

Techno-economic and performance assessment of semi-continuous anaerobic digestion of domestic organic waste with digestate recirculation in the Dominican Republic[☆]

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ABSTRACT

Domestic organic waste (DOW) represents an abundant but underutilized biomass resource for renewable energy production, particularly in developing countries where waste management and energy access remain key challenges. This study assesses the technical, agronomic and techno-economic feasibility of producing biogas from DOW using a simplified anaerobic digestion approach based on pH monitoring and controlled digestate recirculation. A 0.1 m³ biodigester previously inoculated with rumen and cow dung was operated under mesophilic and tropical climate conditions, evaluating hydraulic retention times (HRT) of 30 and 60 days and a digestate recirculation ratio of approximately 16% to stabilize pH. Experimental results demonstrate that DOW can be effectively converted into biogas under low-technology operating conditions, achieving stable methane production without the need for advanced monitoring or strict control of multiple physicochemical variables. A HRT of 60 days showed improved performance compared to 30 days. Methane concentration averaged 56.3%, which, although lower than that of cow dung biogas, is sufficient for energy generation using commercially available engines. Digestate reuse promoted successful vitroplant acclimatization without the need for inorganic fertilization, highlighting its agronomic potential. By combining experimental operation with an empirical numerical model, this work provides practical indicators for assessing digestion performance under variable feedstock conditions typical of municipal food waste. Environmental assessment indicates avoided CO₂ emissions on the order of 600–3300 tCO₂-year⁻¹ for a 1-MW plant, depending on operational assumptions and emission factors. Techno-economic analysis shows payback periods ranging from 4 to 9 years and 6–22 years; and internal rates of return between 10.8%–18.5% and 19%–31%, with plant factors of 33.3% and 60%. These results demonstrate that DOW-based biogas systems can support decentralized, low-cost waste-to-energy solutions with environmental and agricultural benefits, particularly in developing and emerging economies.

Introduction

Regarding global efforts toward environmental preservation include international agreements (United Nations, 1998; United-Nations, 2015) and the Sustainable Development Goals (SDGs), particularly affordable and clean energy (SDG 7) and climate action (SDG 13). Anaerobic biological treatment of the organic fraction of municipal solid waste is a process which has received increased attention during the last few years.

Conversion of these wastes to methane provides energy and has a beneficial effect on the environment (Bouallagui et al., 2003). Anaerobic Digestion (AD) is a microbiological process of decomposition of organic matter in the absence of oxygen, common to many natural environments. A wide range of micro-organisms are involved in the anaerobic process which has two main end products: biogas and digestate. Biogas is a combustible consisting of methane (50 to 70%), carbon dioxide (30 to 50%) and small amounts of other gases such as (N₂), oxygen (O₂), hydrogen (H₂) and hydrogen sulfide (H₂S). Digestate is a decomposed

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Nomenclature*Latin symbols, abbreviations and acronyms*

<i>AD</i>	Anaerobic Digestion, –
<i>Bal</i>	Balance gas (%) = $100 - (\text{CH}_4 + \text{CO}_2 + \text{O}_2)$, %
<i>C</i>	Concentration of organic mater, %
<i>CF</i>	Cash Flow, US\$
<i>CH₄</i>	Methane, %
<i>CO₂</i>	Carbon dioxide, %
<i>C/N</i>	Carbon / Nitrogen ratio, –
<i>CPI</i>	Consumer Price Index, %
<i>DOW</i>	Domestic Organic Waste, kg
<i>E_{net}</i>	Net energy, kWh
<i>Ė_{net}</i>	Net power, kW
<i>HRT</i>	Hydraulic Retention Time, days
<i>H₂S</i>	Hydrogen sulfide, ppm
<i>IRR</i>	Internal Rate of Return, %
<i>LHV</i>	Lower Heating Value, kWh·m ⁻³
<i>MM</i>	Molar mass, kg·kmol ⁻¹
<i>m</i>	Mass, kg
<i>NG</i>	Natural Gas, –
<i>NH₄⁺</i>	Ammonium, –
<i>NPV</i>	Net Present Value, US\$

<i>N₂</i>	Residual Nitrogen, –
<i>O₂</i>	Oxygen, %
<i>OLR</i>	Organic Load Rate, kg·m ⁻³ ·day ⁻¹
<i>PF</i>	Plant Factor or Capacity Factor, %
<i>SDG</i>	Sustainable Development Goals, –
<i>t</i>	Time, days
<i>ṽ</i>	Flow rate, m ³ ·h ⁻¹
<i>V</i>	Volume, m ³
<i>VFA</i>	Volatile Fatty Acids, –
<i>Y</i>	Yield (biogas and methane), m ³ ·kg ⁻¹
<i>y</i>	Molar fraction of component i, %

Greek symbols

<i>η</i>	Efficiency, –
<i>ρ</i>	Density, kg·m ⁻³

Subscripts and superscripts

<i>B</i>	Biodigester
<i>e</i>	Electrical
<i>i</i>	Index for time or measurement interval
<i>m</i>	Mechanical
<i>mix</i>	Mixture
<i>T</i>	Total

substrate, rich in nutrients and therefore suitable as fertilizer (Al Seadi et al., 2008; Casanovas et al., 2019; Chen et al., 2016; Khalid et al., 2011; Lorenzo Acosta et al., 2005; Magaña et al., 2006; Marcelo-Aldana & Viera-Sernaqué, 2017; Nganyira et al., 2023; Sagagi et al., 2010; Salam et al., 2015; Shaibur et al., 2021).

In different countries, studies about biogas production using different sources have been conducted, including cattle manure. For biogas production, pig manure can produce an average of 0.1 m³·pig⁻¹·day⁻¹ and cow manure around 0.32 to 0.6 m³·pig⁻¹·day⁻¹ (Vera-Romero et al., 2014). Depending on the climate conditions, the HRT can grow from 20 to 40 days (Aili Hamzah et al., 2023), and the Lower Heating Value (LHV) could be in the average around 6.1 kWh·Nm⁻³ for a CH₄ from 50 to 70% (Aili Hamzah et al., 2023; Al Seadi et al., 2008; Bouallagui et al., 2007; Casanovas et al., 2019; Lorenzo Acosta et al., 2005; Magaña et al., 2006). Other researchers have conducted research about biogas production using cow dung, including the use of the digestate as a fertilizer and the co-digestion of manure from different animals (Barragán Monroy et al., 2024; Kusmiyati et al., 2023; Palavecino et al., 2016; Salam et al., 2015; Shaibur et al., 2021), and the production of biogas using co-digestion with organic waste including food waste and plant residues with cattle manure (Adekunle et al., 2019; Chen et al., 2016; Hakimi et al., 2023; Iweka et al., 2021; Nganyira et al., 2023; Thakur et al., 2023; Wang et al., 2021), sewage sludge (Ghosh et al., 2020; Pasciucco et al., 2023), and the combination of bio-flocculated sewage sludge and cow dung (Thakur et al., 2023). Additional recent research also demonstrates that co-treatment of sewage sludge and organic waste can improve stability and methane yield when optimized loading and mixing strategies are applied (Javier et al., 2024).

When producing biogas using organic waste, there are important parameters in the literature, such as the pH, HRT, Carbon/Nitrogen ratio (C/N), organic load rate (OLR), and the inoculation material. Methane formation takes place within a relatively narrow pH interval, from about 5.5 to 8.5. The acidogenic microorganisms usually have lower value of optimum pH between 5.2 and 6.3. The optimal pH value ranges between 6.5 and 8, and the process is severely inhibited if the pH-value decreases below 6.0 or rises above 8.3 (Al Seadi et al., 2008; Casanovas et al., 2019; Khalid et al., 2011; Kumar Pramanik et al., 2019; Lorenzo Acosta et al., 2005; Zupancic & Viktor, 2012). The HRT can be between 15 and

80 days depending on the climate conditions, for mesophilic conditions, is between 30 and 60 days (Al Seadi et al., 2008; Casanovas et al., 2019; Marcelo-Aldana & Viera-Sernaqué, 2017). Regarding the C/N, for acidogenesis and methanogenesis the expected ranges are 10–45 and 20–30, respectively (Zupancic & Viktor, 2012). C/N ratio of substrates affect HRT, biogas yield and the rate of frequency of evacuation. Additionally, organic wastes differ in their C/N ratio when compared to cattle manure, for example, C/N ratio for cow dung (24), vegetable wastes (11–19), cassava peel (55), yam peel (36), sweet potato peel (40–46), beans wastes (24–30), rice wastes (90–130), fish wastes (2.5–5.5) (Orhorhoro et al., 2016). Furthermore, during experimental research, C/N ratio around 8.5–11.26 (Ávila-Hernández et al., 2018; Chen et al., 2016; Wang et al., 2021) were reported for food waste. Other ranges of C/N (13.2–43) and pH (4.16–6.5) can be found in the literature for different food waste types (Kumar Pramanik et al., 2019; Rossi et al., 2021). The optimal C/N ratio is often between 20 and 35 (Khalid et al., 2011). In respect to OLR (in kg·m⁻³·day⁻¹), ranges can be found between: 0.78 to 43, (Khalid et al., 2011; Kumar Pramanik et al., 2019; Rossi et al., 2021; Zhang et al., 2007). The inoculation material could be cattle manure, sludges, commercial bacteria, and digestate from a well-functioning biogas plant (Al Seadi et al., 2008; Ávila-Hernández et al., 2018; Bouallagui et al., 2003; De Groof et al., 2021; Joshi et al., 2024; Kumar Pramanik et al., 2019; Pavi et al., 2017; Sagagi et al., 2010; Santos et al., 2023; Wang et al., 2021). A well-designed experimental research reported no inoculation, but recirculation material from the digestate representing about 25% of the substrate (Lattieff, 2016). The biogas yield using DOW is between 0.05 and 0.4 m³·kg⁻¹ (Aguilar-Virgen & Taboada-González, 2011; Cardenas & Zapata, 2016). Recent analyses also report that food-waste digestion performance is highly sensitive to pretreatment intensity, feedstock variability, and microbial stability, particularly in semi-continuous systems, which complicate process scaling in low-technology contexts (Darmey et al., 2025; Zhang et al., 2023). In addition to biogas generation, several studies have highlighted the agronomic value of digestate as a soil amendment. Research shows that digestate can improve soil structure, increase nutrient availability, and support crop productivity when applied under controlled conditions (Alburquerque et al., 2012; Möller & Müller, 2012; Nkoa, 2014; Roj-Rojewski et al., 2018; Tambone et al., 2010). These works also emphasize that the fertilizing properties of digestate depend

on feedstock composition and digestion conditions, and that its use can substitute part of the inorganic fertilization required in agricultural systems. This evidence reinforces the importance of evaluating digestate from domestic organic waste not only as a by-product, but as a potentially valuable resource within a circular bioeconomy framework.

The renewable energy contribution in the Dominican Republic reached 18.1% in 2024 (Energy and Mines Ministry of the Dominican Republic, 2024) and increased to 22.2% during the January–September 2025 period (Energy and Mines Ministry of the Dominican Republic, 2025). Biomass remains the least represented source, contributing only about 0.9% of total generation. Approximately 68% of national electricity production relies on natural gas (NG) and coal. In addition, the price paid for imported NG increased by more than 50% during January–September 2025 compared to the 2024 average (from 2.2 to 3.5 US\$.MMBTU⁻¹). This rising dependence on fossil fuels, coupled with significant NG price volatility, underscores the relevance of evaluating biogas-based energy alternatives. These conditions highlight the strategic importance of developing decentralized biogas systems, particularly because their economic competitiveness improves when NG prices rise. Nowadays, the country's landfills are mostly open-air; the different waste categories are not classified. Organic waste represents a large and underutilized opportunity for energy recovery in the Dominican Republic. Waste characterization studies indicate that the organic fraction constitutes approximately 50–60% of municipal solid waste (Cuervo et al., 2021; Franco et al., 2022), and waste generation rates range from 0.7 to 1.2 kg-person⁻¹.day⁻¹ (Wolf, 2018). For a municipality of 250,000 inhabitants, this corresponds to roughly 250 tons of waste per day, of which around 125 tons are organic. Using conservative biogas yields from the literature, this amount of organic waste could generate approximately 1250 Nm³.day⁻¹ of biogas, which could produce around 2 MWh of energy with a 30% efficiency engine and 5.5 kWh.m⁻³ of LHV, demonstrating that domestic food waste represents a significant and currently unexploited renewable energy resource for local communities. An interesting research was conducted about biogas production with sargassum alone and combined with food waste, being the Sargassum from 45 to 100%, using cattle manure as inoculum (Castro et al., 2022), and the methane percent was between 50 and 59% for most of the studied scenarios. Despite these findings, national waste-characterization studies and research on biomass-to-energy pathways have consistently emphasized the need to investigate biogas production from the domestic organic fraction of municipal waste; however, no experimental studies addressing this recommendation have been reported to date.

