gas emissions due to the stationary combustion of different fuels (LGP, firewood and biogas). This information can be found in Chapter 2, Volume 2 of the guidelines published by the panel [29,30]. Default emission factors for stationary combustion in the residential sector were used. To convert the obtained values in kg CH_4 and kg N_2O to kg CO_2-eq, the IPCC 2021 GWP 100y method was used.

The average emissions for fuels were calculated based on a functional unit of 361.79 MJ, the energy equivalent of the amount of biogas produced in the biodigestion system analyzed, 15.73 m^3 (field measurement). This average of biogas produced includes the variability in different farms, the daily supply of manure, and the amount of water, among other aspects. Therefore, actual measurement data was used instead of calculations based on the quantity of manure utilized.

Results and discussion

The integrated analysis of small-scale biodigesters demonstrates interconnected effects across the water, energy, food and sustainability axes. Gas generation, nutrient cycling via digestate, and household sanitation improvements act synergistically to optimize resource use under semi-arid conditions. Thus, the discussion below is divided into three axes and articulates how these processes jointly influence each nexus component, while recognizing feedback between them**.**

All numerical summaries are descriptive and reflect observed patterns within the surveyed contexts. Given the non-probability, program-linked sample and adaptive behaviors (e.g., feed ratio adjustments), estimates are not intended for population inference or causal attribution.

3.1. *Axis 1 - impact on water security*

Water availability proved the binding constraint in the management of “*biodigestor sertanejo*” for smallholders in the Brazilian semi-arid setting. Most of them primarily rely on stored rainwater to feed the digester, the downtime during prolonged droughts limiting gas output and delaying digestate handling. When and where water was abundant and suitable for the biodigester, farmers used it adequately, increasing the chances of success.

Most of the families interviewed reported that their primary source of water comes from rainwater cisterns (44 %) and wells (36 %), whether of private or community use (Fig. 4). However, two-thirds of the 3.3 million rural households in the Brazilian semi-arid suffer water limitations for agricultural and domestic uses [31]. Most of the water supply comes from social programs that use water tanker trucks. In addition, for 68 % of the population, the government program does not supply all the water demanded, so it is necessary to use alternative water sources for consumption and family maintenance [32]. Scarcity and lack of access to adequate water can lead the population to use untreated water, which is subject to contamination by anthropogenic action and causes an increase in the incidence of generalized waterborne diseases [33,34]. The situation becomes even more concerning when we consider that the primary source of economic income for these families comes from rainfed cropping systems and livestock production, two activities heavily dependent on water availability.

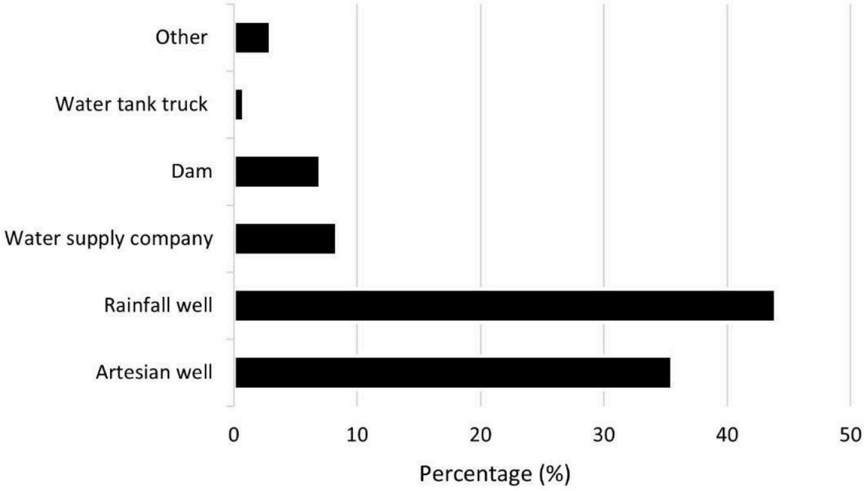

Fig. 4. Source of water for general consumption on rural properties.

Given the chronic water scarcity in the Brazilian semi-arid region, rigorous investigation of pre-treated domestic effluents as substitutes for clean water in anaerobic digestion processes becomes imperative. However, factors such as ammonia, metals, and organic compounds present in wastewater can compromise anaerobic digestion efficiency [35]. The specific application of treated domestic wastewater for manure dilution in biodigester systems requires detailed investigation into the presence of inhibitory compounds, alterations in the carbon-to-nitrogen ratio, and impacts on microbiological stability to validate this sustainable water management strategy.

As with all biodigester systems, biodigester technology requires water for proper degradation and biogas production [36]. Previous studies have reported that the ideal ratio for the mixture of rural biodigesters is 1:1 water-to-manure [37]. Although families had been instructed to feed the biodigester at this ratio, only 74 % reported following it. In comparison, 4 % reported a 4:1 ratio, and 15 % reported a 1:4 ratio (water: manure) daily (Fig. 5). They report that when the manure is drier, they add more water, and when it is wetter, they add less. Comastri Filho [37] states that the standard 1 manure: 1 water ratio ensures a regular gas flux in continuous-loading digesters. When a higher concentration of water is added relative to the quantity of substrates, it can damage the growth rate of the microorganisms [38], and the reverse can cause clogging of the biodigester pipes.

