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BIOTECHNOLOGY

Bioenergy Recovery in Full-Scale Anaerobic Co-digestion of Swine Wastewater and Pig Bedding Material

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ABSTRACT. Pig farming represents a rapidly expanding segment of Brazil's agricultural sector, concomitant with the generation of substantial volumes of wastewater, the effective management of which demands strategic solutions. Anaerobic digestion has been identified as a promising solution for the preliminary treatment of these effluents, concurrently yielding methane-rich biogas, which possesses the capability to generate thermal or electrical energy. This study evaluates a new anaerobic treatment method, through the co-digestion of swine wastewater (SWW) and bedding material (BM) on a real scale, changing the production of bioenergy. The experiment was divided into four phases: Phase 1, monitoring the biodigester operating solely with swine wastewater (SWW); Phase 2, application of SWW + 2 tonnes of BM (SWW+2 T); Phase 3, SWW + 6 tonnes of BM (SWW + 6 T); and Phase 4, SWW + 10 tonnes of BM (SWW+10 T). Loads of 320 (± 2.3) to 805 (± 18) kg COD d^{-1} in the summer and from 310 (± 1.5) to 780 (± 13) kg COD d^{-1} in the winter were applied. The concentrations of methane and CO_2 were measured by gas chromatography. Biogas productions three times higher were recorded when 12 tons of BM were applied, which, when converted into bioenergy potential, resulted in the generation of 635 kWh per day of bioenergy in the summer and 270 kWh per day in the winter. Methane yield was highest in the summer with the application of 12 tons of BM (0.34 $m^{3\ K}gCOD_{Rem}{}^{-1}$). Volatile solids and COD removals ranged between 60-70% and 61-84%, respectively. The findings highlight that the use of deep bedding alongside SWW contributes significantly to biogas production, and co-digestion is recommended to enhance electricity generation on farms, with the added benefit of treating two waste types in a single reactor.

Keywords: Bioenergy; Bioresource; Resource recovery; Sustainability; Swine farming.

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Introduction

Pig farming is one of the fastest-growing agricultural activities in Brazil (Rodrigues et al., 2020), with the country trailing only behind Canada, the European Union, and the United States (D'aquino et al., 2019). The growth in this sector has introduced new technologies and increased the number of pigs per site, leading to a higher concentration of waste, which contains high levels of organic matter and nutrients (D'Aquino et al., 2019; Wu et al., 2020). When improperly discharged into water bodies, this waste can cause severe environmental damage (Leite et al., 2021; Mendonça et al., 2018; Souza et al., 2020; Nascimento et al., 2020).

Anaerobic digestion is an attractive alternative for the primary treatment of swine effluents, with the added benefit of methane gas production, which can be used as a biofuel for thermal or electrical energy generation (Mendonça et al., 2017; Ajay et al., 2020). The biogas and biofertilizer produced from the anaerobic digestion of agricultural waste have high added value and are currently of commercial and industrial interest (Mendonça et al., 2021; Deng et al., 2021; Egwu et al., 2021). It is expected that in near future, 25% of all bioenergy produced globally will come from anaerobic fermentation (Atelge et al., 2020).

The use of anaerobic digestion for swine waste results in the production of biogas, which can be converted into bioenergy, thus providing an alternative for reducing greenhouse gas (GHG) emissions and reliance on fossil fuels (Yang et al., 2023). The biogas generated during treatment, when used for energy conversion, offsets 24% of the GHG emissions from the entire treatment system (Niu et al., 2013).

Biogas consists of a gaseous mixture, primarily composed of methane (50 to 75%), which has significant energy potential (Nguyen et al., 2021), as well as CO_2 (25 to 50%) (Prabhu et al., 2021), making biogas a renewable energy source. The exploitation of biogas, a product of the anaerobic digestion process, is a growing activity in electricity generation, offering many economic and environmental benefits (Antonelli et al., 2016). Biogas from swine farming has become a major source of renewable energy (Sousa et al., 2017), as the increase in pig production, and consequently the generation of waste, has made anaerobic digestion for bioenergy production a significant benefit due to its production potential and reduction of environmental impacts caused by pig farming.