In summary, most of the studies reviewed focus on biogas production from livestock manure or on co-digestion of organic waste with manure or wastewater sludge, often under controlled temperature and with various pre-treatment steps (Kumar Pramanik et al., 2019). Recent work reinforces these concerns, noting that pretreatment intensity and integrated AD-pyrolysis configurations can significantly affect the overall energy balance and process feasibility of organic-waste digestion systems (Sarwar et al., 2026). In contrast, there are very few experimental studies that evaluate anaerobic digestion of domestic organic waste alone under simple, low-technology conditions, and even fewer that report integrated assessments combining biogas quality, digestate use as fertilizer, and techno-economic performance. Additionally, recent studies show that decentralized biogas systems frequently encounter operational limitations such as inadequate pH control, loading instability, and lack of robust process monitoring, emphasizing the need for simplified and resilient digestion strategies (Singh et al., 2024). The novelty of this study lies in evaluating domestic organic waste under semi-continuous anaerobic digestion using a simplified operational strategy based on digestate recirculation for pH stabilization, without thermal or mechanical pretreatment. Unlike previous works mainly focused on co-digestion or highly controlled systems, this study integrates biogas quality assessment, comparison with a full-scale cow dung biodigester, digestate evaluation as fertilizer, and environmental

and techno-economic analysis within a single framework. To the authors' knowledge, no experimental study has previously examined mono-digestion of domestic organic waste under these low-technology operational conditions in the Dominican Republic or in similar resource-constrained contexts. The biogas produced with DOW is going to be compared to the reference biogas of a full-scale biodigester using cow dung. This work hypothesizes that domestic organic waste can sustain stable semi-continuous anaerobic digestion when digestate recirculation is used to stabilize pH, producing biogas suitable for energy generation and a digestate appropriate for agricultural use.

Materials and methods

Experimental facility

The experimental research was conducted at IIBI. The biodigester used in this experimental research was made of EPDM rubber (Fig. 1), with approximately 1.75 m of length and of 0.26 m of diameter, for a gross volume around 0.1 m³ (92.9 L; 24.54 gal). There is a pipe with a valve in the middle of the biodigester bag to control the gas extraction and a 2 L medical use bag for extracting gas samples when measuring. The sample bag has a non-return valve and outlet valve. The biodigester was built by Bolívar Rodríguez. For this experimental study, the digestate extraction and substrate feeding was performed manually, making sure that the hydraulic sealing was enough to avoid gas leak during the process and to avoid surpassing biodigester capacity.

The facility has a biogas engine and stove of 3 and 3.25 kW, respectively, and 20 W (0.02 kW) biogas booster pumps. The booster pumps have a maximum flow of 40 L.min⁻¹ (2.4 m³.h⁻¹). There are also gas flow meters that were regularly used to measure the amount of gas extracted from the biodigester bag while measuring, transferring gas to another storage bag or using equipment. The flow meters used (EKATON GB/T6968-2011, G2.5), provided by Teewin, have minimum and maximum flow rates of 0.025 and 4 m³.h⁻¹, respectively. Additionally, there are dehydrators and desulfurizers to clean the gas and avoid damaging elements. The desulfurizers have a pressure gauge integrated. Additionally, the research facility has a portable biogas analyzer (Biogas 5000), manufactured by LandTec (Landtech, 2019).

Data collection

Climatic conditions, HRT, OLR, and pH

Temperature was not measured during the present experiment because it was not an experimental variable and the biodigester did not include temperature control. The system was designed to replicate the operating conditions of low-technology rural biodigesters, where temperature and other environmental variables are not externally regulated and digestion occurs under natural climatic conditions. The reactor

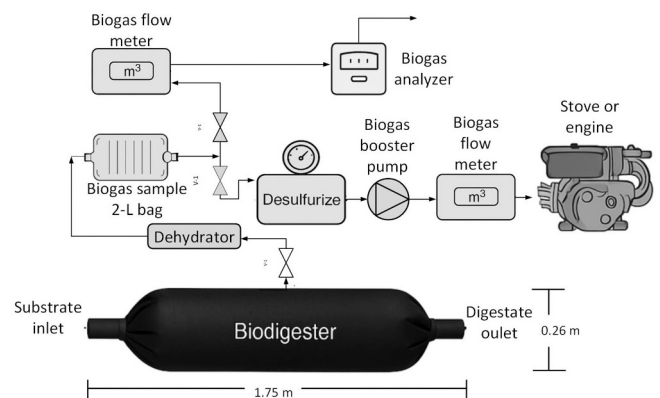


Fig. 1. Biodigester.

operated outdoors under the ambient temperatures typical of the Dominican Republic (approximately 25–33 °C), which fall within the mesophilic range for anaerobic digestion (Al Seadi et al., 2008; Casanovas et al., 2019; Marcelo-Aldana & Viera-Sernaqué, 2017). This environmental information is provided solely for contextual purposes and was not used for data analysis.

For the HRT (Eq. (1)) (Al Seadi et al., 2008), two values were initially considered (30 and 60 days). The biodigester capacity is around 93 kg. Therefore, for a total mass of 60 kg into the biodigester, the mass flow rates for 30 and 60 days would be 1 and 2 kg·day⁻¹, respectively.

$$HRT = \frac{\text{Digestion Volume}}{\text{Volumetric flow rate}} = \frac{\text{Digestion mass}}{\text{mass flow rate}} \quad (1)$$

The OLR (kg·m⁻³·day⁻¹) was calculated using Eq. (2) (Al Seadi et al., 2008). Where \dot{m} is the feeding flow (kg·day⁻¹), C is the concentration of organic matter (%), and V_B is the biodigester volume (m³).

$$OLR = \frac{\dot{m} \cdot C}{V_B} \quad (2)$$

The pH was measured at the substrate and the digestate. The device used for measuring the pH was a Hatch portable meter, model HQ40d, which used to be calibrated using the buffers or standard solutions for calibration available in IIB's labs.

Biogas CH₄, LHV and other variables

Before measuring the gas mixture, an automatic fresh-air purge was performed on the biogas analyzer for approximately 30 s following the device manual (Landtech, 2019). Once all readings stabilized at zero, the biogas measurement sequence was initiated. Each biogas sample was analyzed for about 30 s or until the signal reached a stable level with a maximum oscillation of ±0.1%. To ensure that the biodigester remained hydraulically and pneumatically independent from the analyzer during sampling, the outlet valve was opened only long enough to fill a 2-L sampling bag, from which the measurements were subsequently taken. The analyzer quantified methane (CH₄, %), carbon dioxide (CO₂, %), oxygen (O₂, %), hydrogen sulfide (H₂S, ppm), and the balance gas (Bal, %). The residual nitrogen fraction was calculated according to the manufacturer (Eq. (3)), where $Bal = 100\% - (CH_4\% + CO_2\% + O_2)$, and 3.76 corresponds to the O₂:N₂ molar ratio in atmospheric air (79/21).

$$\text{Residual } N_2 = \text{Balance} - (O_2\% \cdot 3.76) \quad (3)$$

Among the other variables calculated using gas compositions are density and LHV. The biogas density (ρ_{biogas}) was determined using the biogas mixture molar mass (MM_{mix}) and the ideal gas relationship at standard conditions at 0 °C and 1 atm (22.4 m³·kmol⁻¹). The MM_{mix} was calculated as the sum of the products of the molar fraction and molar mass of each component in the biogas. The density was then obtained from Eq. (4), where y_i and MM represent the volume fraction and molar mass of each gas component, respectively (Ávila et al., 2018; Cengel & Boles, 2011).

$$\rho_{\text{biogas}} = \frac{\sum (y_i \cdot MM) \left[\frac{\text{kg}}{\text{kmol}} \right]}{22.4 \left[\frac{\text{m}^3 \text{N}}{\text{kmol}} \right]} \quad (4)$$

The biogas and methane yield were estimated using Eqs. (5) and (6) (Castro et al., 2022). Where the volume (V_i) produced during a short period of time (t_i) is extrapolated throughout the total mass (m_T) and total time (t_T) of the experiment. The biogas and methane yields are calculated three times. The short periods of time were three series of consecutive measuring (consecutive dates), where the total biogas was extracted from the biodigester, all occurred during the month of march (12 to 15); (17 to 21), and (24 to 28). The total time of the experiment was 268 days, starting when DOW addition started to be constant (January 22, 2025), to middle October 2025 when the gas production

stopped.

$$Y_{\text{biogas}} = \frac{V_i}{t_i} \cdot \frac{t_T}{m_T} \quad (5)$$

$$Y_{\text{methane}} = Y_{\text{biogas}} \cdot CH_4\% \quad (6)$$

The biogas LHV was calculated considering that methane is the only combustible component. The LHV of methane (802 MJ·kmol⁻¹) was divided by the molar volume at standard conditions (22.4 m³·kmol⁻¹), resulting in a specific energy of 35.8 MJ·m⁻³ (Santos et al., 2023). The LHV of the mixture was thus obtained using Eq. (7).

$$LHV_{\text{biogas}} = \frac{LHV_{CH_4}}{22.4 \left[\frac{\text{m}^3 \text{N}}{\text{kmol}} \right]} \cdot CH_4\% = 35.8 \left[\frac{\text{MJ}}{\text{m}^3 \text{N}} \right] \cdot CH_4\% \quad (7)$$

Inoculum

The inoculum to activate the biodigester was a mixture of cow dung (10 kg), cow rumen (10 kg), and water (41 kg) for a relation of 1:2 (2 kg of water for each kg of cow dung or rumen), which was deposited into the biodigester on November 07, 2024 (Table 1). The cow rumen and dung were collected at Grupo Alonzo, Sierra Prieta. The cow dung and rumen densities were around 960 and 958 kg·m⁻³, respectively. Considering the measured densities when the cow rumen and dung were mixed with water, the density for the mixture was around the water density (1000 kg·m⁻³). From now on, for volume estimations, 1 kg of mixture equals 1 L of mixture.

The mass and density of the rumen, cow dung, water, and mixture were measured using specific gravity hydrometer and the relation between mass and volume, as shown in Eq. (8) after using different scales available at IIBI.

$$\rho = \frac{m}{V} \quad (8)$$

where ρ is the density $\left(\frac{\text{kg}}{\text{m}^3} \right)$; m is the mass (kg), and V is the volume occupied (m³)

Finally, about 20 days after depositing the inoculum, methane concentrations became detectable in the biogas headspace (63.6–67.9% CH₄ on 11/29/2024, 12/02/2024 and 12/10/2024). These values were not part of a biogas-production estimation protocol; they were only used to confirm that the inoculum had reached stable anaerobic activity. The detailed methodology used to quantify biogas composition is described in the previous subsection (Biogas CH₄, LHV and other variables).

DOW collection, blending and feeding

The DOW was collected at home and from different restaurants around the zone. In the context of this experimental research, it is important to emphasize that most of the DOW consisted of food residues, which included fruit and vegetable peels (banana, mango, avocado, and others, excluding orange and lemons), root crops such as cassava, yam, potatoes and sweet potatoes, as well as staples like pasta, rice and beans. Additional contributions came from meat, fish scraps, eggs, bread and wheat-flour cakes remnants, seasoning by-products (garlic, onion, peppers, cilantro). The DOW was blended with water and mashed using a 20 L food waste disposer (PX-FWD-20 L), manufactured by Puxin, with a rated power of 3 kW. The DOW & water relation initially proposed was 1:1 (1 kg of water for each kg of DOW) (Nganyira et al., 2023). The time for blending the organic waste went from 15 s to 60 s (depending on the material, the amount of waste, and the selected power level).

After mixing in the blending machine a sample of about 20 g used to be taken for the pH measuring. The team used to extract the respective fraction from the biodigester outlet before feeding to avoid any possible interactions between the feeding and extracting material. In the

Table 1
Biodigester activation with cow rumen and dung.

Date [mm/dd/yyyy]	Cow dung [kg]	Cow dung density [kg/m ³]	Cow rumen [kg]	Cow rumen density [kg/m ³]	Water mass [kg]	Water mass per kg of cow dung or rumen [kg]	Total mass inside the biodigester [kg]	Aprox. feeding mass flow for HRT = 30 days [kg/day]	Aprox. feeding mass flow for HRT = 60 days [kg/day]
11 7 2024	10.0	960.1	10.0	957.9	41.1	2.1	61.1	2.0	1.0

extraction process, the sample for the pH measure and fertilizer test was collected. The biogas used to be measured before extracting the digestate.

The carbon-to-nitrogen (C/N) ratio, total solids (TS), and volatile solids (VS) of the substrate mixture and inoculum were not measured experimentally due to the lack of local laboratory facilities equipped for such analyses. However, because this study examined the anaerobic mono-digestion of a single substrate (domestic food waste) and did not involve comparisons among different substrate types or formulations, these parameters were not treated as experimental variables. The food waste used in this work reflects the natural variability of municipal organic residues, making C/N, TS, and VS inherent properties of the feed rather than controlled parameters. Previous studies working with real food-waste mixtures such as food waste and sargassum systems (Castro et al., 2022) discuss the relevance of the C/N ratio but do not always report experimentally measured values when substrate composition varies inherently. Furthermore, the C/N ratio of food waste can range from very low (e.g., fish waste, 2.5–5.5) to extremely high (e.g., rice waste, 90–130), while cattle manure typically presents a C/N ratio of around 24 (Orhorhoro et al., 2016). In this context, operational and process-stability indicators such as pH, hydraulic retention time (HRT), organic loading rate (OLR), and methane concentration provide a practical and informative framework for assessing digestion performance under simplified, low-technology conditions.

Brief experiment using digestate as fertilizer

The residue from the fermentation process in the biodigester used at IIBI site was collected. At the time of collection, the residue presented a pH of 7.21. Two (2) dilutions were tested using banana (Musa AAA, cv. Grand Nain) and plantain (Musa AAB, cv. Macho × Hembra ¾) vitroplants, to evaluate their fertilizing effect over a 15-day period.

Dilutions

- Two (2) volumes of water per one volume of biopreparation (2:1).
- Three (3) volumes of water per two volumes of biopreparation (3:1).