Using animal manure in biodigestion can be particularly beneficial for protecting watercourses and promoting the health and sanitation of rural lands [38]. Due to the need to feed the biodigester, the continuous practice of collecting animal waste and cleaning corrals and pigsties contributes to the appropriate disposal of waste, avoiding water contamination, and ensuring better water quality and improved health conditions for farm animals [9]. Besides that, the water used in fertigation carries the digestate. It acts as a nutrient-laden stream, improving soil structure and near-surface water dynamics, thereby reducing soil evaporation losses and increasing crop water-use efficiency and uptake relative to pure-water irrigation, which is beneficial for crop systems production in dryland areas. This effect was reported for biogas-slurry irrigation under drip/deficit irrigation regimes, as well as in greenhouse trials [39].

3.2. Axis 2 - impact on energy security

Progress in producing and using bioenergy, mainly from modern biomass, has become a meaningful way to fight poverty [40]. Reducing the use of traditional fuels such as fossil fuels, coal, and wood also has many ecological benefits for ecosystems. It is essential to mention that rural communities in developing countries are strongly dependent of traditional bioenergy sources [13].

The interviews revealed differences in energy consumption between farmers with active biodigesters and those with inactive ones. While the consumption of traditional cooking gas (LPG) on properties with an active biodigester is 83 %, on those with an inactive biodigester, it is 95 %. Notably, producers with an active biodigester purchase LPG less frequently, with only 7 % of those interviewed making monthly purchases. In contrast, 26 % of farmers with an inactive biodigester reported purchasing LPG every month, paying between US$ 20 and US$ 25 for their last cylinder (values from November 2023).

As for where they purchase LPG, 57 % of farmers prefer to buy from small local businesses, which, despite being more expensive, are preferable due to the distance between the farms and municipal centers.

These findings are consistent with other similar studies, such as the research by Ding et al. [41], which identified in the semi-arid region of China that the high heating efficiency of biodigesters provides considerable savings since families who owned biodigesters consumed 10 % less energy than those without biodigesters to meet basic household needs and heating requirements. Studies by Bennel-Yinteman [42] also found that the use of biogas for cooking and lighting reduced the consumption of 7.7 million liters of kerosene in Nepal. Thus, biogas production can reduce energy costs (heating, cooking, and fertilizers), generating considerable savings for families to invest in other purposes, such as buying non-produced food and improving well-being [43].

The use of biodigesters to produce methane gas as a substitute for LPG has not yet been widely studied in the context of family farming in the Brazilian semi-arid region, especially in Pernambuco [25]. However, there are approximately 874 *biodigestor sertanejo* units in Brazil in various states installed by the NGO Diaconia, notably in the state of Ceará, with 316, and Pernambuco, with 192. There is potential for expansion to 50,000 to 200,000 units and biogas production of 10 million m^3 $year^{-1}$ [9]. This value is higher than the total biogas production potential estimated for Nepal, which is around 3043.58 million m^3/year [44].

Furthermore, according to Ding et al. [39], biogas from biodigesters is more thermally efficient than traditional energy sources such as coal or firewood. Consequently, small-scale biogas systems can contribute with several Sustainable Development Goals (SDGs), such as agricultural productivity/food security (SDG 1), clean fuel supply (SDG 7), climate change mitigation (SDG 13) and also forest protection (SDG 15) by reducing the need for firewood [45].

Nevertheless, independently of using biogas from the biodigesters, it was found that charcoal and firewood are complementary energy sources for cooking food among the families interviewed. These energy sources are generally used in combination because factors such as the

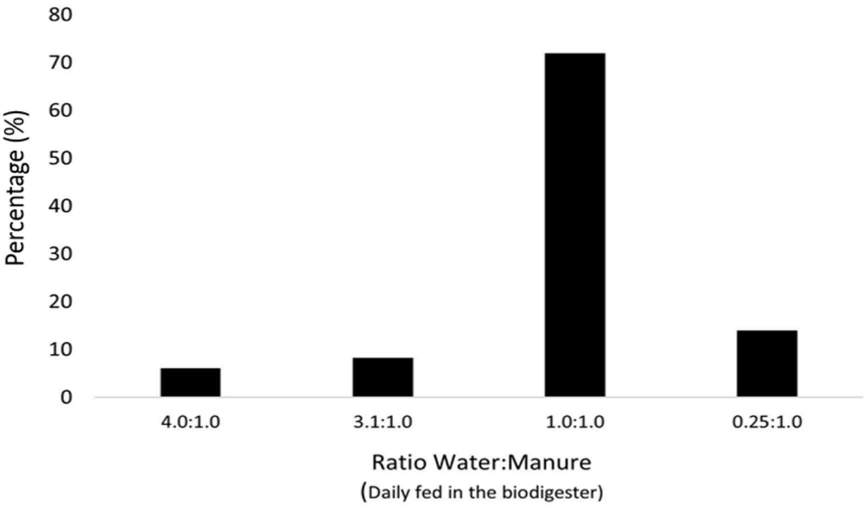

Fig. 5. Water: manure ratio of the substrate fed daily in the biodigesters studied in family farms within the semi-arid region of NE Brazil.