The use of bedding material (BM) in pig farming has proven to be advantageous due to the in-situ composting of pig waste. This farming method reduces the generation of wastewater on farms but increases the production of solid waste. Various materials can be used for bedding, with sawdust, hydrolysed sugarcane bagasse, or rice husks being the most common (Costa & Marvulli, 2020; Souza et al., 2020). Despite the in-situ composting of waste, the material often does not leave the production system stabilised for direct use as organic compost, which would favour its application in co-digestion.

Co-digestion enhances methane yield by promoting a positive interaction between microorganisms and substrate assimilation (Mendonça et al., 2022). In the present study, the anaerobic co-digestion of swine wastewater with BM was analysed, with the aim of increasing biogas production, methane yield, and bioenergy generation, as well as assessing the effectiveness of waste treatment in terms of organic matter, solids, and nutrient removal.

Materials and methods

Experimental set up

This experiment was conducted on a pilot scale at a pig farm in the finishing phase, located in the northern region of Minas Gerais State, Brazil. The average annual temperature of the area is 24°C, with a minimum of 20°C and a maximum of 39°C. The temperature of the wastewater inside the biodigester was monitored using probes placed 2.5 metres below the liquid surface, where an average operating temperature between 20 (± 5) °C and 33 (± 4) °C was recorded. The experiments in the reactor were conducted during two seasons, summer and winter, as the reactor lacked artificial heating, and the aim was to encompass periods with extreme temperatures.

The wastewater is generated by mixing clean water with faeces, urine, feed residues, hair, etc., and discharged every three days into an equalisation tank. Part of the SWW (40 m^3 d^{-1}), equivalent to the production of 1,500 finishing-phase pigs, was fed into the reactor. The flow rate was measured using a Parshall flume (Hydrometer, Brazil). In this equalisation tank (ET), mixtures of swine wastewater and BM were prepared. A 10 HP mixer was used to homogenise the ET. After mixing, the material was pumped to a grinder and then flowed by gravity through another flow measurement flume before entering the reactor.

The reactor had been operating for two years, using only wastewater, prior to the addition of BM for co-digestion. Thus, before the introduction of BM, biogas production and the formation of adapted anaerobic sludge were already established.

The experiment was divided into four phases: Phase 1, monitoring the biodigester operating solely with swine wastewater (SWW); Phase 2, application of SWW + 2 tonnes of BM (SWW+2 T); Phase 3, SWW + 6 tonnes of BM (SWW+6 T); and Phase 4, SWW + 10 tonnes of BM (SWW+10 T). The four proposed phases were tested during both summer and winter, a crucial factor given that the reactor did not have controlled heating.

The physical-chemical characteristics of the SWW and the SWW + BM mixtures in each experimental phase are presented in (Table 1).

Table 1. Characterization of SWW and mixtures with BM in the tested phases.

Phase	pH	COD	N_t	P_t	K_t	TS	VS	VFAs
	UpH	mg L^{-1}						
1	$7_{(0.8)}$	$9,000_{(90)}$	$1200_{(6)}$	$159_{(15)}$	$660_{(12)}$	$13100_{(90)}$	$7900_{(30)}$	$1700_{(1.3)}$
2	$6.5_{(0.2)}$	$11,094_{(30)}$	$1360_{(1.3)}$	$350_{(2)}$	$754_{(1.2)}$	$14025_{(104)}$	$8680_{(33)}$	$2100_{(5.2)}$
3	$6.3_{(0.1)}$	$15,000_{(7)}$	$1861_{(3)}$	$432_{(0.2)}$	$839_{(5)}$	$17.879_{(160)}$	$11635_{(57)}$	$2563_{(11)}$
4	$6_{(0.5)}$	$18,000_{(8)}$	$3670_{(11)}$	$596_{(0.5)}$	$963_{(0.2)}$	$18900_{(210)}$	$12288_{(69)}$	$2600_{(2.6)}$

SWW – Swine wastewater; T – tons; $_t$ – total; TS - Total Solids; VS - Volatile Solids; VFAs - Volatile Fatty Acids. Values between parentheses indicate standard deviation. These are the general averages for all phases analysed in summer and winter.

The BM consisted of sawdust, faeces, urine, and food scraps, layered over a period of 9 months. For each mixture prepared in each phase, the characterisation presented in Table 1 was carried out. The BM was removed from the farms and immediately applied after weighing the truck with the material. It was then placed in the yard next to the ET and introduced into it via a tractor.