Application frequencies

- Every two days
- Every three days

Plant material

Two genotypes of Musa spp. were used:

- Plantain vitroplants (Macho × Hembra ¾)
- Banana vitroplants (Grand Nain variety)

Fifty-cell trays filled with Sunshine Mix #4 substrate were used, each containing vitroplants at one week of acclimatization.

The nutrient solutions were applied using a watering can with a fine dispersed spray, as routinely practiced in the acclimatization nursery of the Plant Biotechnology Department (CEBIVE). For both solutions (2:1 and 3:1), 100 mL were mixed with 400 mL of water to obtain a total volume of 500 mL.

Treatments

- Dilution #1 + banana vitroplants + application every 2 days

- Dilution #1 + plantain vitroplants (¾) + application every 2 days
- Dilution #2 + banana vitroplants + application every 3 days
- Dilution #2 + plantain vitroplants (¾) + application every 3 days

Two (2) trays containing vitroplants were used for each dilution and variety, totaling eight (8) trays with 50 vitroplants each.

To determine whether the pH varied with dilution, the pH of each mixture was measured. The original biol presented a pH of 7.21, and after dilution, the values were as follows:

- Dilution 2:1-pH: 7.75
- Dilution 3:1 - pH: 7.41

Numerical model for DOW estimation and economic-environmental analysis

Nine (9) biogas generators were considered from the market; a provider also offers catalog to select the booster pump to guarantee the necessary gas flow. The engine efficiency, flow rate or amount of engine were estimated using Eq. (9) common in thermodynamics studies (Cengel & Boles, 2011).

$$\eta_{engine} = \frac{\dot{E}_{net}}{LHV_{gas} \cdot \dot{V}_{gas}} = \frac{E_{net}}{LHV_{gas} \cdot V_{gas}} \quad (9)$$

where; η_{engine} is the engine efficiency, \dot{E}_{net} is the net power (kW), E_{net} is the net energy (kWh), LHV_{gas} is the biogas lower heating value (kWh·Nm⁻³), V_{gas} is the gas volume (m³), \dot{V}_{gas} is the gas flow rate (m³·h⁻¹). The LHV considered was the one found during this experimental research when producing biogas using DOW. Table 2 shows the engines considered from the market.

Biogas booster pump energy

According to the elements available in the lab, for the 3-kW engine, the pump able to produce the required flow has a maximum capacity of 20 W, which is 0.7% of the engine net power. Following Table 2 and catalog for biogas elements provided by one manufacturer, the pump power able to produce the capacity of each generator is also about 0.7% of engine net power. Therefore, for this numerical model, the pump net energy was considered as 1% of the engine energy.

The amount of DOW necessary to produce specific energy is estimated with Eq. (10), using the biogas yield found in this experimental study and the required gas volume (V_{gas}) for every scenarios.

$$DOW_{amount} = \frac{V_{gas}}{DOW_{biogas,yield}} \quad (10)$$

The number of people that could produce the amount of required DOW was calculated considering from the literature that the production factor is 1.0 kg_{residues}·person⁻¹·day⁻¹. Also, that the DOW represents about 50% of all the residues. Therefore 0.5 kg_{DOW}·person⁻¹·day⁻¹. ($Dow_{person,day}$).

$$Number_{ofpeople} = \frac{DOW_{amount}}{Dow_{person,day}} \quad (11)$$

DOW blending machine energy

The blending machine's power is 3 kW, with two power levels. The

Table 2

Comercially available engines considered for the energy estimation.

Brand or provider*	Engine Power [kW]	Gas flow [m ³ /h]	Gas flow [L/min]	Pump power from catalog [kW]	Pump power respect to the engine power [%]	Gas consumption [m ³ /kWh]	Engine efficiency [-]	Country
TeenWin	2.8	2.0	33.3	0.02	0.7%	0.7	0.25	China
Puxin	3.0	2.1	35.0	0.02	0.7%	0.7	0.26	China
Puxin	5.0	3.5	58.3	0.04	0.8%	0.7	0.26	China
TeenWin	6.8	4.5	75.0	0.04	0.6%	0.7	0.27	China
Jenbacher	360.0	163.6	2727.3	2.49	0.7%	0.5	0.40	Germany
Jenbacher	548.0	231.7	3861.9	3.76	0.7%	0.4	0.43	Germany
Jenbacher	635.0	274.9	4581.5	4.39	0.7%	0.4	0.42	Germany
Jenbacher	851.0	368.4	6140.0	5.66	0.7%	0.4	0.42	Germany
Jenbacher	1067.0	461.9	7698.4	7.30	0.7%	0.4	0.42	Germany

* *Italic*: calculated values using the average LHV found during the experimental study.

use time was related to DOW amount and water added; about 30 to 60 s for every 5 kg or DOW. Therefore, if the amount of DOW needed to produce a specific amount of gas is known, the energy to be spent during blending can be estimated considering the power and the time of use. For the engines efficiency going from 0.2 to 0.4, the blending energy was from 6% to 3% of the engine energy. For this numerical study, the blending machine energy was fixed at 5% of the engine net energy, regardless of the engine's efficiency.

Digestate recirculation pump energy

Since this study proposes digestate recirculation as an operational strategy to stabilize outlet pH and ensure biogas production, the associated energy consumption depends on the recirculation pump capacity and operating time. Digestate recirculation pumps are distinct from the biogas booster pump used to supply gas to the engine. While the biogas booster pump operates continuously during engine operation, digestate recirculation is performed intermittently and only when required based on outlet pH conditions.

Commercially available digestate recirculation pumps for DOW- or cow dung-based biogas systems typically have rated powers around 0.75 kW, although the exact value depends on flow rate, handled material, total dynamic head, and pump efficiency. In practical operation, recirculation can be carried out with short daily duty cycles (e.g., a few minutes per day), resulting in a very limited auxiliary energy demand compared to the engine-generator output.

Based on a review of market-available equipment and representative operating conditions (biogas generators rated between 3 and 5 kW and digestate recirculation pump operation of approximately 5 min·day⁻¹), the resulting energy consumption associated with digestate recirculation represents less than 0.5% of the daily engine energy output. To conservatively account for digestate recirculation and minor auxiliary elements (e.g., fans), an auxiliary consumption equal to 1% of the engine energy was adopted in the base-case analysis (Table 3). A sensitivity analysis evaluating auxiliary consumption in the range of 0.5–2% confirmed that the main economic and environmental conclusions are not significantly affected by this assumption.

Net energy estimations

The net energy of the plant was estimated by subtracting the energy consumed by continuously and intermittently operating elements

(including the biogas booster pump, blending machine, and digestate recirculation pump) from the engine net energy. Electrical efficiency (η_e) and mechanical efficiency (η_m) were assumed to be 0.95 and 0.9, respectively:

$$Energy_{plant_{net}} = \eta_e \cdot \eta_m \cdot (E_{engine_{net}} - E_{pump_{net}} - E_{mashing-machine_{net}} - E_{engine_{others-elements}}) \quad (12)$$

Economic and environmental impact

A fixed net engine power of 1 MW (1000 kW) was considered for the environmental and economic evaluation. The plant factors (PF) assumed for this study were 33.3% and 60%. This assumption reflects realistic operating conditions for small-scale and decentralized biogas plants based on domestic organic waste (DOW).

The PF assumptions vary widely depending on system scale, feedstock stability, maintenance, grid demand, and operational strategy. Some regional potential studies report PF as high as 0.9 (Vera-Romero et al., 2014; Vera-Romero et al., 2015), corresponding to near-continuous operation under idealized feedstock availability. However, such values represent upper-bound theoretical scenarios rather than typical real-world operations. Institutional operational data indicates lower but still significant PF for biomass and biogas systems. The U.S. Energy Information Administration reports average PF of approximately 62% for biomass and biogas power plants operating under real conditions (U.S. Energy Information Administration, *Annual Electricity Report*, 2024). Available at: https://www.eia.gov/electricity/annual/html/epa_04_08_b.html [Accessed: Dec. 21, 2025]. In contrast, large centralized and dispatchable thermal power plants using fossil fuels can achieve higher PF; for example, the coal-fired Punta Catalina power plant in the Dominican Republic operated with an average PF of approximately 74% in 2024, according to the design capacity and the produced energy during the respective year (Energy and Mines Ministry of the Dominican Republic, 2024).

In this context, unlike centralized thermal plants, decentralized biogas systems are subject to intermittent feedstock handling, scheduled maintenance, biological process variability, and demand-driven operation, particularly in rural or low-demand contexts. Continuous baseload operation is therefore rarely achieved. Consequently, assuming a PF of approximately one-third of nominal capacity represents a conservative

Table 3

Recirculation pump energy estimation.

Engine Power [kW]	Engine working time [h/day]	Engine energy [kWh]	Recommended recirculation pump [kW]	Recirculation pump working time [min]	Recirculation pump energy [kWh]	Pump energy/Engine energy [%]
3.0	5.0	15.0	0.75	5.00	0.063	0.42%
3.0	8.0	24.0	0.75	5.00	0.063	0.26%
5.0	5.0	25.0	0.75	5.00	0.063	0.25%
5.0	8.0	40.0	0.75	5.00	0.063	0.16%

Note: recirculation pump operation corresponds to intermittent digestate recirculation based on outlet pH.

and realistic scenario for techno-economic assessment, avoiding over-estimation of energy production and economic performance. Additionally, in the Dominican Republic, waste source separation and stable organic feedstock supply remain significant operational challenges due to limited infrastructure and collection practices typical of developing countries. Variability in domestic organic waste quality and availability further constrains continuous operation of decentralized biogas systems. These contextual limitations reinforce the use of a conservative PF in the present assessment, reflecting realistic operational conditions rather than idealized scenarios. Higher utilization factors could be achievable under optimized grid integration or continuous thermal demand; however, such conditions were intentionally not assumed in this study. To capture both conservative and improved operational conditions, the economic and environmental assessment was performed considering two plant factor scenarios: a base case of 33.3% and an enhanced utilization scenario of 60%.

The energy estimation with environmental and economic analysis was performed in Excel, and includes NPV, IRR, using Eqs. (13) (14), respectively (Wang et al., 2021), where I is the initial investment, k is the life of the plant (25 years), CF is the cash flow, and i is the interest rate. The Consumer Price Index (CPI) of 3.76%, reported by the Central Bank of the Dominican Republic, was used as the annual inflation rate in the model. This value was applied to escalate operating expenses and electricity revenues each year, while the economic viability was assessed separately using interest rates between 0 and 10% (steps of 2%).

$$NPV = -I + \sum_{k=1}^n \frac{CF}{(1+i)^k} \quad (13)$$

$$0 = -I + \sum_{k=1}^n \frac{CF}{(1+TIR)^k} \quad (14)$$

The investment ratio respect to the engine capacity was set in the range from 2000 to 3500 US\$.kW⁻¹. For the estimation of the total income, the energy price was set at 14.5 cUS\$.kWh⁻¹. For the general and administrative expenses, a ratio of 4 cUS\$.kWh⁻¹ was considered. According to the report from MEM during 2024 and January–September 2025 (Energy and Mines Ministry of the Dominican Republic, 2024; Energy and Mines Ministry of the Dominican Republic, 2025), the average price for purchased energy was 15 cUS\$.kWh⁻¹.

For the avoided cost by not using conventional fuels, NG was evaluated. The generator efficiency was set at 30%. The LHV_{NG} was fixed as 10.45 [kWh.Nm⁻³] (España Informe Inventarios GEI 1990-2022, 2024). The volume of NG was calculated with the equation for biogas volume estimation (9). The NG price was fixed between 2.5 and 4 US\$.MMBTU⁻¹, following the report from MEM: 2024 (1.76–2.9 US\$.MMBTU⁻¹) (Energy and Mines Ministry of the Dominican Republic, 2024) and 2025 (2.9 to 4.12 US\$.MMBTU⁻¹) (Energy and Mines Ministry of the Dominican Republic, 2025) (Table 4). For CO₂ emissions estimation, different emission factors were identified in the literature. A fuel-specific emission factor of 55.99 kgCO₂.GJ⁻¹, equivalent to 0.2016 kgCO₂.kWh⁻¹, was taken from official Spanish governmental inventories (2024 edition) (España Informe Inventarios GEI 1990-2022, 2024). In addition, a recent study reports a system-average emission factor of 0.6277 tCO₂.MWh⁻¹ (Relova-Delgado et al., 2025) for the electricity mix of the National Interconnected Electric System (SENI) of the Dominican Republic, reflecting the national electricity mix dominated by fossil fuels (approximately 78%), including coal (28.8%), natural gas (38.8%), and fuel oil #6 (10.2%).

Table 4
Environmental and economic analysis parameters.

CPI [%]	Interest rate [%]	Investment ratios [US \$/kW]	NG price [US \$/MMBTU]	Energy selling price [cUS \$/kWh]	Administrative and general expenses [cUS \$/kWh]	Plant life [years]
3.76	0–10	2000–3500	2.5–4	14.50	4	25

Results analysis

First addition of DOW and biogas production follow up

A total mixture of 2 kg was added to the biodigester on December 18, but nothing was extracted. The total mixture into the biodigester now had around 61 kg of inoculum and 2 kg of DOW & water mixture with a relation of 1:1 (1 kg of DOW and 1 kg of water), for a total mass around 63 kg. Results are shown in Table 5. On December 21, the methane in the biogas was around 45%. On January 9, 10, 15 and 20, the CH₄ was around 60%, 63.8%, 56.3% and 47.2%, respectively.