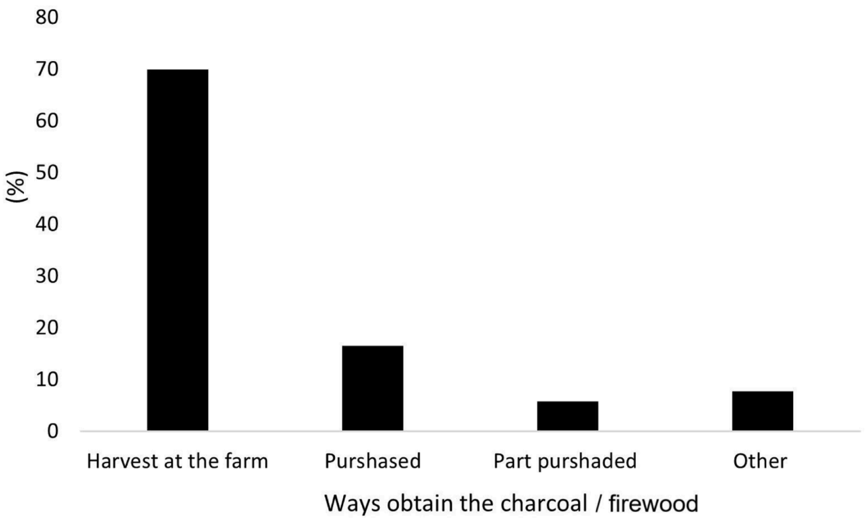

Fig. 6. Percentage of the source of charcoal/firewood collected by families interviewed.

amount of rain and the availability of wood on the property interfere with the momentary choice of these sources. Despite consuming more LPG, farms with an inactive biodigester were slightly less dependent on firewood (76 % of cases) and charcoal (39 % of cases) than farms with an active biodigester (83 % and 46 % of cases, respectively). Despite this, about 70 % of these families interviewed obtain firewood/charcoal from small fragments of native vegetation in their small farms (Fig. 6). Most wood/charcoal harvests are used in traditional stoves (57 % of cases). However, many families (32 % of cases) have been using ecological stoves, a social technology that consumes up to 50 % less wood/charcoal than a conventional stove, given similar heating to traditional wood stoves for cooking [46].

3.3. Axis 3 - impact on food security

The household biodigester not only promotes a cleaner energy source for cooking, but also allows for the subsequent use of digested animal manure as a fertilizer agricultural production [33]. The use of digestate as a biofertilizer can help improve the physical, chemical, and biological health of the soil, while promoting crop productivity [47]. When applied as a biofertilizer, digestate can increase the productivity of family farms, which in many cases cannot afford synthetic fertilizers, contributing directly to food security [9]. In semi-arid regions of China, Ding et al. [41] found a 49 % reduction in chemical fertilizer use by households with access to digestate.

However, in the interviews, no families were found to use chemical fertilizers on their crops, only animal manure or digestate when available. 80 % of families with active biodigesters reported applying digestate to their crops, with 30 % using it on vegetable crops and 70 % on corn, beans, and other crops. Of those interviewed, 72 % of the land used for agricultural production is <4 ha (Fig. 7). Most crop management practices are caried out by the family members, whose primary purpose of cultivation is subsistence production (58 %), while only 42 % produce a surplus for commercialization. The main crops grown are beans (30 %), corn (32 %) and vegetables (12 %).

3.3.1. Biofertilizer quality and agronomic potential

The use of digestate enhances food security in drylands by enabling smallholders to fertilize their fields, thereby increasing the likelihood of successful crop yields in regions where agriculture is increasingly complex to sustain due to climate change. These outcomes align with the

Table 1
Characterization of the digestate produced in the anaerobic digestion process of cattle manure.

Parameters	Results
pH (25 °C)	6.8 ± 0.3
Conductivity (μS cm^{-1})	>2000
COD (mgO_2 L^{-1})	27.7 ± 1.4
TOC (mg L^{-1})	9.7 ± 0.5
TKN (mg L^{-1})	382.7 ± 40.4
TS (%)	4.9 ± 0.16
VS (%)	4.3 ± 0.27
VS/TS (%)	87.75

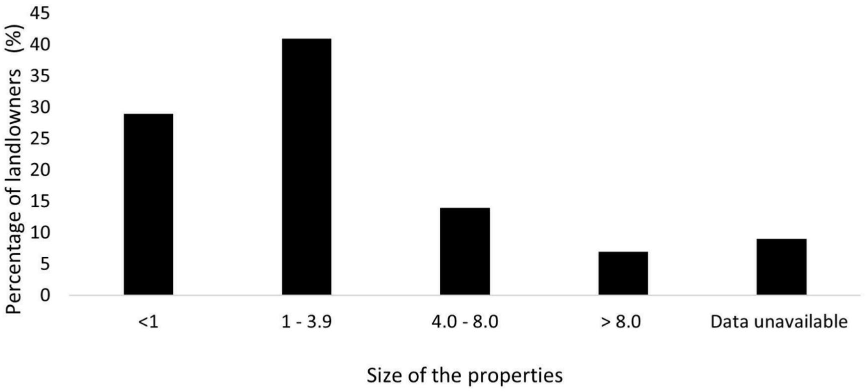

Fig. 7. Size of the cultivated area on rural properties.

digestate's N and K levels (Table 1) and same-day incorporation in semi-arid soils, which reduces N losses. Although only 18 % of households with operational biodigesters reported using it for fertigation – typically applied weekly and diluted in water – the physicochemical and microbiological analyses confirm its safety and nutritional richness (Table 1).