In the SWW line, before its entry into the ET, it passed through a sand box and a fine mechanical screen.

After the TE, both the SWW and the proposed mixtures were subjected to a solid grinder to reduce particle sizes (Figure 1).

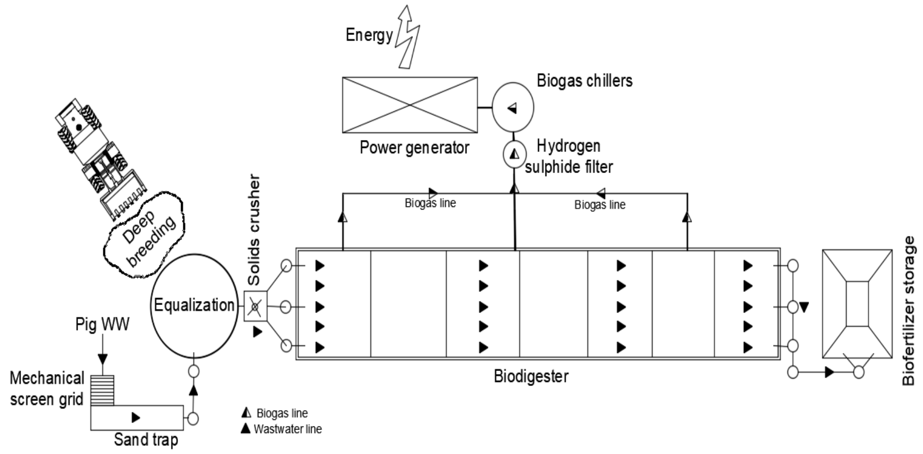

Figure 1 Full-scale experimental setup showcasing all components of the waste treatment system and bioenergy production.

Description of the treatment system

The pilot anaerobic treatment system used in this research was a plug flow type, as described by Mendonça et al. (2017). The reactor had a working volume of 2000 m^3, with a surface length of 60 m, a surface width of 12 m, and a working depth of 4.3 m. The average hydraulic retention time (HRT) was 50 days (± 2 days). The reactor was operated during the four experimental phases with organic loads ranging from 320 (± 2.3) to 805 (± 18) kg COD d^{-1} in the summer and from 310 (± 1.5) to 780 (± 13) kg COD d^{-1} in the winter. The temperature was measured at a height of 2 metres from the liquid surface. Six temperature sensors were placed every 10 metres along the 60-metre length of the biodigester.

A PEAD (polyethylene) cover was positioned over the biodigester for biogas storage, with a total volume of 1,000 m^3. Along the cover, there were 3 biogas outlets leading to the generator set (model ER-BR, GMWM 150, 150 kVA, Brazil). The biogas flow rate was measured 24 hours a day using a non-intrusive µLtrasonic gas flowmeter (BF-3000B).

Before reaching the generator set, the biogas passed through a hydrogen sulphide (H_2S) filter and a chiller to remove moisture. After the biodigester, there was a storage tank for the biofertilizer (digestate) (Figure 1).

Sampling planning and gas measurement validation

The measurement of biogas flow rate, as well as CH_4 and CO_2 concentrations, was conducted daily for 70 days (both in winter and summer). Measurements were made using a gas flow meter coupled with a gas concentration measurement and quantification system from Bioenergy GmbH, Germany. The flow meter and gas concentration system were installed in the gas line between the biogas chillers and the power generator (Figure 1). The reliability of the CH_4 and CO_2 data measured by the inline equipment was previously calibrated in the laboratory using gas chromatography with the Varian 430-GC equipment, equipped with a thermal conductivity detector and a Varian Capillary Column Select™ Permanent Gases/CO_2 HR - Malsieve 5 A Parabond Q Tandem #CP7430. Helium was used as the carrier gas (52 mL min^{-1}). The injection used in the chromatograph was 0.5 mL of biogas, collected from the gas line before the H_2S filter (Figure 1), the same location where H_2S concentrations were measured using a sensor probe (Komyo RikaGaku Kogyo - AP-20, Japan) (Lin et al., 2013). Each analysis described in the next section was performed in the equalisation tank (before entering the reactors) and at the reactor outlets at the end of each of the four monitoring phases.