When the DOW was first added to the digester, the biogas production behavior reflected a classical transition phase observed in anaerobic systems, which is well explained in the biogas handbook (Al Seadi et al., 2008). Although the inoculum was deposited earlier (rumen + cow dung), the addition of a new substrate (DOW) requires metabolic adjustment. During hydrolysis, polymers such as carbohydrates, lipids, nucleic acids, and proteins are converted into glucose, glycerol, purines, and pyridines. During acidogenesis, the products of hydrolysis are converted by acidogenic (fermentative) bacteria into methanogenic substrates. Simple sugars, amino acids, and fatty acids are degraded into acetate, carbon dioxide, and hydrogen, as well as into volatile fatty acids (VFA) and alcohols. Products from acidogenesis that cannot be directly converted to methane by methanogenic bacteria are further transformed into substrates for methanogenic substrates during acetogenesis. VFA and alcohol are oxidized into methanogenic substrates such as acetate, hydrogen, and carbon dioxide. The gradual increase in CH₄ concentration during this phase indicates that the anaerobic environment improved as the microbial community adapted to the organic composition of DOW.

Prior to the first addition of DOW, the biodigester was operated exclusively with inoculum. Approximately 20 days after inoculum deposition, methane concentrations in the biogas headspace reached values between 63.6 and 67.9% CH₄, confirming that stable anaerobic activity had been established. These measurements were not part of the biogas production quantification protocol and were only used to verify inoculum activity. Following the first addition of DOW, a temporary decrease in methane concentration was observed, reaching approximately 45%, accompanied by higher CO₂ and detectable O₂ fractions, reflecting the metabolic transition associated with the introduction of a new substrate.

As the microbial community adapted to the organic composition of DOW, methane concentrations progressively increased, reaching values up to 63%, while CO₂ and O₂ levels decreased. This evolution pattern is consistent with previous experimental studies conducted under inoculum-dominated conditions. Methane concentrations of approximately 59.94% were reported in a reactor treating 2% food waste and 98% bio-flocculated sludge, and 60.29% in a reactor operating with 50% food waste and 50% bio-flocculated sewage sludge (Thakur et al., 2023). Similarly, in an experimental study using livestock manure and cheese whey as substrates, methane concentrations around 64.25% were reported (Sánchez-Sánchez et al., 2018). These comparisons indicate that both the magnitude and temporal evolution of methane observed in the present study fall within the expected range for inoculum-dominated systems during the initial operational stage.

According to the typical biogas composition ranges reported in the literature, methane concentrations in stabilized anaerobic digestion systems generally range between 50 and 70%, carbon dioxide between 25 and 45%, and oxygen is usually present at concentrations below 2%

Table 5

First addition of DOW, following the biogas production.

Measuring order	Date [mm/dd/yyyy]	Addition of DOW&water mixture [kg]	Total mass inside biodigester [kg]	CH ₄ [%]	CO ₂ [%]	O ₂ [%]	H ₂ S [ppm]	Bal [%]	Calculated residual N ₂	Biogas Density [kg/m ³]	Total biogas lower heating value [kWh/Nm ³]
1	12 18 2024	2.00	63.1	-	-	-	-	-	-	-	-
2	12 21 2024	-	63.1	45.0	22.3	8.5	9.0	24.20	7.8	0.98	4.5
3	1 8 2025	-	63.1	-	-	-	-	-	-	-	-
4	1 9 2025	-	63.1	60.1	26.6	1.5	38.0	11.80	6.2	1.05	6.0
5	1 9 2025	-	63.1	62.2	27.7	0.7	34.0	9.30	6.7	1.08	6.2
6	1 10 2025	-	63.1	63.8	23.7	2.3	11.3	10.28	1.8	0.98	6.3
7	1 15 2025	-	63.1	56.3	15.3	6.3	9.0	22.20	1.5	0.81	5.6
8	1 20 2025	-	63.1	47.2	12.8	8.6	27.0	31.40	0.9	0.72	4.7

(Al Seadi et al., 2008; Lorenzo Acosta et al., 2005). In the present study, biogas compositions measured around January 9–10 fell within these ranges, with methane concentrations exceeding 60%, carbon dioxide remaining within the expected interval, and oxygen levels decreasing to values close to or below 2%. This confirms that, at this stage, the biodigester operated under conditions consistent with a well-established anaerobic environment.

pH and HRT monitoring and control

During the evaluation of the HRT, which modified the OLR, there was a strong relationship between CH₄, O₂ and OLR. Fig. 2 and Fig. 3 show the evolution of CH₄% and CO₂% when the OLR was modified for HRT of around 32 and 36 days, and for 60 days, respectively. The axes represent CH₄% (left) and O₂% (right). CH₄% is represented with grey circles and O₂% is represented with black triangles. As can be seen, CH₄% average increased when reducing the OLR, and the O₂% average tended to decrease. When the OLR was 10 kg·m⁻³·day⁻¹, for approximately 32 days of HRT, the CH₄% and O₂% averaged 45.7% and 5.2%, respectively. And, when the OLR was 8.8 kg·m⁻³·day⁻¹, for approximately 36 days of HRT, the CH₄% and O₂% averaged 49.1% and 3.9%, respectively. The digestate recirculation started on January 31 (representing 16% of the feeding material). For 32 and 36 days of HRT, the mass flow rates were around 2 and 1.77 kg/day, respectively.

On February 7, the mass flow was decreased to 1.22 kg·day⁻¹, for

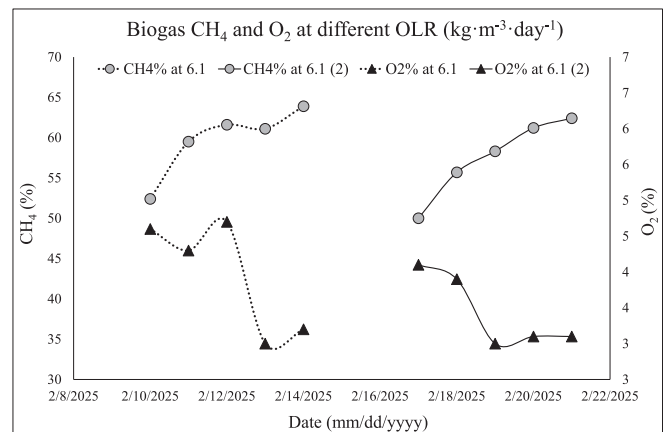


Fig. 3. CH₄% and O₂% for different ORL for HRT around 60 days.

HRT of 60 days and OLR around 6.1 kg·m⁻³·day⁻¹. Afterward, from February 10 to 21, CH₄ and O₂ averaged 58.6% and 3.7%, respectively. According to the conditions and results, it was evident that in order to produce CH₄ between 50 and 65%, it was necessary to work with HRT of around 60 days instead of 30 days. The information found in the literature about reducing the organic load rate and the recirculation of a

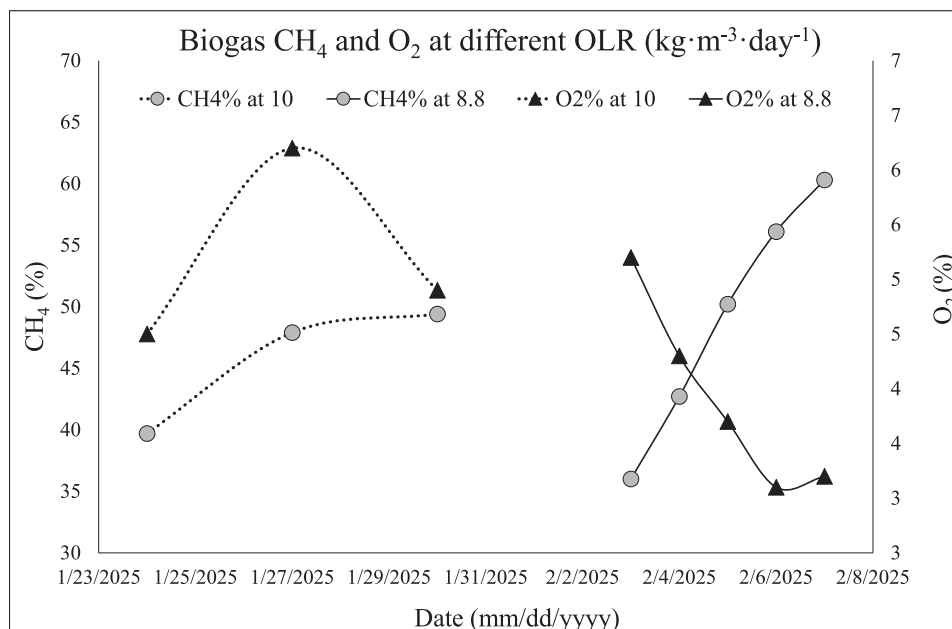


Fig. 2. CH₄ and O₂ for different OR for HRT around 30 and 35 days.

fraction from the digestate to increase the pH has been confirmed. The results agree with the trend reported in an experimental studied where the OLR was between 6.8 and 10.5 kgVS·m⁻³·day⁻¹ (Zhang et al., 2007).

Additionally, during all the experimental study, the CH₄% used to decrease the day after feeding the biodigester, but the following days it used to start a reposition to be over 60%. However, when working with HRT of around 60 days instead of 30 days, the improvement was enough to have 50–60% of methane, as can be seen in Fig. 4.

Overall, extending the HRT from around 30 days to around 60 days resulted in a substantial improvement in biogas quality. When comparing both operational gaps, methane increased from average values of 46–49% to 59%, while oxygen decreased from 5.2 to 3.9% to approximately 3.7%. This represents an improvement of roughly 25–30% in CH₄% content and a reduction of about 30% in O₂. These differences confirm that reducing the OLR and increasing the HRT were essential to achieving a fully anaerobic and methanogen-dominated environment.

The evolution of the outlet pH and the OLR when changing the HRT is seen in Fig. 5. The axes represent the pH with black triangles (right) and the OLR with grey circles (left). When feeding the biodigester for HRT around 30 and 35 days or OLR 10 and 8.8 kg·m⁻³·day⁻¹, respectively, the pH was 6.94 and 6.88. On the other hand, when increasing the HRT to 60 days, the pH rose to 7.11 and 7.48.

Overall, the strong inverse relationship between OLR and CH₄% and the direct improvement with longer HRT is consistent with optimized anaerobic digestion performance. The patterns presented above emerge from key mechanistic reasons:

(a) Lower OLR reduces VFA accumulation and stabilizes pH: high organic loading rates increase acidogenesis, leading to temporary VFA accumulation and pH drops. Methanogens, being pH sensitive, become inhibited under acidic conditions. When OLR was reduced, the pH increased, less acid was produced, allowing methanogens to fully convert VFAs into methane. (b) Longer HRT prevents failure of methanogens and increases substrate conversion efficiency: The duplication rate of anaerobic bacteria is usually 10 days or more (Al Seadi et al., 2008). At short HRTs (around 30 days), these archaea risk being washed out faster than they can reproduce. Increasing HRT to 60 days ensured that microorganisms remained in the system long enough to complete the sequential hydrolysis - acidogenesis - acetogenesis - methanogenesis process, boosting methane production. Some components of DOW (fibers, proteins, lipids) require longer degradation times. A 60-days HRT

allows hydrolytic and fermentative microorganisms enough time to fully degrade complex organics. (c) Reduction of O₂ is linked to improved anaerobic conditions: O₂ in biogas generally originates from small-entrapped air pockets during feeding or insufficiently anaerobic micro zones. Additionally, a more active methanogenic community consumes reducing equivalents (H₂), pushing the oxidation-reduction potential more negative and eliminating residual O₂ more rapidly. This explains why O₂ levels decrease as CH₄ increases. These results also confirm that maintaining a recirculation rate close to 16% was sufficient to stabilize alkalinity and sustain outlet pH values between 7.1 and 8. This moderate recirculation acted as a buffer, preventing excessive acidification after feeding events and supporting the microbial balance required for stable CH₄.