Samples of digestate were analyzed in triplicate and revealed a slightly acidic pH (6.8 ± 0.3), which is favorable to nutrient availability and microbial activity in the soil [48]. Electrical conductivity values greater than 2000 $\mu S.cm^{-1}$ indicated the presence of high concentrations of soluble salts, which can facilitate nutrient uptake. However, this observation necessitates caution regarding potential soil salinization in low-leaching conditions. The elevated COD (27.7 ± 1.4 $mgO_2\ L^{-1}$) and TOC (9.7 ± 0.5 mg L^{-1}) values are indicative of substantial organic content, which is vital for soil fertility [49]. Total Kjeldahl nitrogen (382.7 ± 40.4 mg L^{-1}), along with high volatile and total solids (4.30 ± 0.27 % and 4.90 ± 0.16 %, respectively). Marois et al. [50] point out that the fermentative process produces biofertilizers with significant organic matter availability and reduced microbial community, similar to the results obtained in this study.The digestate also exhibited essential macronutrients, including potassium (695.3 ± 34.8 mg L^{-1}), calcium (127.2 ± 6.4 mg L^{-1}), magnesium (221.6 ± 11.1 mg L^{-1}), phosphorus (25.8 ± 1.3 mg.L^{-1}) and sulfur (7.4 ± 0.4 mg L^{-1}), micronutrients such as iron (6.12 ± 0.31 mg L^{-1}) and zinc (0.32 ± 0.02 mg L^{-1}), and in concentrations comparable to commercial fertilizers [51,52]. These values (Supplementary material - Table S2) indicate agronomic viability for improving soil structure and plant development [45,53–55].

Toxic elements, including cadmium (Cd) and lead (Pb), were not detected. Quantification of other trace elements revealed concentrations well below the regulatory limits. Table 2 presents a comparison between measured concentrations and the thresholds established by the Brazilian Ministry of Agriculture and Livestock (MAPA) and the European Union.

The microbiological safety of the samples was assessed using the chromogenic test ReadyCult® Coliforms 100 (MERCK). All digestate samples exhibited a positive response for total coliforms, as indicated by a blue-green coloration. However, none of these samples were found to contain *E. coli*, as no fluorescence was observed under UV light. Therefore, the absence of fluorescence indicates that *E. coli*, if present, was below this detection limit, and thus within acceptable microbiological levels for agricultural use. These findings suggest low sanitary risk when the digestate is handled appropriately. However, regular microbiological monitoring is recommended, especially when applied to crops intended for raw consumption.

However, other studies highlight the agronomic efficacy of the biofertilizer. Increases in crop yields of up to 50 % (tobacco, alfalfa, barley) were reported by Martí-Herrero et al. [53]. In comparison, rice showed up to 57 % higher protein content when grown with digestate instead of chemical fertilizer [56]. Nevertheless, crop-specific sensitivity to the salinity or nutrient content of digestate must be considered, and application should be tailored to the crop stage and soil conditions [45,58].

Thus, in addition to replacing fossil-based chemical fertilizers, digestate contributes to nutrient recycling, soil health and climate change mitigation, reinforcing its role as a multifunctional tool for sustainable agriculture in semi-arid regions.

Table 2
Heavy metal content (mg kg^{-1}, dry basis) in the digestate and comparison with regulatory limits.

Element	Digestate	MAPA IN n° 61/2020	EU Regulation 2019/1009
Cadmium (Cd)	ND	3	1.5
Lead (Pb)	ND	150	120
Chromium (Cr)	0.0100 ± 0.0003	500	—
Chromium VI	—	—	2
Nickel (Ni)	0.040 ± 0.002	70	100
Copper (Cu)	0.080 ± 0.004	450	600
Zinc (Zn)	0.32 ± 0.02	1500	1500

ND: Not Detected
—: Not specified in regulation.

Table 3
Average estimated annual emissions of CH_4 and N_2O in $kgCO_{2eq}$/year within farms in the semi-arid region of Pernambuco for different processes of animal manure disposal.