Analytical methods

Total and soluble chemical oxygen demand (COD), total solids (TS), volatile solids (VS), total nitrogen (Nt), alkalinity (CaCO3), pH, total phosphorus (Pt), and total potassium (Kt) were determined according to the Standard Methods (APHA, 2012) and performed in triplicate. Volatile fatty acids (VFAs) were evaluated by High-performance liquid chromatography (HPLC) equipment Agilent model 1100. The temperatures in the column, injector, and detector were 50, 80, and 120°C, respectively.

Methane yield and energy measurement

The methane production yield was calculated in accordance with (Equation 1), following the recommendations of Mendonça et al. (2017).

$$CH_4Yield = \frac{Q_{Biogas}\times([CH_4])}{Qin \times (Si - Sf)} \tag{1}$$

where: CH_4Yield = Methane production yield (m^3 kg COD removed^{-1});
CODRem = COD removed (kg);
QBiogas = Measured biogas flow rate (m^3 day^{-1});
[CH_4] = Methane concentration in the biogas;
Qin = Flow rate of SWW or SWW and BM mixture;
Si = Initial COD concentration in SWW or SWW + BM (inlet);
Sf = COD concentration at the outlet of the biodigester.
Biogas flow was converted to standard temperature and pressure conditions (273.15 K and 1 atm).

Energy measurements (kWh and kWh m^{-3}) produced were obtained after the combustion of the biogas in the generator set (Otto cycle), as recommended by Rockenbach et al. (2016). Measurements were obtained via a telemetry system comprising an electrical energy analyser DMI T50 T, coupled with three current transformers (100/50 mA) of the clamp type, 4 reference voltage clamps for 3 phases and neutral, and an external 12 V 3 A power source with a voltage range of 90 V ~ 240 V (Remote Data Logger - Kit DMI T50 T).

COD mass balance

The mass balance will be performed to obtain data that does not yet exist for this type of process, that is, the COD consumption reaction rate (rc). This rate is important for constructing consolidated mass balances applied to the exclusive data obtained in this study. The mass balance equation for the component of interest in the reactor is formulated as follows:

$$\frac{d(C_{COD})}{dt} = \frac{(C0_{DQO} - C_{DQO})}{HTR} \tag{2}$$

$$\frac{d(C_{COD})}{dt}.V = Q \cdot \left(C0_{DQO} - C_{DQO}\right) - rc.V - rp.X \tag{3}$$

where: C0: COD concentration in the influent (mg L^{-1}) – Table 3; C: COD concentration in the effluent (mg L^{-1}) – (Table 4); V: reactor working volume (L); Q: waste flow rate (L s^{-1}); t: time (hydraulic retention time - HRT) (h); $rp = \mu\ ks.$: microbial cell production reaction rate (0,62 mg L^{-1} h^{-1}); *rc*: COD consumption reaction rate (methane generation) (mg L^{-1} h^{-1}), X: Biomass concentration (mg L^{-1}). Observation: The inlet and outlet flow rates are the same in this model. The objective of the mass balance is to identify the rc values for each experimental phase and each of the seasons studied.

The occurrence rate of production of new methanogenic archaea was obtained from the product between the specific cell growth rate (μ), in the range of 2 to 4 days (Kothari et al., 2014), and the saturation constant (ks), in the range of 10 to 50 mg L^{-1} (Cho et al., 2013).

Analytical methods

The analytical methods used in this research will involve descriptive statistics, with the aim of evaluating the average values and standard deviation of the data analyzed in the work. Excel software will be used to generate graphs.

Results and discussion

Biogas Production in Summer and Winter

Biogas is a set of gases resulting from the digestion and anaerobic decomposition of human, plant and animal wastes produced in the absence of oxygen by the action of anaerobic bacteria, particularly methanogens (Jameel et al., 2024). As reported by Singh et al. (2025), its production is influenced by several factors, including carbon/nitrogen (C/N) ratio, temperature, organic loading rate, hydraulic retention time and total solids content, among others.

Temperature is a critical factor in biogas production, affecting the rate and efficiency of anaerobic digestion. It is directly related to the microbial activity involved in the decomposition of organic matter and the production of biogas and affects the growth and metabolism of microbial communities (Jameel et al., 2024; Singh et al., 2025). Most studies have been carried out under mesophilic conditions (35°C), followed by thermophilic (55°C) and hyperthermophilic (70°C), although psychrophilic conditions (< 20°C) are also used (Elihimas et al., 2025).