A multiple linear regression model was developed to estimate methane concentration as a function of key operational parameters (Eq. (15)), including hydraulic retention time (HRT), organic loading rate (OLR), pH, flowrate, and recirculation, for a fixed DOW:water dilution ratio of 1:1. The results indicate that methane concentration increases with increasing HRT and decreases with increasing OLR, reflecting the dominant role of residence time and organic load on methanogenic performance. pH also exhibited a measurable influence on methane content, highlighting its role in modulating methanogenic activity under quasi-steady operating conditions. Although flowrate was included in the regression analysis, its coefficient converged to a negligible value due to its intrinsic dependency on HRT and OLR, as flowrate explicitly appears in their mathematical definitions (Al Seadi et al., 2008). Recirculation did not contribute to the model because it was maintained at an approximately constant value (around 16%) throughout the experimental campaign and therefore did not introduce variability into the dataset. Fig. 6 compares experimental and numerically predicted methane concentrations, showing that most data points fall within a ± 10% deviation, which confirms the robustness and predictive capability of the proposed empirical model under stable operating conditions.

$$CH_4 [\%] = 90.0679 + 0.3354 \bullet HRT - 1.4079 \bullet OLR - 5.8936 \bullet pH \quad (15)$$

Biogas production under fixed conditions

At this moment, the installation was considered in stable conditions, the feeding flow was between 1.13 and 1.30 kg·day⁻¹ to guarantee HRT

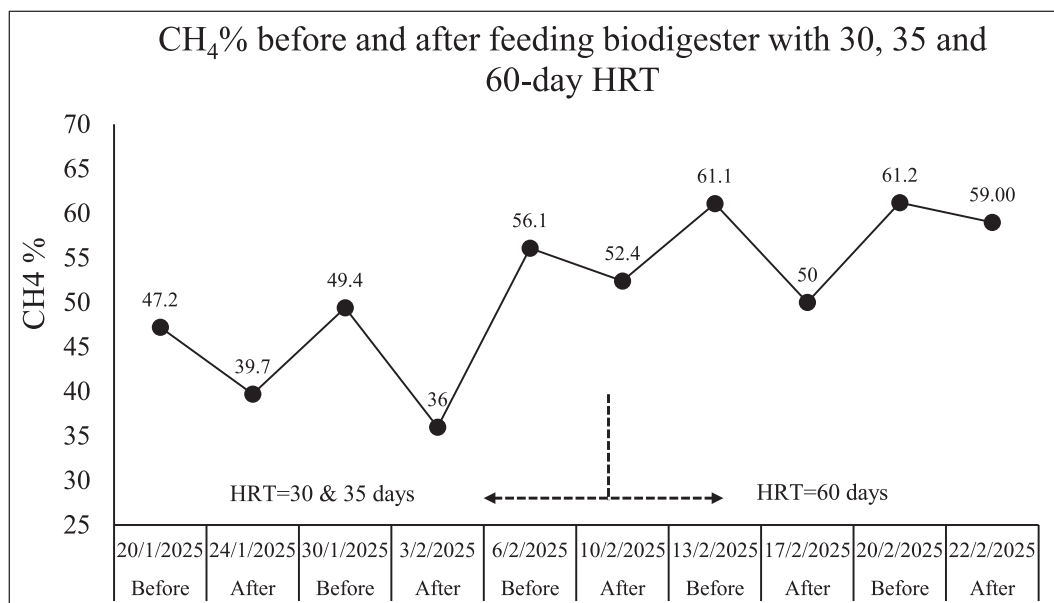


Fig. 4. Methane concentration before and after feeding events for HRTs of 30–35 days and 60 days. The dashed line indicates the transition to longer HRT operation.

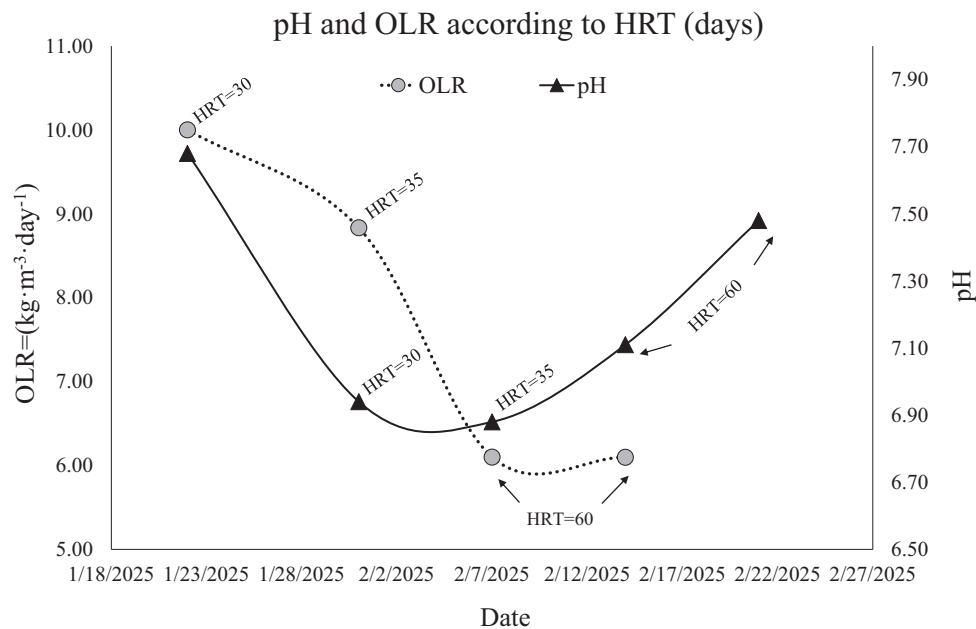


Fig. 5. pH and OLR according to different HRT.

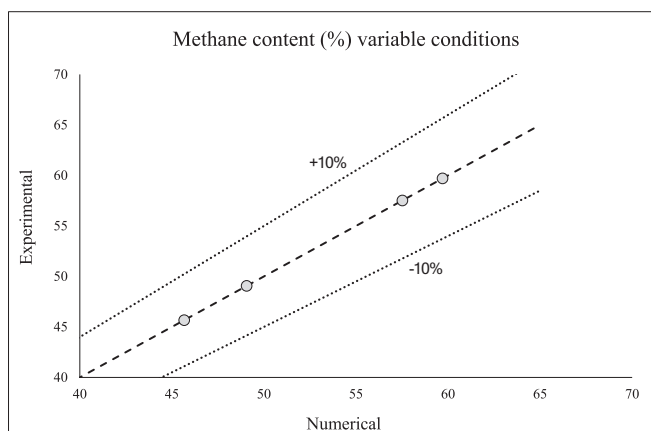


Fig. 6. CH₄% model validation under variable conditions.

around 60 days, the recirculation represented about 16% of the feeding substrate, and the DOW & water mixture relation was 1:1 (Table 6). On March 14, the total mixture of water and DOW added to the biodigester was around (61.05 kg), approximately equal to the initial inoculation mass (61.1 kg). The total mass including the inoculum recirculation was 70.2 kg, which meant that the initial inoculum had been replaced by the feeding and recirculation material.

Fig. 7 shows the behavior of the OLR, digestate pH and substrate pH. The black triangles represent the digestate pH and the white triangles represent the substrate pH. The OLR is represented by the grey circles. The digestate pH averaged around 7.64, the substrate pH averaged around 3.92, and the OLR average was around $6.1 \text{ kg}\cdot\text{m}^{-3}\cdot\text{day}^{-1}$. On March 7, there was an increase in the digestate pH (8.01), which was due to an increase in the HRT (65 days) in the previous feeding (March 3), when an OLR around $5.6 \text{ kg}\cdot\text{m}^{-3}\cdot\text{day}^{-1}$ and a mass flow (feeding flow) around $1.13 \text{ kg}\cdot\text{day}^{-1}$ were registered. With the objective of having the HRT average around 60 days, on March 14, the OLR was increased to $6.5 \text{ kg}\cdot\text{m}^{-3}\cdot\text{day}^{-1}$ and the feeding flow at that exact date was $1.30 \text{ kg}\cdot\text{day}^{-1}$, for HRT around 56 days. Afterward, the pH was around the optimal values. According to the results, the experiment was around the optimal value of HRT and the flow needed to be measured and

controlled to be around these conditions and guarantee the biogas production.

From the point after establishing the HRT around 60 days to the end of the feeding and measuring (from February 7 to May 8), the CH₄% and O₂% averaged around 55.43% and 2.9%, respectively, and the LHV was around $5.51 \text{ kWh}\cdot\text{Nm}^{-3}$. Although the results were good, the dilution was changed to 1:2 on April 11 and 25. As a result, from April 14 to May 8, the CH₄% and O₂% average were around 51.6% and 0.8%, respectively. However, from April 28 to May 8, the CH₄% average was 55.9% and the O₂% averaged around 0.2%. On the other hand, from February 10 to April 11, when the DOW & Water relation was 1:1, the CH₄% and the O₂% were around 56.3% and 3.43%, respectively. Although both dilutions showed good results, 1:1 dilution provides a practical balance for biogas generation using DOW, avoids over-dilution and excessive water consumption, which could reduce organic loading and biogas production.

Regarding biogas yield estimation, gas volume measurements used for yield calculations were conducted until May 8. However, after this date, the biodigester remained fully pressurized with biogas at least until May 23 and continued producing gas until mid-October, indicating sustained methanogenic activity beyond the measurement period. Based on the available measurements, the average biogas yield was approximately $0.12 \text{ Nm}^3\cdot\text{kgDOW}^{-1}$, while the average methane yield was $0.0651 \text{ Nm}^3\text{CH}_4\cdot\text{kgDOW}^{-1}$. Biogas and methane yields were estimated using a mass-based extrapolation approach for pilot-scale fed-batch systems, following the methodology previously reported by (Castro et al., 2022) for fed-batch anaerobic digestion.

Near the end of the experimental campaign, a gas leak was identified at the upper section of the biodigester. Leak detection was carried out using a soap-solution test, which revealed gas bubbling at the surface. The leak was not readily apparent during most of the operation because biogas production was sufficient to keep the biodigester visibly inflated, masking gradual gas losses. This leakage may have caused part of the produced biogas to bypass the measurement and sampling system, leading to an underestimation of the total biogas and methane yields. In addition, gas losses may have reduced the effective duration of gas accumulation within the system, further contributing to uncertainty in yield estimation. Consequently, the yields reported in this study should be interpreted as conservative estimates rather than maximum achievable values. Future implementations should include systematic leak-

Table 6
Production of biogas under fixed conditions.

Measurement number	Date [mm/dd/yyyy]	Addition of DOW&water mixture [kg]	Extraction of digestate [kg]	Recirculation of digestate [kg]	CH ₄ [%]	CO ₂ [%]	O ₂ [%]	H ₂ S [ppm]	Bal [%]	Calculated residual N ₂	pH digestate (outlet)	pH substrate (DOW&Water mixture)	HRT [days]	Biogas Density [kg/m ³]	Total biogas lower heating value [kWh/Nm ³]	Organic load rate [kg/m ³ ·day]
1	2 21 2025	7.36	8.5	1.2	62.4	30.0	3.1	15.0	4.5	7.2	7.48	3.94	60.0	1.17	6.21	6.1
2	2 22 2025	–	–	–	59.0	31.1	3.5	32.0	6.3	6.9	–	–	–	1.17	5.87	
3	2 24 2025	–	–	–	57.3	29.6	4.6	31.0	8.5	8.8	–	–	–	1.17	5.70	
4	2 25 2025	–	–	–	58.4	29.9	4.2	24.0	7.5	8.3	–	–	–	1.17	5.81	
5	2 26 2025	–	–	–	60.4	28.4	4.1	13.0	7.2	8.2	–	–	–	1.15	6.01	
6	2 28 2025	–	–	–	59.2	26.0	5.1	22.0	9.7	9.5	–	–	–	1.13	5.89	
7	3 3 2025	7.22	8.7	1.2	55.9	25.5	5.8	27.0	12.7	9.1	7.490	4.34	64.8	1.10	5.56	5.6
8	3 5 2025	–	–	–	55.0	29.4	4.9	39.0	10.7	7.7	–	–	–	1.14	5.47	
9	3 6 2025	–	–	–	57.0	32.1	3.5	32.0	7.4	5.8	–	–	–	1.16	5.67	
10	3 7 2025	7.29	8.5	1.2	61.1	30.0	3.3	17.0	5.7	6.7	8.010	3.95	60.0	1.16	6.08	6.1
11	3 10 2025	–	–	–	57.3	27.2	5.1	27.0	5.1	14.1	–	–	–	1.19	5.70	
12	3 11 2025	–	–	–	59.0	27.9	4.3	19.0	8.7	7.5	–	–	–	1.13	5.87	
13	3 12 2025	–	–	–	61.8	29.5	3.2	12.0	5.4	6.6	–	–	–	1.15	6.15	
14	3 13 2025	–	–	–	62.7	28.4	3.5	14.0	5.4	7.8	–	–	–	1.15	6.24	
15	3 14 2025	11.00	12.8	1.8	62.8	26.6	3.9	10.0	6.6	8.1	7.680	3.65	56.1	1.13	6.25	6.5
16	3 15 2025	–	–	–	55.9	31.6	4.1	69.0	8.5	6.9	–	–	–	1.17	5.56	
17	3 17 2025	–	–	–	53.7	30.6	4.8	25.0	10.9	7.1	–	–	–	1.14	5.34	
18	3 18 2025	–	–	–	54.5	30.5	4.6	31.0	10.5	6.8	–	–	–	1.14	5.42	
19	3 19 2025	–	–	–	54.1	38.0	2.4	46.0	5.4	3.6	–	–	–	1.21	5.38	
20	3 20 2025	–	–	–	51.7	41.7	1.9	53.0	4.9	2.2	–	–	–	1.24	5.14	
21	3 21 2025	4.0	4.6	0.6	50.7	39.2	2.7	30.0	7.4	2.8	7.740	3.99	59.7	1.21	5.04	6.1
22	3 24 2025	–	–	–	49.8	37.7	2.9	26.0	9.6	1.3	–	–	–	1.16	4.95	
23	3 25 2025	–	–	–	49.4	36.0	3.3	26.0	11.4	1.0	–	–	–	1.12	4.91	
24	3 26 2025	–	–	–	55.3	40.9	0.9	32.0	2.9	0.5	–	–	–	1.22	5.50	
25	3 27 2025	6.4	7.8	1.1	51.3	38.9	2.0	64.0	7.8	0.3	7.670	3.10	59.3	1.16	5.10	6.1

(continued on next page)

Table 6 (continued)