Emissions	Untreated manure deposited in the fields	Used as fertilizer in cropping fields	Fugitive emissions from biodigester
Relative to CH_4	13.2	28.1	140.5
Relative to direct N_2O	333.6	166.8	0.0
Relative to indirect N_2O	33.40	11.7	58.4
Total	380.2	206.6	198.96

3.4. *Axis 4 - impact of sustainability*

3.4.1. *Emissions related to manure disposal*

Emissions were estimated by considering factors such as volatile solids (VS), maximum methane production capacity (Bo), different waste disposal processes within farms and herd characteristics. Results are present in Table 3. In this scenario, the biodigester receiving an average load of 20.0 kg day^{-1} of manure, the most recurrent scenario among those interviewed, showed emissions of 198.9 kg CO_{2eq} per year, which represents lower emissions than keeping the manure in the open fields and corrals without treatment or applying it as organic fertilizer in the cropping fields. In part, the lower emissions result from the anaerobic condition of the biodigestion process, which leads to a lower generation of N_2O and, therefore, lower total GHG emissions despite the fugitive emissions of CH_4 from the biodigester .

Another positive impact regarding GHG emissions derived from anaerobic digestion is the production of CH_4 used for cooking, which replaces fossil fuels, such as LPG, a cooking fuel commonly used by the population in this region. According to the IPCC, liquefied petroleum gas emits approximately 63 gCO_2eq/MJ during combustion. Life cycle modeling indicates that emissions from LPG production range from 12 to 24 gCO_2eq/MJ [57,59,60]. Therefore, LPG is associated with emissions between 75 and 87 gCO_2eq/MJ.

As seen in the results, if we consider a rate of 5 % of methane fugitive emissions from the biodigesters, it would amount to an average emission of 140 $kgCO_2$-eq or 4.7 $kgCH_4$ per year, considering that the calculations used the GWP100 value of 30 gCO_2eq per gram of CH_4. Therefore, the remaining 95 %, representing 94 kg of methane per year, is used as a substitute for LPG. This is equivalent to 4450 MJ per year, considering that the lower calorific value of methane is 50 MJ/kg, thus we obtain a carbon intensity of 44 gCO_2eq/MJ for the biogas, not considering emissions from the construction of the digestor. If this energy was obtained using LPG, there would be emissions between 352.5 and 408.9 $kgCO_2$-eq per year, which is avoided using biogas. However, since there would be an emission of 198 $kgCO_{2\text{-}eq}$ as seen in Table 3, the net avoided emission is between 135 and 188 $kgCO_2$-eq per year. Thus, considering the emissions from the operation of the biodigester, there is a net reduction of between 40 % and 50 % in GHG emissions. In the following section, considerations about the emissions related to building the biodigester will be made in order to better compare them with the life cycle emissions from LPG.

3.4.2. *Emissions related to the material used to build the biodigester*

Table 4 presents the emissions associated with the materials used to construct the biodigester. The main hotspot identified was the use of cement (373.22 kg CO_2-eq). However, substituting cement with other materials in this process is not possible due to the lack of low-cost,

Table 4
GHG emissions associated with the manufacture of the Biodigester.

Impact category	Cement	Polyvinylchloride	Clay brick	Sand	Zinc	Iron sinter
GWP100 – fossil	366.96	147.93	43.77	35.37	34.83	2.42
GWP100 – biogenic	5.00	0.35	0.06	0.14	0.23	0.00
GWP100 - land transf.	1.26	0.15	0.02	0.11	0.13	0.00
GWP100 – total	373.22	148.42	43.85	35.62	35.20	2.43
	Steel	Gravel	Acrylic filler	Pig iron	Total	
GWP100 – fossil	2.46	1.18	0.47	16.49	651.90	
GWP100 – biogenic	0.00	0.01	0.00	0.00	5.80	
GWP100 - land transf.	0.00	0.01	0.00	0.01	1.70	
GWP100 – total	2.47	1.21	0.47	16.50	659.40	

durable materials suitable for construction. Several studies point to technologies under development to replace traditional concrete, such as sustainable concrete with the substitution of plastic waste [61] or with the partial substitution of cement with red mud [62], but the materials are not yet accessible for replacement by local populations.

Polyvinylchloride (PVC) presented the second highest emissions, followed by gravel and clay bricks. PVC is used in the water tank and pipes of the biodigester. The remaining materials account for 8.83 % of the emissions. These values help understand the impact of the construction phase, but structural durability must also be considered. During the interviews, it was found that a significant number of biodigesters already presented malfunctions and defects, with technical interventions required to resume biogas production.

Considering that 109 biodigesters are operational, the overall GHG emissions associated with the construction of these devices is 71.87 t CO_2-eq. The previous section found that the biodigesters could avoid the emissions of 135 to 188 kg CO_2-eq per year when substituting LPG. In that sense, the environmental payback time (the time required to amortize the emissions generated in the construction of the system) of this substitution is between 3.5 and 5 years [60]. Considering that the lifespan of these biodigesters can be up to 20 years, the environmental payback time can be further decreased by either improving biogas production through adjustments to operating parameters [63], or employing low-carbon materials to build the biodigesters [64].