The analysis examines biogas production, methane yield and bioenergy production in winter and summer, evaluating the anaerobic co-digestion of pig effluent with organic matter.

In summer, during Phase 1, biogas production (using only SWW) was stable, with an average of 103 m^3 biogas day^{-1} (± 7.3 m^3 biogas day^{-1}), as shown in (Figure 2). From Phase 2 onwards, significant increases in biogas production were recorded, reaching Phase 4 with a production three times higher (316.6 m^3 biogas day^{-1}) compared to Phase 1 (Figure 2). Starting from Phase 2, there was a considerable increase in CH_4 concentration in the biogas and a reduction in CO_2 concentrations (Table 2). On average, in Phases 3 and 4, methane concentrations were 66% (± 2%) and 72% (± 2.6%), respectively. There was an 11% increase in the average methane concentration when comparing Phase 4 to Phase 1.

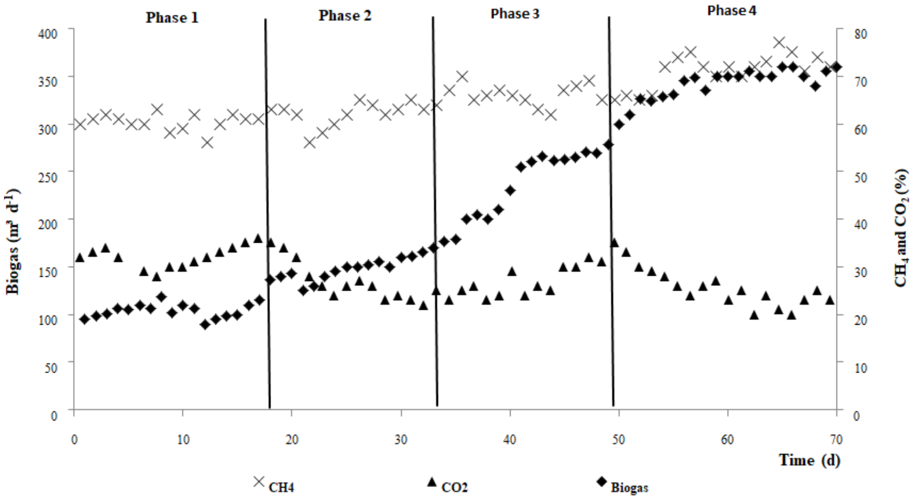

Figure 2. Biogas production in summer and CH_4 and CO_2 concentrations during the four experimental phases in the summer period.

The volumetric biogas production increased from 0.06 (Phase 1) to 0.2 m^3 biogas m^{-3} $reactor^{-1}$ (Phase 4). The addition of BM also increased methane yield, which rose from 0.22 to 0.34 m^3 kg COD $removed^{-1}$ (Table 2). Notably, the addition of BM during the summer period resulted in improvements in both the quality and quantity of the biogas produced. In Phase 4, the methane yield approached the theoretical maximum value that can generally be achieved, which is 0.35 m^3 kg COD $removed^{-1}$ (Mendonça et al., 2017). As the volume of BM increased, the methane yield also increased (Table 2).

According to the study by Elihimas et al. (2025), the organic loading rate has a significant effect on methane production. A high loading can lead to the accumulation of volatile fatty acids (VFAs), which inhibit methanogenesis, while a low loading can limit the availability of substrate for microbial activity. Proper adjustment of the organic loading rate is essential to maintain microbial stability and maximise methane production. The operational temperature values per phase, as well as the organic loads resulting from the mixtures applied to the biodigester, are presented in (Table 2).

In summer, there were noticeable differences between all experimental phases (see the sixth column in (Table 2) - kWh day^{-1}), indicating that each addition of BM resulted in higher electrical energy production. In winter, no significant differences were observed in Phases 2 and 3, with differences only noted in Phase 4 compared to the previous two phases. This indicates that, although the addition of BM in Phases 2 and 3 increased biogas production in winter, to effectively produce more biogas during this season, it was necessary to use the maximum amount of BM applied in Phase 4.

The energy production coefficients per volume of biogas produced, measured after the generator set, were 1.7, 1.75, 1.84, and 2 kWh m^{-3} for Phases 1, 2, 3, and 4, respectively.