Measurement number	Date [mm/dd/yyyy]	Addition of DOW&water mixture [kg]	Extraction of digestate [kg]	Recirculation of digestate [kg]	CH ₄ [%]	CO ₂ [%]	O ₂ [%]	H ₂ S [ppm]	Bal [%]	Calculated residual N ₂	pH digestate (outlet)	pH substrate (DOW&Water mixture)	HRT [days]	Biogas Density [kg/m ³]	Total biogas lower heating value [kWh/Nm ³]	Organic load rate [kg/m ³ ·day]
26	3 28 2025	–	–	–	49.2	48.5	0.9	65.0	1.4	2.0	–	–	–	1.34	4.89	
27	3 31 2025	–	–	–	54.4	42.4	0.8	48.0	2.5	0.5	–	–	–	1.24	5.41	
28	4 2 2025	–	–	–	54.6	42.1	0.8	28.0	2.6	0.4	–	–	–	1.23	5.43	
29	4 7 2025	10.0	11.6	1.7	61.4	16.6	7.6	13.0	14.5	14.1	7.910	3.50	60.5	1.05	6.11	6.0
30	4 9 2025	–	–	–	43.5	50.3	0.7	96.0	5.6	3.0	–	–	–	1.35	4.33	
31	4 11 2025	5.9	6.9	1.0	49.4	47.8	0.7	111.0	2.1	0.5	7.770	3.40	59.2	1.31	4.91	4.1
32	4 14 2025	–	–	–	38.5	54.7	0.8	122.0	6.0	3.0	–	–	–	1.40	3.83	
33	4 16 2025	–	–	–	44.1	49.7	1.2	137.0	5.0	0.5	–	–	–	1.32	4.39	
34	4 21 2025	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
35	4 22 2025	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
36	4 25 2025	8.0	9.3	1.3	46.3	35.5	3.5	49.0	14.7	1.5	7.580	3.06	63.6	1.10	4.60	3.8
37	4 28 2025	–	–	–	51.4	45.5	0.3	137.0	2.9	1.8	–	–	–	1.29	5.11	
38	4 30 2025	–	–	–	54.3	44.9	0.3	119.0	0.5	0.6	–	–	–	1.28	5.40	
39	5 1 2025	–	–	–	55.1	44.5	0.3	145.0	0.1	1.0	–	–	–	1.29	5.48	
40	5 2 2025	–	–	–	55.6	44.1	0.3	105.0	0.0	1.1	–	–	–	1.28	5.53	
41	5 7 2025	–	–	–	59.4	40.2	0.1	191.0	0.4	0.0	–	–	–	1.22	5.91	
42	5 8 2025	–	–	–	59.5	40.5	0.1	155.0	0.0	0.4	–	–	–	1.23	5.92	

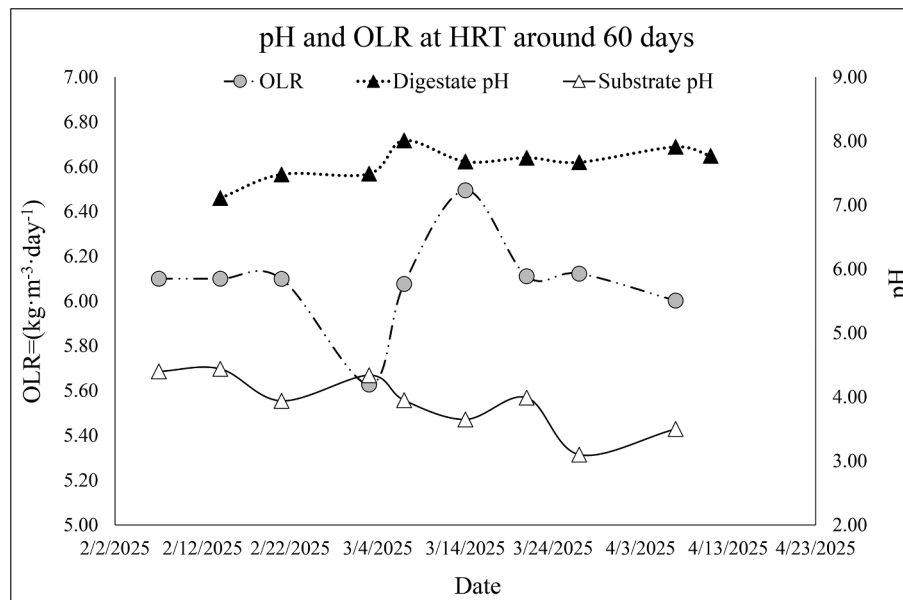


Fig. 7. pH at the inlet and outlet between January 22 and April 25.

tightness verification prior to and during operation, the use of more robust and gas-tight biodigester materials, and continuous gas flow monitoring to further reduce uncertainty. According to the literature, biogas yields from organic waste typically range between 0.05 and 0.40 $\text{Nm}^3 \cdot \text{kgDOW}^{-1}$, placing the values reported in this study within the expected range.

Under fixed operational conditions of stable pH (average around 7.64), HRT around 60 days, and recirculation around 16%, methane concentrations remained consistently between 50 and 60%. This stability indicates that the system reached a mature metabolic balance. Recirculation improves alkalinity and microbial density and acts as a buffer, stabilizing and maintaining pH while supporting continuous methanogenic activity. Mesophilic digestion favors both hydrogenotrophic and acetoclastic pathways, where acetate is converted into methane and hydrogenotrophic methanogens consume H_2 and CO_2 . Residual O_2 dropped to an average of nearly 2%, as the biodigester operated under stable conditions with an OLR around $6 \text{ kg} \cdot \text{m}^{-3} \cdot \text{day}^{-1}$ and gentle mixing. As the microbial community matures, any trace O_2 is rapidly consumed by microorganisms within the biodigester, resulting in an increasingly anaerobic environment. Regarding energy content, the LHV increases with CH_4 concentration since it depends directly on the methane fraction; therefore, the observed value of approximately $5.5 \text{ kWh} \cdot \text{Nm}^{-3}$ is consistent with CH_4 fractions approaching 50–60%.

These results align with typical biogas values reported for DOW substrates under stable anaerobic digestion conditions. Comprehensive reviews and handbooks generally describe methane contents in the range of 50–70% for well-operated systems (Al Seadi et al., 2008; Casanovas et al., 2019; Lorenzo Acosta et al., 2005). Furthermore, experimental studies focused on food waste digestion and co-digestion using different inoculum, including cattle manure, cow dung, sewage sludge, and digestate from full-scale reactors, report methane concentrations that closely match those observed in this study. Reported CH_4 fractions commonly range between approximately 50 and 65%, depending on substrate composition, co-digestion strategy, and operational stability (Bouallagui et al., 2003; Castro et al., 2022; Chen et al., 2016; Hakimi et al., 2023; Lattieff, 2016; Nganyira et al., 2023; Rossi et al., 2021; Sánchez-Sánchez et al., 2018; Santos et al., 2023; Thakur et al., 2023; Wang et al., 2021). Therefore, the methane concentrations achieved in this work fall well within the experimentally reported ranges for food waste-based anaerobic digestion systems, supporting the robustness and representativeness of the obtained results under stable operating

conditions.

The model previously developed was validated against the experimental results obtained under nearly fixed operating conditions, including a 1:1 dilution ratio and a 60-day HRT. Under these conditions, most of the predictions fall within an error band of $\pm 10\%$, as shown in (Fig. 8). The plot also includes experimental and numerical data from the previous section (pH and HRT monitoring and control section), where the model was developed using a broader range of operating conditions, including HRT values between 30 and 60 days, OLR between 5.63 and $10 \text{ kg} \cdot \text{m}^{-3} \cdot \text{day}^{-1}$, and pH values from 6.88 to 8.0.

To sum up, according to the results, the authors recommend that biogas production from DOW under mesophilic conditions should consider an HRT of approximately 60 days, digestate recirculation, and continuous monitoring of digestate pH. Adjustments to HRT, OLR, and recirculation rate (if necessary) are suggested to maintain pH within the range recommended in the literature to ensure stable and sustained biogas production.

Using digestate as fertilizer

The vitroplants acclimatized successfully and exhibited adequate development with both dilutions, without the need for additional inorganic fertilization (e.g., NPK 15-15-15 or NPK 20–20–20). Fig. 9 shows

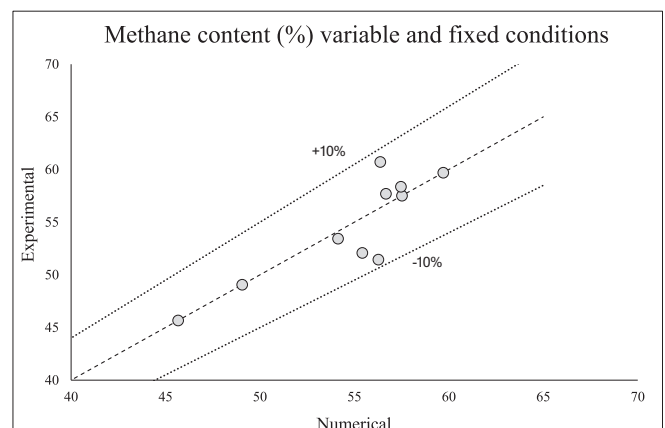


Fig. 8. Model validation under variable and fixed conditions.



Fig. 9. Acclimatization in nursery.

results for vitroplants 15 days old planted in a nursery.

The emergence of the flag leaf was observed nine (9) days after the initial application of the biol.

This biopreparation may represent a viable alternative for fertilizing *Musa* spp. vitroplants during the early stages of ex vitro acclimatization.

In an experimental study performed in Spain, with digestate from biogestor using pig slurry and wastewater and found that the addition to soil provided a source of available nutrients (nitrogen and phosphorus) in the short-term and had positive effects on soil biological properties such as microbial biomass and enzyme activities, compared to the non-amended soil (Albuquerque et al., 2012). An experimental research conducted in Poland, using digestate from biomass biogestor,

where pH range almost similar to the one used in this experimental research (7.4 to 7.8), found that the high amount of nutrients and organic matter in digestate from organic biogestor have a high potential as valuable agricultural fertilizers (Roj-Rojewski et al., 2018).

The successful use of digestate used in the present experimental research for plant growth can be explained by the transformation of organic nitrogen into ammonium (NH_4^+) during anaerobic digestion, which produces a readily available nitrogen source for plants (Möller & Müller, 2012). The mineralization of phosphorus and potassium increases their solubility and accessibility. Also, digestate contributes organic matter that improves soil structure and moisture retention, essential for root establishment (Nkoa, 2014; Tambone et al., 2010).

At the present stage of the study, digestate application was intended as an exploratory, qualitative assessment of agronomic feasibility rather than a controlled agronomic trial; therefore, quantitative plant growth metrics and statistical analysis were not included. Further research is recommended to evaluate the fertilization potential of digestate using quantitative indicators.

Comparing biogas from DOW to a real scale biodigester using cow dung

Biogas produced with inoculum only was measured to identify when the facility was ready to receive the DOW and as a reference when measuring the biogas produced with cow dung in a real scale biodigester. The results were presented at [Inoculum section](#). The CH₄% and LHV for the biogas with inoculum only (at IIBI) and the one produced with the real scale biodigester using cow dung are among the values found in the literature ([Aili Hamzah et al., 2023](#); [Al Seadi et al., 2008](#); [Casanovas et al., 2019](#); [Lorenzo Acosta et al., 2005](#)). The CH₄% average for the real scale biodigester using cow dung was around 64.3% and the LHV was around 6.39 kWh·Nm⁻³ ([Table 7](#)).

The results confirm the values found in the literature about biogas production using DOW under mesophilic conditions without any electrical or mechanical temperature control to modify the conditions inside the biodigester. The LHV around 5.5 kWh·Nm⁻³ and CH₄ around 55% are lower than for the biogas using cow dung, but in the range for biogas to be considered as a quality fuel ([Barragán Monrroy et al., 2024](#)). Although methane concentration from DOW was lower than that obtained from cow dung, it remained well above the around 50% threshold typically required for efficient combustion in biogas engines. This confirms that DOW-derived biogas is energetically viable even without codigestion or chemical supplementation.

Cow dung typically produces biogas with higher methane content than DOW, and this difference aligns with biochemical and structural characteristics of the substrates. Since cows pre-digest food through rumination their manure is practically homogeneous and contains partially hydrolyzed carbohydrates, which makes it easier for anaerobic microbes to convert the remaining volatile solids into methane. Also, the cow dung has more stable C/N ratio (20–30), typically around the optimal range for anaerobic digestion ([Zupancic & Viktor, 2012](#)). Additionally, cow dung has higher buffering capacity containing natural bicarbonates and minerals that stabilize pH. On the other hand, DOW variability fluctuates containing fresh carbohydrates, lipids, and proteins that undergo full hydrolysis. The DOW substrate typically contains very low or very high C/N ratios ([Orhorhoro et al., 2016](#)), due to high protein kitchen waste, which can release excess ammonia that temporarily inhibits methanogens.

Despite the inherent differences, the biogas production using DOW still achieved methane yields within the expected literature range, confirming the feasibility of DOW as a viable biogas substrate. Furthermore, the biogas production using DOW could represent a solution for electricity and heat production if waste is correctly separated at the origin. The biogas production using cow dung is still an individual solution for farmers to provide themselves with electricity and heat for

personal use to grind the animal food and cooking. Whereas, producing biogas and electricity using DOW, besides individual and personal use, could be used by municipalities to generate electricity and sell it to the grid, which can improve the energy mix in a country where the biomass energy production represents only 1%.

Putting all together, these findings allow for the formulation of a conceptual model for DOW-based anaerobic digestion under tropical conditions. Biogas performance is primarily governed by the following operational variables: (1) a hydraulic retention time of at least 60 days, ensuring complete degradation of complex organics; (2) an organic loading rate around 6 kg·m⁻³·day⁻¹, avoiding volatile fatty acid accumulation; (3) a stable outlet pH between 7 and 7.8, supported by digestate recirculation; (4) a DOW & Water dilution ratio of 1:1, optimizing biodegradability and flow properties and reducing water consumption. This integrated operational framework provides a reproducible baseline for scaling decentralized DOW-based biogas plants.