In addition, each biodigester produces an average of 15.73 m^3 of biogas per month, the average for the study site. Over 20 years, normalizing emissions from the Sertanejo biodigester by the amount of biogas produced, the value would be 0.17 $kgCO_2\text{-eq}/m^3$. With this figure, it is possible to compare construction emissions with other studies in the literature. Pérez et al. [66] also identified emissions for the construction of a Chinese biodigester (0.24 $kgCO_2\text{-eq}/m^3$) and for a tubular plastic biodigester (0.26 $kgCO_2\text{-eq}/m^3$). In the Chinese model, which is similar in composition to the biodigester evaluated, cement accounted for 54.74 % of GWP, corroborating the 56.60 % share in the biodigester model. In turn, Nzila et al. [66] found an emission value of approximately 1.75 $kgCO_2\text{-eq}/m^3$, considering the construction of a Chinese model biodigester and the use of $1m^3$ of biogas, the tubular and fixed dome models showed lower impacts, which highlights the importance of how the systems are constructed.

Estéves et al. [67] pointed out that in the literature, the construction phase of biodigesters is only computed once and that its impact is diluted over the useful life of the system, which often makes the collaboration of emissions insignificant, Fuchsz and Kohlheb [68] and Mezzullo et al. [69] also highlight this parameter as irrelevant in some scenarios, especially for large scale. Therefore, the life cycle assessment of biodigester construction must be evaluated for each case. For the biodigester model evaluated in the present study, since it is a local system developed and used in NE Brazil, this quantification had not been carried out, and it was possible to observe the impact of the construction on the biogas produced. In turn, although common, repairs and emissions associated with them occur randomly, and their inclusion in calculations can be evaluated on a case-by-case basis.

3.4.3. *Emissions due to combustion*

Table 5 shows the greenhouse gas emissions scenario for the combustion of biogas produced in the biodigester evaluated and the corresponding emissions from obtaining the same amount of energy from liquefied petroleum gas, a scenario considered an open cycle. A scenario was also presented in which the carbon dioxide emitted by the combustion of biogas is considered in a closed cycle, i.e., taking into account its absorption growth and/or production cycle, which results in zero emissions from the use of the resource, since the cellular respiration that causes growth absorbs the gases emitted.

The average emissions from the biodigester network analyzed were based on average production of 15.73 m^3 $biodigester^{-1}$ $month^{-1}$; therefore, the average value of energy produced over one month for each farm was 361.79 MJ, with a high degree of variability depending on the size and type of herd in each farm. In all scenarios, the use of biogas showed lower levels of GHG emissions, with 19.81 $kgCO_2$-eq/month, followed by LPG with 22.89 $kgCO_2$-eq/month. In the scenario where renewable fuel (biogas) is considered in a closed cycle, the impact of substitution was even more significant.

The annual use of biogas, as opposed to LPG, decreases an average of 273.24 kg of GHG emissions for each farm, in the closed cycle. In terms of payback, the excess emissions from opting for anaerobic digestion are compensated for in just one month of using biogas compared to no treatment and in three months compared to agriculture, as shown in Table 5 for untreated manure deposited in fields and used as fertilizer in crop fields, respectively.

About firewood, as pointed out by Smith et al. [70], solid fuels tend to have a worse environmental performance when used for cooking, mainly due to higher emissions of pollutants and greenhouse gases.

Table 5
Greenhouse gas emissions related to biogas combustion produced in biodigesters in the Pernambuco semi-arid region, LPG, and firewood.

Fuel	Monthly Energy (MJ)	$kgCO_2$	$kgCH_4$	kgN_2O	$kgCO_2$-eq	Comparison with Biogas
Open Cycle						
Biogas	361.79	19.7537	0.0018	<0.0000	19.8151	-
LPG		22.8289	0.0018	<0.0000	22.8903	+15.52 %
Firewood		40.5208	0.1085	<0.0000	43.5595	> 100 %
Closed Cycle						
Biogas	361.79	-	0.0018	<0.0000	0.0602	-
LPG		22.8289	0.0018	<0.0000	22.8308	> 100 %
Firewood		-	0.1085	<0.0000	3.0390	> 100 %

Furthermore, the use of firewood highlights a worrying situation in the semi-arid region: cooking inside homes leads to serious health problems for the population, especially women [71]. According to the World Health Organization [72], every year, 3.2 million people die from diseases caused by domestic air pollution due to the incomplete combustion of solid fuels and kerosene used for cooking, with women and children being the most exposed to smoke and thus the most vulnerable since they are responsible for household chores, especially cooking food. In the interviews, 32 % reported cases of respiratory illness in the family, and 11 % noted that there had been a reduction after replacing the conventional wood stove with biogas. So, the consortium of the biodigester and the "ecological wood stove" (with a more efficient design) can be considered a healthier and more environmentally appropriate alternative to the conventional wood stove. Another alternative for reducing GHG emissions from firewood is sustainable forest management plans [73]. This change can be observed when emissions are considered on a closed-cycle basis (Table 5): the impacts of firewood are significantly lower, corresponding to <10 % of the scenario when manure is disposed of in the fields without treatment. Biogas proved to have a lower environmental impact in all scenarios than firewood.

We also collected data on charcoal use. Considering the same energy demand (361.79 MJ), emissions would be 40.59 kg CO_2-eq month^{-1}, slightly less than the use of firewood. However, it is necessary to note that charcoal production in the region is not sustainable, as carbonization technologies with low conversion efficiency and gaseous effluents exist.