Table 2. Biodigester operation parameters, biogas quality and production, methane yield, and bioenergy generation.

Phase Winter	CH_4 (%)	$^1CH_4$ yield m^3 KgCOD$_{Removed}$$^{-1}$	^{2}kWh m^{-3}	m$^3_{biogas}$ d^{-1}	^{2}kWh d^{-1}	H_2S (ppm)
1	60$_{(1)}$	0.199	1.70	77$_{(10)}$	129	125$_{(88)}$
2	63$_{(0.5)}$	0.186	1.75	104.7$_{(11)}$	184	224$_{(80)}$
3	65$_{(1.1)}$	0.176	1.80	122$_{(9)}$	219	280$_{(75)}$
4	68$_{(2)}$	0.202	1.90	141$_{(8)}$	267	541$_{(44)}$
Summer						
1	61$_{(3)}$	0.219	1.70	103$_{(3)}$	175	95$_{(26)}$
2	63$_{(2)}$	0.222	1.75	140$_{(1)}$	246	198$_{(50)}$
3	66$_{(0.5)}$	0.261	1.84	214$_{(2)}$	393	302$_{(19)}$
4	72$_{(2)}$	0.343	2.00	317$_{(29)}$	635	614$_{(92)}$

The table shows the average value of each phase with its respective standard deviation. VOL - Volumetric organic load. Values between parentheses indicate standard deviation. ^{1} Standard deviation < 0.01. ^{2} Measure collected after biogas burning in generator.

Another important observation is that the microbiology colonising the reactor quickly adapted to the increased concentrations of organic matter via BM. In other words, the higher the BM input, the better the quantitative and qualitative production of biogas in summer. This occurred in response to the increased organic load available for conversion to biogas.

The study by Banerjee, Prasada and Selvaraju (2022) shows that anaerobic bacteria are more active in mesophilic and thermophilic conditions, while extreme temperatures can affect their survival and disrupt anaerobic digestion. Temperature has a direct effect on the rate of decomposition and biogas production, with higher temperatures tending to accelerate these processes. Thus, in summer, favourable thermal conditions favour the rapid adaptation of the reactor microbiota to the increased concentrations of organic matter by the microbial biomass. No accumulation of VFAs was observed in summer, with removals ranging from 77 to 95% (Table 3).

Table 3. Removal of COD, solids, volatile fatty acids (VFAs) and pH change.

Phase	COD mg L^{-1}	*kgCOD m^{-3}		TS mg L^{-1}		VS mg L^{-1}	**kg SVm^{-3}		VFAs mg L^{-1}		pH Out
Winter	In		R (%)	In	R (%)	In		R (%)	In	R (%)	
1	8,000$_{(30)}$	0.18	74	13,550$_{(101)}$	80	7,800$_{(15)}$	0.17	65	992$_{(8)}$	90a	7.0
2	12,600$_{(9)}$	0.28	70	14,200$_{(95)}$	65	8,890$_{(33)}$	0.19	51	2,500$_{(2)}$	80b	7.5
3	16,566$_{(35)}$	0.36	70	17,951$_{(40)}$	60	12,645$_{(57)}$	0.28	50	2,786$_{(23)}$	76b	7.5
4	20,100$_{(49)}$	0.44	60	19,025$_{(35)}$	50	13,282$_{(49)}$	0.29	40	3,000$_{(17)}$	72b	7.9
Summer											
1	8,100$_{(14)}$	0.18	85	11,960$_{(38)}$	85	7,851$_{(24)}$	0.17	70	1,250$_{(3)}$	95a	7.5
2	12,550$_{(23)}$	0.27	79	13,890$_{(71)}$	80	8,980$_{(16)}$	0.20	65	1,999$_{(58)}$	90a	8.0
3	16,301$_{12)}$	0.36	75	18,500$_{(210)}$	75	12,339$_{(27)}$	0.27	64	3,420$_{(4)}$	88a	7.5
4	20,234$_{(70)}$	0.44	69	19,106$_{(32)}$	72	13,320$_{(18)}$	0.29	60	3,688$_{(26)}$	80b	7.5

In - influente; R – removal. Values between parentheses indicate standard deviation. *kg of COD added per cubic meter of reactor. **kgSV m^{-3} = kg of volatile solids added per cubic meter of reactor.