Energy production using real engines from the market

Initial calculations were performed to identify the net energy and amount of DOW needed for different commercially available engines ([Table 8](#)). For the present energy estimation, the working time was fixed at 8 h. For a fixed biogas yield of 0.1 Nm³·kg⁻¹, a single family or a municipality could estimate the energy to be produced if considered one of the engines used for this numerical study. Also, the flow rate for specific engine power and gas volume could be found here and can be considered for selecting biogas booster pump and flow meter. The engine already in the lab has a net power of 3 kW and the required flow rate is 2.1 m³·h⁻¹ according to the manufacturer. Therefore, for the LHV = 5.5 kWh·Nm⁻³, the engine efficiency would be around 26%. This validates the results shown when considering an engine efficiency of 25% and a 3-kW engine, where the required biogas flow is 2.18 m³·h⁻¹.

If the biogas yield considered is 0.05 Nm³·kg⁻¹, the amount of DOW and the number of people required to produce them are going to double the calculated values. To put the results in perspective, if a municipality fixed an engine efficiency around 30% and selected the 1 MW engine, it would need a population of at least 103,467 people if considered a biogas yield of 0.1 Nm³·kg⁻¹, but for a biogas yield around 0.05 Nm³·kgDOW⁻¹, they would need about 203,934 people. It's also important to highlight that a municipality can have people that daily move to work or study to other municipalities and receive people from other municipalities, thus the number of people required to produce a specific DOW amount is not quite an accurate factor but can be used as a reference.

Brief environmental and economic estimations

According to the selected operating assumptions, for a 1-MW plant and two representative plant factors (PF) of 33.3% and 60%, approximately 2.92–5.26 GWh of electricity would be produced annually using biogas from the proposed DOW-based system. If the same amount of

Table 7
Biogas from Cow Dung Vs. Biogas from DOW.

Biogas with DOW (1:1 and 1:2). Location: IIBI, Santo Domingo, D.N. Dominican Republic								
Measurement number	Date [mm/dd/yyyy]	HRT [days]	CH ₄ [%]	CO ₂ [%]	O ₂ [%]	H ₂ S [ppm]	Bal [%]	LHV [kWh/m ³]
Average	Average	60	56.30	32.96	3.43	32.40	7.20	5.60
Real-scale biodigester using Cow Dung. Location: Andrés Bautista's farm, La Vega, Dominican Republic								
Measurement number	Date [mm/dd/yyyy]	HRT [days]	CH ₄ [%]	CO ₂ [%]	O ₂ [%]	H ₂ S [ppm]	Bal [%]	LHV [kWh/m ³]
1	6 10 2025	–	65.2	34.6	0.1	790.0	0.0	6.48
2	6 17 2025	–	63.4	36.4	0.2	750.0	0.0	6.30

Table 8
Results for biogas yield of 0.1 Nm³·kgDOW⁻¹.

Engine _{power} [kW]	η_{engine} [-]	Engine _{energy} [kWh/day]	Pump _{energy} [kWh/day]	Blender _{energy} [kWh/day]	Other _{energy} [kWh/day]	Net _{energy} [kWh/day]	Engine _{gas} flow [m ³ /s]	Engine _{gas} volume [m ³ / day]	DOW _{required} quantity [kg/ day]	Number _{of} required people [People/day]	Net _{energy} mass ratio [kWh/ ton]
2.80	0.20	22.40	0.22	1.12	0.22	17.81	2.55	20.36	203.60	407.30	87.47
3.00	0.20	24.00	0.24	1.20	0.24	19.08	2.73	21.82	218.20	436.40	87.47
5.00	0.20	40.00	0.40	2.00	0.40	31.81	4.55	36.36	363.60	727.30	87.47
6.80	0.20	54.40	0.54	2.72	0.54	43.26	6.18	49.45	494.50	989.10	87.47
360.00	0.20	2880.00	28.80	144.00	28.80	2290.00	327.30	2618.00	26,182.00	52,364.00	87.47
548.00	0.20	4384.00	43.84	219.20	43.84	3486.00	498.20	3985.00	39,855.00	79,709.00	87.47
635.00	0.20	5080.00	50.80	254.00	50.80	4039.00	577.30	4618.00	46,182.00	92,364.00	87.47
851.00	0.20	6808.00	68.08	340.40	68.08	5413.00	773.60	6189.00	61,891.00	123,782.00	87.47
1067.00	0.20	8536.00	85.36	426.80	85.36	6787.00	970.00	7760.00	77,600.00	155,200.00	87.47
2.80	0.25	22.40	0.22	1.12	0.22	17.81	2.04	16.29	162.90	325.80	109.30
3.00	0.25	24.00	0.24	1.20	0.24	19.08	2.18	17.45	174.50	349.10	109.30
5.00	0.25	40.00	0.40	2.00	0.40	31.81	3.64	29.09	290.90	581.80	109.30
6.80	0.25	54.40	0.54	2.72	0.54	43.26	4.95	39.56	395.60	791.30	109.30
360.00	0.25	2880.00	28.80	144.00	28.80	2290.00	261.80	2095.00	20,945.00	41,891.00	109.30
548.00	0.25	4384.00	43.84	219.20	43.84	3486.00	398.50	3188.00	31,884.00	63,767.00	109.30
635.00	0.25	5080.00	50.80	254.00	50.80	4039.00	461.80	3695.00	36,945.00	73,891.00	109.30
851.00	0.25	6808.00	68.08	340.40	68.08	5413.00	618.90	4951.00	49,513.00	99,025.00	109.30
1067.00	0.25	8536.00	85.36	426.80	85.36	6787.00	776.00	6208.00	62,080.00	124,160.00	109.30
2.80	0.30	22.40	0.22	1.12	0.22	17.81	1.70	13.58	135.80	271.50	131.20
3.00	0.30	24.00	0.24	1.20	0.24	19.08	1.82	14.55	145.50	290.90	131.20
5.00	0.30	40.00	0.40	2.00	0.40	31.81	3.03	24.24	242.40	484.80	131.20
6.80	0.30	54.40	0.54	2.72	0.54	43.26	4.12	32.97	329.70	659.40	131.20
360.00	0.30	2880.00	28.80	144.00	28.80	2290.00	218.20	1745.00	17,455.00	34,909.00	131.20
548.00	0.30	4384.00	43.84	219.20	43.84	3486.00	332.10	2657.00	26,570.00	53,139.00	131.20
635.00	0.30	5080.00	50.80	254.00	50.80	4039.00	384.80	3079.00	30,788.00	61,576.00	131.20
851.00	0.30	6808.00	68.08	340.40	68.08	5413.00	515.80	4126.00	41,261.00	82,521.00	131.20
1067.00	0.30	8536.00	85.36	426.80	85.36	6787.00	646.70	5173.00	51,733.00	103,467.00	131.20
2.80	0.35	22.40	0.22	1.12	0.22	17.81	1.46	11.64	116.40	232.70	153.10
3.00	0.35	24.00	0.24	1.20	0.24	19.08	1.56	12.47	124.70	249.40	153.10
5.00	0.35	40.00	0.40	2.00	0.40	31.81	2.60	20.78	207.80	415.60	153.10
6.80	0.35	54.40	0.54	2.72	0.54	43.26	3.53	28.26	282.60	565.20	153.10
360.00	0.35	2880.00	28.80	144.00	28.80	2290.00	187.00	1496.00	14,961.00	29,922.00	153.10
548.00	0.35	4384.00	43.84	219.20	43.84	3486.00	284.70	2277.00	22,774.00	45,548.00	153.10
635.00	0.35	5080.00	50.80	254.00	50.80	4039.00	329.90	2639.00	26,390.00	52,779.00	153.10
851.00	0.35	6808.00	68.08	340.40	68.08	5413.00	442.10	3537.00	35,366.00	70,732.00	153.10
1067.00	0.35	8536.00	85.36	426.80	85.36	6787.00	554.30	4434.00	44,343.00	88,686.00	153.10
2.80	0.40	22.40	0.22	1.12	0.22	17.81	1.27	10.18	101.80	203.60	174.90
3.00	0.40	24.00	0.24	1.20	0.24	19.08	1.36	10.91	109.10	218.20	174.90
5.00	0.40	40.00	0.40	2.00	0.40	31.81	2.27	18.18	181.80	363.60	174.90
6.80	0.40	54.40	0.54	2.72	0.54	43.26	3.09	24.73	247.30	494.50	174.90
360.00	0.40	2880.00	28.80	144.00	28.80	2290.00	163.60	1309.00	13,091.00	26,182.00	174.90
548.00	0.40	4384.00	43.84	219.20	43.84	3486.00	249.10	1993.00	19,927.00	39,855.00	174.90
635.00	0.40	5080.00	50.80	254.00	50.80	4039.00	288.60	2309.00	23,091.00	46,182.00	174.90
851.00	0.40	6808.00	68.08	340.40	68.08	5413.00	386.80	3095.00	30,945.00	61,891.00	174.90
1067.00	0.40	8536.00	85.36	426.80	85.36	6787.00	485.00	3880.00	38,800.00	77,600.00	174.90

electricity were generated using conventional fossil-based generation, the associated CO₂ emissions would range from 588 to 1833 tCO₂·year⁻¹ for PF = 33.3% and from 1059 to 3300 tCO₂·year⁻¹ for PF = 60%, depending on the emission factor applied (0.2016 kgCO₂·kWh⁻¹ for natural gas and 0.6277 kgCO₂·kWh⁻¹ for the Dominican Republic electricity mix of the National Interconnected Electric System (SENI)). Over a 25-year project lifetime, this corresponds to avoided emissions of approximately 14,700–45,800 tCO₂ (PF = 33.3%) and 26,485–82,480 tCO₂ (PF = 60%). These values represent the potential CO₂ emissions avoided by displacing electricity generation from natural gas and other conventional fossil fuels with biogas-based electricity.

The environmental-economic benefit of replacing NG was quantified through avoided fuel consumption required to generate the same electricity. For NG prices between 2.5 and 4.0 US\$·MMBTU⁻¹, the avoided fuel cost over 25 years increases linearly with NG price (Fig. 10), ranging from US\$ 1.0–1.6 million (PF = 33.3%) to US\$ 1.8–2.9 million (PF = 60%). Because the NG plant is not installed, these values represent avoided external fuel expenses rather than project cash flow, but they illustrate the advantage of fossil-fuel displacement.

Annual income and operating expenses over the 25-year project life for PF = 33.3% and PF = 60% are presented in Fig. 11. Incomes increase

faster than expenses due to the inflation-indexed electricity price, resulting in progressively higher net revenues. Incomes and expenses are the same under a fixed PF independently of the investment ratio, since the inflation factor has been fixed and used for calculating both parameters.

Fig. 12 (a) and (b) show the sensitivity of Net Present Value (NPV) and payback period to investment ratio and interest rate for plant factors of 33.3% and 60%, respectively. As expected, NPV decreases with increasing interest rate, while higher investment ratios result in lower NPV across all cases. For a plant factor of 60%, NPV values range from 3.2 to 18.7 million US\$ for an investment ratio of 3500 US\$·kW⁻¹, and from 4.8 to 20.2 million US\$ for 2000 US\$·kW⁻¹. The payback period varies from 4 to 5 years for the lower investment ratio to 6–9 years for the higher investment ratio, depending on the interest rate. Under the conservative scenario (PF = 33.3%), payback periods increase to 6–9 years (2000 US\$·kW⁻¹) and 10–22 years (3500 US\$·kW⁻¹). Correspondingly, NPV values range from 0.27 to 8.86 million US\$ for 3500 US\$·kW⁻¹ and from 1.77 to 10.36 million US\$ for 2000 US\$·kW⁻¹. These results highlight the strong dependence of economic performance on plant utilization while confirming the economic feasibility of the system even under conservative operating assumptions.

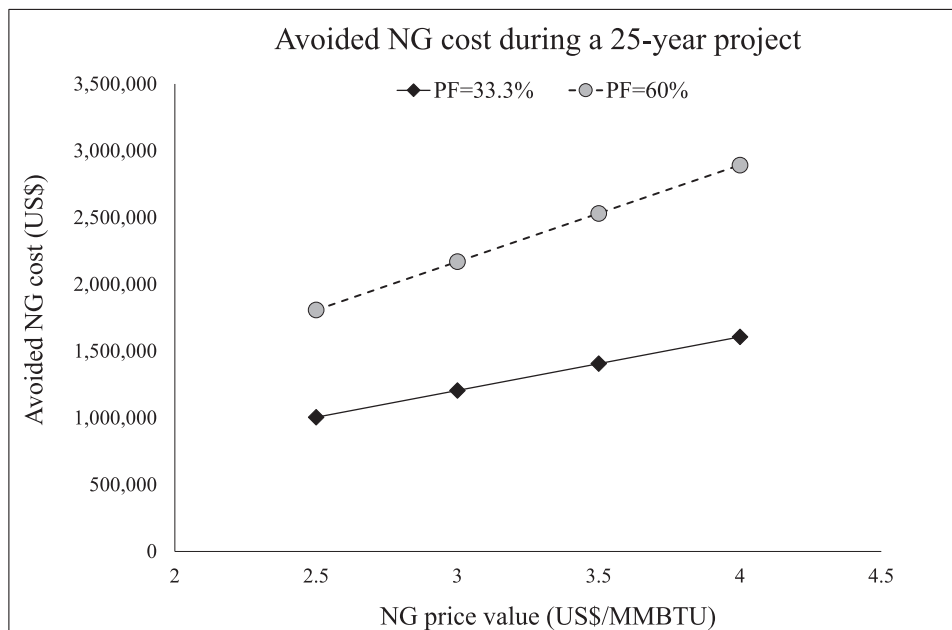


Fig. 10. Avoided NG cost for different NG prices. CPI = 3.76%.