The results found in the present study converge with those presented by Singh et al. [74] in one of the most extensive studies on using fuels for cooking. The authors evaluated eight fuels, including LPG, biogas, firewood, and charcoal. The test showed that LPG and biogas have the lowest emission rates from production to use and the lowest GHG emissions, with biogas having the lowest impact.

Thus, understanding the environmental impacts of rural biodigesters in the semi-arid region, based on LCA, offers a systemic and unprecedented view of the contribution of this technology to the WEF nexus, to support public policies focused on sustainability and socio-environmental resilience in rural communities in the semi-arid region.

3.5. *Insights on economic sustainability and further perspective*

Improving the use of technology can reduce the pressure on local firewood resources, as well as reduce the time spent cooking food and collecting this biomass; an effort usually delegated to women and children [53]. According to Tolessa [67], women in rural families change their behavior when biogas is promoted and firewood consumption is reduced, devoting more time to other activities that can increase the family's source of income.

Another benefit of the biodigester is increasing family income. Despite its rarity, nearly 10 % of farmers sell the biodigester's effluent as biofertilizers, thereby boosting their families' income. The production

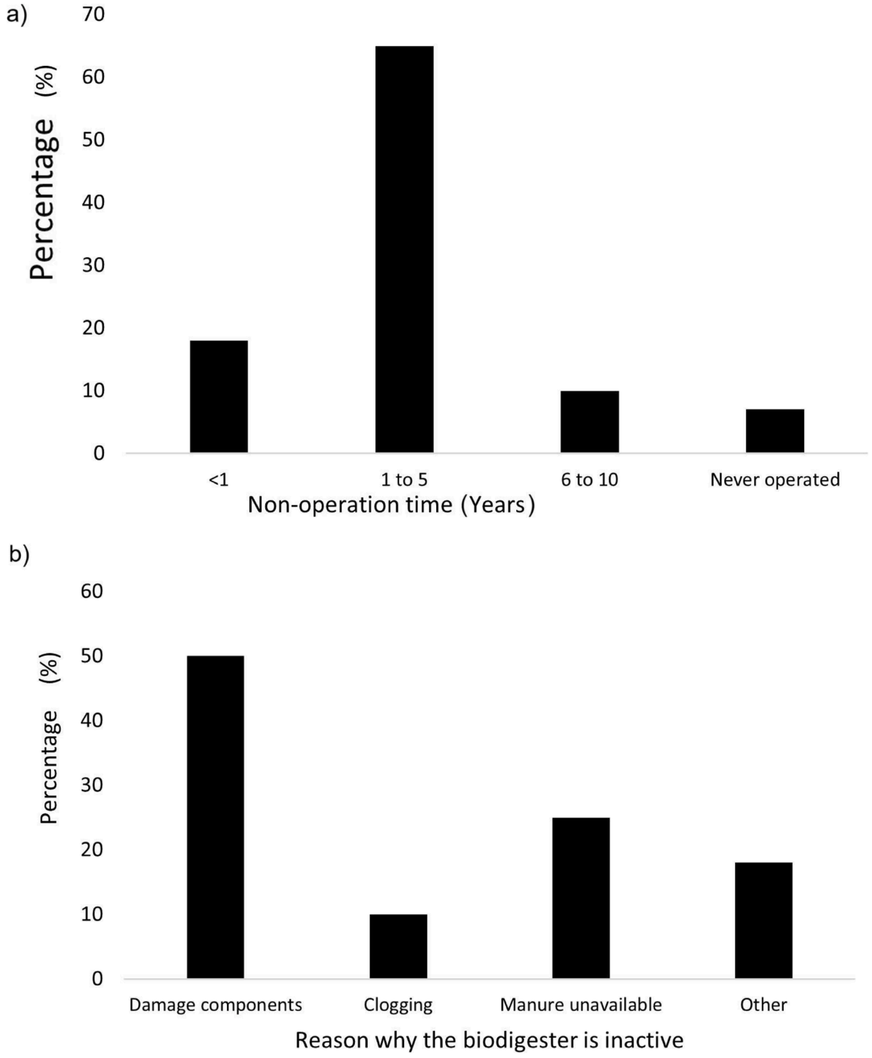

Fig. 8. a) Length of time the biodigester has not been in operation and b) reason for non-operation.

and sale of artisan-processed products, such as cakes and snacks, is also a potential way for families to earn extra income, using the availability of biogas for cooking and baking these products. When considering the economy generated by not buying LPG, the savings are even more significant when compared to the economic impact of using biogas. The cost of implementing the "*biodigestor sertanejo*" on the farms is approximately USD 820.00 [9], less than half the cost of the Chinese and Taiwanese biodigester models [65]. Considering an average production of biogas of 15.73 m^3 per month for each biodigester, the annual economy in the initial year of implementation are USD 201.3, so in just four years the initial investment is recovered, considering an average yearly increase of 4.77 % per year, in the cost of cooking gas in Brazil [75]. Souza [36] emphasizes in his study that the use of biogas to replace LPG, firewood, and coal generates savings in the range of 4 % to 5 % of the monthly average.