Considering the data obtained here Figure 2 and Table 2, a realistic projection for a farm with, for example, 10,000 pigs can be made. Using an HRT of 46 days and an organic load at the system inlet of 160 kg COD d^{-1}, a reactor with a volume of 7,360 m^3 would be required. Considering the value of 0.2 m^3 biogas m^{-3} reactor^{-1} obtained in Phase 4 for summer (considered optimal for this research), the production would be 1,472 m^3 biogas per day. This amount would correspond to approximately 3,000 kWh of electrical energy or 10.8 GJ of thermal energy per day. Cândido et al. (2022), operating a full-scale pig waste treatment system (SISTRATES) on a pig farm in Paraná State, Brazil, recorded a generation of 1,880.6 kWh day^{-1}. In the present study, considering only the anaerobic digestion of pig waste, the production recorded was 128.8 kWh (winter) and 175 kWh day^{-1}. If this energy potential were applied to a farm of 10,000 pigs, we would reach amounts of 2,458 to 2,503 kWh day^{-1}, which is close to the values found by Cândido et al. (2022) in full-scale reactors.

Another important point to highlight is that the alkalinity inside the reactor during the experiments, both in summer and winter, was within the ideal range for anaerobic reactor operation proposed by Grady and Lim (1980), between 2,500 and 5,000 mg L^{-1}.

A negative aspect observed with the addition of BM was the gradual increase in H_2S concentrations in the biogas. In Phase 1, the average concentrations were 95 ppm, and in Phases 2, 3, and 4, they increased to 198, 302, and 614 ppm, respectively. This demonstrates that sulphidogenesis was also maximised with the increased organic load, so to avoid compromising the lifespan of the biogas burning system (generator set), it is necessary to always use filters or mechanisms to reduce this gas.

In winter (Figure 3), during Phase 1, biogas production (using only SWW) was unstable, with an average of 77 m^3 biogas day^{-1} (± 10.4), with a maximum value of 92 m^3 biogas day^{-1} and a minimum of 63 m^3 biogas day^{-1}. With the addition of BM in Phase 2, an increase in biogas production was observed, culminating in a maximum production in Phase 4 with a value of 141 m^3 biogas day^{-1}, which is 1.8 times higher than that recorded with SWW alone (Phase 1). The progressive increase in biogas production, along with the concurrent rise in methane concentration (Table 2), demonstrates a benefit to the anaerobic system, which was operating at temperatures between 18 and 20°C, considered low for systems operating in the psychrophilic range.

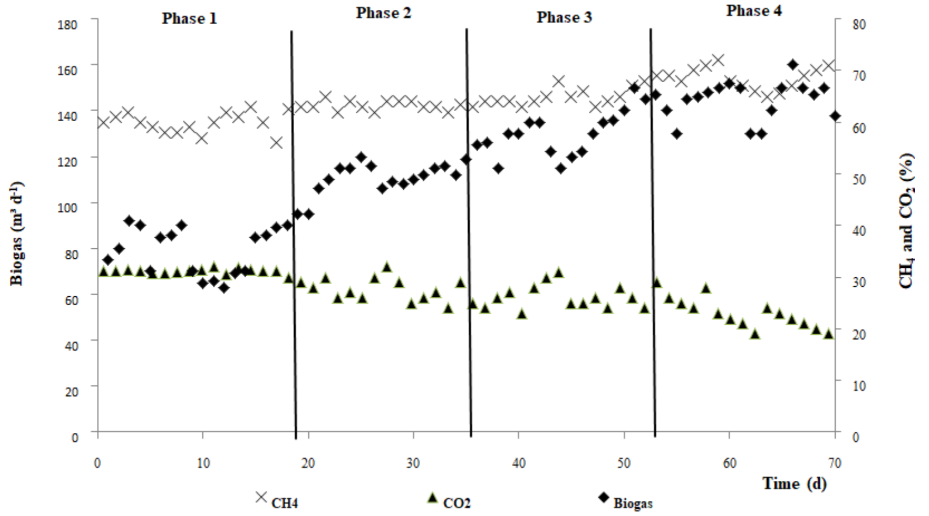

Figure 3. Biogas production in winter and CH_4 and CO_2 concentrations during the four experimental phases in the winter period.