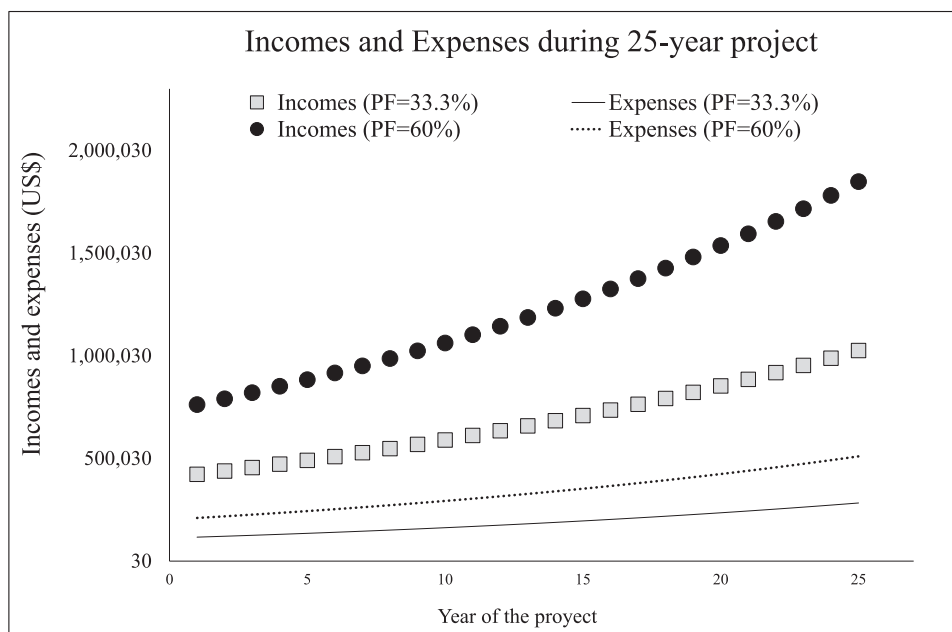


Fig. 11. Incomes and expenses for the project life (25 years). CPI = 3.76%, energy selling price 14.5 cUS\$/kWh⁻¹, general and administrative expenses 4 cUS\$/kWh⁻¹.

The IRR decreases monotonically with increasing investment ratio. For a lower investment cost (2000 US\$/kW⁻¹), IRR values range from 31.28% to 19.02%, while for a higher investment cost (3500 US\$/kW⁻¹), IRR decreases from 18.54% to 10.84% Fig. 13. These results indicate that the project remains economically attractive across all investment scenarios considered.

Economic, environmental, and practical implications

The results obtained in this study demonstrate that biogas production from domestic organic waste (DOW) under controlled mesophilic conditions can represent a practical and scalable solution to address energy and waste management challenges in both rural areas and low-density zones within municipalities of major cities. The operational

stability observed at an HRT of approximately 60 days, coupled with digestate recirculation, provides a robust framework that can be replicated at community or decentralized scales.

From a practical perspective, the proposed system is particularly suitable for rural communities, where organic waste management infrastructure is limited and access to reliable energy sources may be constrained. At the same time, the approach is equally applicable to peri-urban or low-population-density areas within large municipalities, where decentralized biodigesters can reduce organic waste disposal volumes while producing renewable energy locally.

Beyond energy recovery, the digestate generated during the process presents additional environmental and agricultural benefits. Its potential use as a fertilizer contributes to nutrient recycling, supporting local

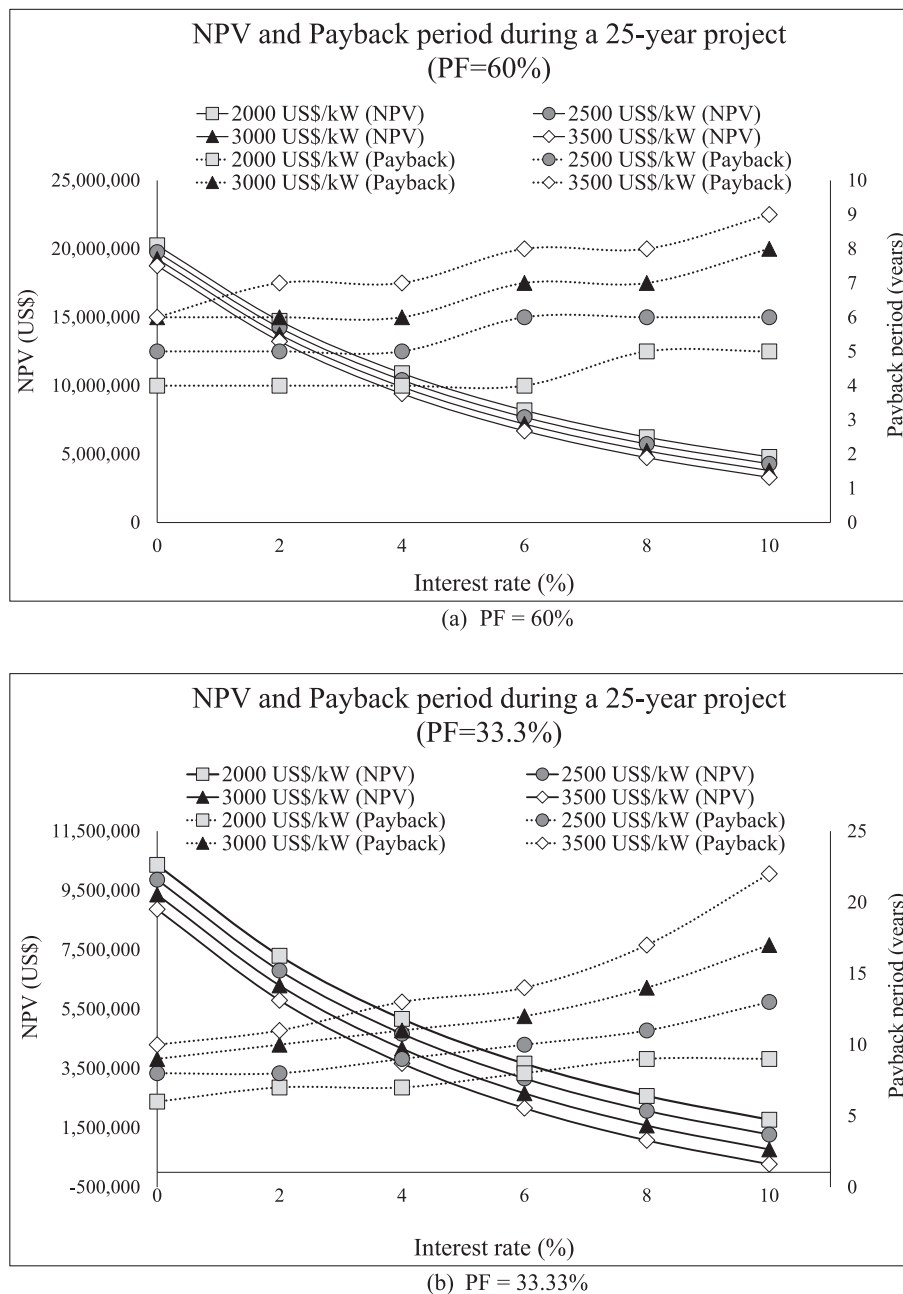


Fig. 12. NPV for different interest rates. CPI = 3.76%, energy selling price 14.5 cUS\$/kWh⁻¹, general and administrative expenses 4 cUS\$/kWh⁻¹. PF = 60% (a) and 33.32% (b).

agriculture and reducing dependence on synthetic fertilizers. This dual benefit strengthens the circular economy approach of the system, linking waste management, renewable energy generation, and agricultural productivity.

Overall, the findings of this study provide practical guidelines for the design and operation of small- to medium-scale anaerobic digestion systems using DOW, supporting further development, optimization, and scaling of biogas production as a sustainable energy solution.

Conclusions

This work assessed experimental biogas production from domestic organic waste (DOW) using a simplified anaerobic digestion approach based on pH control and digestate recirculation, including fertilizer reuse, comparison with a full-scale cow dung biodigester, and

environmental and economic assessment.

This study demonstrates that domestic organic waste (DOW) can be effectively converted into biogas under mesophilic and tropical climate conditions using a simplified operational strategy based on pH monitoring and controlled digestate recirculation. Stable methane production was achieved under quasi-fixed conditions, indicating the establishment of a mature and robust anaerobic digestion process without the need for advanced monitoring or strict control of multiple physicochemical variables.

By combining the experimental operation with an empirical predictive (numerical) model, this work contributes to a clearer understanding of the key parameters governing methane concentration in food waste-based biodigesters operated under low-technology conditions. The results confirm that operational indicators such as outlet pH, hydraulic retention time (HRT), organic loading rate (OLR), and

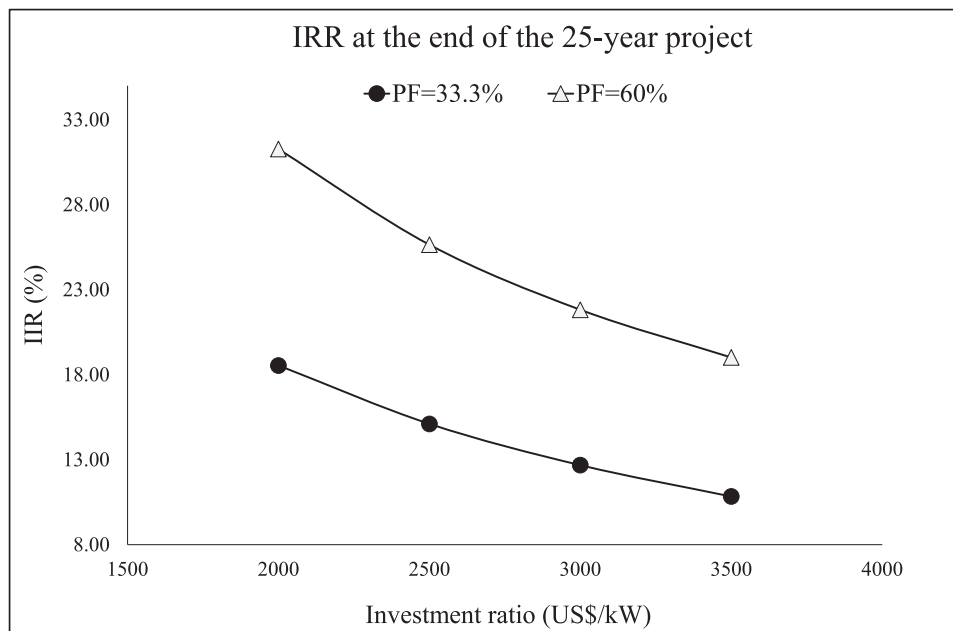


Fig. 13. IRR for different investment ratios. CPI = 3.76%, energy selling price 14.5 cUS\$/kWh⁻¹, general and administrative expenses 4 cUS\$/kWh⁻¹.

methane concentration (CH₄%) provide a practical and informative framework for assessing digestion performance when substrate composition is inherently variable, as is the case with real municipal food waste.

Beyond biogas production, the integration of digestate reuse as fertilizer and the assessment of energy, economic, and environmental performance highlight the potential of this system as a circular and sustainable waste-to-energy solution. This approach is particularly relevant for rural areas and low-density urban zones, where decentralized biogas production can support local energy needs while contributing to organic waste management and agricultural nutrient recovery. The results also indicate that the environmental and economic performance of the system is strongly dependent on operational utilization, highlighting the importance of improved management and integration strategies for future large-scale implementations.

The main limitations of this study are associated with the simplified operational approach adopted and the scale of the experimental system. The biodigester was operated with low technological complexity, without active control of parameters such as the carbon-to-nitrogen (C/N) ratio, total solids (TS), volatile solids (VS) or temperature control. Instead, the operational strategy focused on maintaining the outlet pH within the recommended range and ensuring methane concentrations within expected values, demonstrating stable digestion under minimal monitoring conditions. Consequently, the empirical model developed is valid within the tested operational ranges of HRT, OLR, and pH, and microbial community dynamics were not explicitly characterized.

Future research should focus on scaling up the system under real municipal conditions and incorporating additional substrate characterization parameters, particularly the C/N ratio of the DOW-water mixture, to further optimize methane production. Such studies may require adjusting digestate recirculation rates to improve nutrient balance and microbial activity. Future work should evaluate alternative inoculation strategies, microbial dynamics, long-term operational stability, and the integration of policy, logistics, and social acceptance considerations to support the deployment of DOW-based biogas systems as a scalable and practical contribution to sustainability challenges in developing and emerging economies. Overall, the findings provide experimentally grounded and context-specific evidence to support decision-making on decentralized biogas deployment as part of integrated waste management and renewable energy strategies in

developing-country contexts.

CRediT authorship contribution statement

V.F. Sena-Cuevas: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.B. Rodríguez-Gómez:** Supervision, Investigation. **M.A. Sánchez-Santana:** Supervision, Investigation. **J. Mejía:** Supervision, Investigation. **M. Román:** Investigation. **D. De Dios:** Investigation. **G. Arias:** Investigation. **C. Agüero-Ramos:** Investigation. **A. Tejeda-Castillo:** Investigation. **J.K. Paredes:** Investigation.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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