Although the "*biodigestor sertanejo*" was developed in such a way that it requires simple maintenance that can be carried out by the farmers themselves [9], 66 % of the farms surveyed, the biodigester was not in operation (72) (Fig. 8a). Families reported that the most interruptions occurred in the last five years, mainly due to damage components, especially rupture of the gasometer (a fiberglass water tank) (Fig. 8b). Although 59 % of families wish to reactivate their biodigesters, several obstacles hinder this, including limited financial resources for spare parts, a lack of technical assistance in rural areas, and inadequate animal facilities for manure collection. The ageing rural population and related health problems also reduce the capacity for daily biodigester feeding.

In Brazil's semi-arid Northeast, rural ageing is accelerating — the ageing index rose to 47.9 older persons per 100 children, and the median age increased from 27 to 33 years between 2010 and 2022, while 2.05 million people left rural areas [76]. This demographic change affects labour supply, farm succession, and access to health and social care, highlighting the need for integrated policies that promote rural employment, education, digital inclusion, age-friendly services, and productivity-enhancing technologies.

Livestock production among smallholders remains largely extensive, limited by poor animal housing and management infrastructure, which makes regular manure collection difficult and often renders continuous biodigester operation unfeasible. It is also important to consider the climatic phenomenon of the last great drought, from 2012 to 2017, in which entire herds died in the Northeast, directly affecting the availability of waste to feed biodigesters. In 2013 alone, 71 % of municipalities in the Northeast region had emergency decrees due to drought, significantly impacting family farming production [77]. Rasimph et al. [78] also report that in South Africa many families have difficulty maintaining biodigesters due to a lack of water, maintenance resources, or the lack of sufficient animals to produce manure. Thus, to successfully implement the biodigester, it is essential to understand the needs and perceptions of farming families to identify those that would best adapt to the use of the technology, in addition to investing in specialized training for its operation and educational awareness initiatives to improve its adoption. It is also crucial for organizations implementing the technology to periodically monitor rural properties to identify how families are adapting to it and provide possible orientation or solutions in case of malfunctions, thereby contributing to the longevity of the technology and its social, environmental, and economic benefits.

4. Conclusions

This study provides policy-relevant evidence for family farming in the Brazilian semi-arid region. Household biodigesters offer significant co-benefits by improving sanitation and energy access while reducing greenhouse gas emissions compared to unmanaged manure practices.. Their effectiveness depends on regular operation, sufficient water supply, and proper maintenance, which together enable energy savings, better health outcomes, and the safe agronomic reuse of digestate.

The use of manure for biogas production proved to be the most environmentally efficient option, producing fewer emissions and yielding a high-value product. The construction materials of the biodigester studied had a low environmental impact, and biogas combustion was cleaner than that of other fuels, including firewood. Although underutilized, biodigesters could increase energy and food security by reducing dependence on LPG and firewood, while improving cost amortization.

Although the results demonstrated the social, environmental, and economic benefits of using rural biodigesters in the tropical semi-arid region, some limitations remain. The Life Cycle Assessment focused mainly on greenhouse gas emissions, while other studies may incorporate other variables, such as water consumption, eutrophication, or indirect social impacts. The high biodigester inactivity rate (66 %), associated with technical and maintenance failures, highlights the need for more robust technical-economic analyses to asses alternatives and returns over time. It was also noted that the assessment of digestate was limited, with no long-term agronomic experiments to confirm its effects on different crops and soil conditions. Future research may incorporate these analyses. Additionally, new studies may investigate synergies between biodigesters and other social technologies, such as reuse cisterns and agroforestry systems.

Because the estimates follow IPCC standards, the mitigation results can be directly applied in local climate monitoring. However, the feasibility of the biodigester depends on the adequate availability of manure, water, and technical support. Therefore, a selective implementation approach and sustained technical assistance are recommended, rather than indiscriminate dissemination.

Funding sources

This research was supported by FACEPE [grants: APQ-2274–3.14/24; APQ- 0527–3.07/21; APQ- 0176–19; APQ-0496–5.01/21; Project Biotec-Semiárido APQ- 1379–9.25/21], the National Council for Scientific and Technological Development-CNPq [grants: 465764/2014–2; 441305/2017–2; 308021/2019–3; 140249/2023–0; 309452/2021–0; 440444/2022–5; 406202/2022–2; 303180/2025-0; 140249/2023-00], the Coordination for the Improvement of Higher Education Personnel-CAPES [grants: 88887.136369/2017–00; 88887.507561/2020–00; 88887.571633/2020–00; 88887.906336/2023–00], PRH-FINEP, the Brot für die Welt (Bread for the World). This work is part of the National Observatory of Water and Carbon Dynamics in the Caatinga-NOWCDCB Biome, supported by FACEPE [grants: APQ-0498–3.07/17 ONDACBC], CNPq and CAPES.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank FACEPE for funding the project that led to the data used in this study. We would also like to thank the NGO Diaconia, especially collaborators Waneska Bonfim, Jucier Jorge, Adilson Viana, and Maria Williane Matias, for their support in the field. Thanks also to Professor Genival Barros of the Federal Rural University of Pernambuco (UFRPE).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2025.100602.

Data availability

Data will be made available on request.

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