The potential for biogas production is affected by the quality of the degradable material, as reported by Banerjee, Prasad, and Selvaraju (2022). In the case of the present study, the substrate used during the winter period proved to be effective in maintaining biogas production at levels acceptable for the operation of the motor-generator.

In Table 3, identical letters indicate no significant difference between phases, while different letters represent significant differences between the means of each phase.

Although Castano et al. (2014) reported that acidification of anaerobic reactors begins at temperatures above 20°C, in the present study, there was an increase in all the studied variables in the biogas with the addition of BM. Table 3 shows that the removal of VFAs by the reactor ranged from 72% to 90%. This indicates that the reactor model used in this study, when subjected to the addition of BM, can function effectively, even with increased methane production at temperatures below 20°C. In this sense, it appears that BM provides greater stability for the system in winter, without the accumulation of VFAs to the extent that it negatively impacts the reactor's microbiology.

As in summer, a significant increase in CH_4 concentration in the biogas and a reduction in CO_2 concentrations were observed from Phase 2 onwards (Table 2). On average, in Phases 3 and 4, the methane concentrations were 65% (± 2%) and 68% (± 2.6%), respectively. There was an 8% increase in the average methane concentration comparing Phase 4 with Phase 1 (SW only). Considering the reactor model used in the present study, the methane concentrations were considered significant. Riaño et al. (2011) conducted co-digestion of SWW with winery wastewater and recorded methane concentrations between 49.4% and 64.4% in a CSTR reactor operated at 35°C.

The volumetric production of biogas increased from 0.045 (Phase 1) to 0.082 m^3 biogas m^{-3} $reactor^{-1}$ (Phase 4), a less pronounced increase compared to summer.

The increase in methane yield in winter was not as pronounced between experimental phases, with a minimum value of 0.119 m^3 kg COD $removed^{-1}$ (Phase 1) and a maximum of 0.202 m^3 kg COD $removed^{-1}$ (Phase 4). Although the increase in methane yield in winter was not as high as in summer, it can be considered that BM provided stability to the methanogenesis process. The rapid adaptation of the reactor microbiology to the addition of BM was observed in both summer and winter experiments. This rapid response in increasing the quantity and quality of biogas produced occurred because the predominant microbiology contained in the BM was like that developed inside the biodigester. Therefore, whenever BM was added, there was also a new inoculation of the system and an increase in the ‘food’ supply, keeping the system stable and without accumulating VFAs.

In winter, there was also an increase in H_2S concentrations in the biogas, following a pattern like that observed in summer (Table 2).

Removal of COD, solids, and VFAs

In the present study, the COD removal value of 61% achieved in Phase 4 (winter) was considered the minimum acceptable limit for the operation of the adopted anaerobic system.

Total solids removals were higher during the summer (Table 3). The higher removal of total solids reflects the efficient removal of volatile solids and their conversion into biogas. Volatile solids removals in winter ranged from 40% to 65%, while in summer they ranged from 60% to 70%. The removal of volatile solids can be considered promising for the proposed co-digestion in this study, as Monou et al. (2008) recorded removals of 42.9 to 72% for the co-digestion of pig manure with other plant and animal residues (potato processing and abattoir wastewater).

The methane yield in terms of removed solids during summer for Phases 1, 2, 3, and 4 were 0.23, 0.32, 0.25, and 0.36 m^3 kg SV removed^{-1}, respectively. In winter, the yields were 0.28, 0.30, 0.32, and 0.34 m^3 kg SV removed^{-1} for Phases 1, 2, 3, and 4, respectively.

There was no accumulation of VFAs in the reactor, with removals being efficient between 70 and 95% (Table 3). The same table shows pH values ranging from 7.2 to 8.4, without acidic characteristics, with values being predominantly basic or close to neutral.

Table 4. Mass balance results of COD consumption reaction rate (rs), biomass concentration in reactor, COD out reactor and flow.

Winter Phase	rc mg L^{-1} h^{-1}	X mg L^{-1}	C_{COD} mg L^{-1}	Q m^3 h^{-1}
1	−0.00122	10,052	2,079	4.42
2	−0,00785	12,019	3,780	4.39
3	−0,0156	14,000	4,971	4.28
4	−0,00055	16,102	8,042	4.51
Summer				
1	−0,00521	11,152	1,215	4.39
2	−0,00797	13,000	2,636	4.41
3	−0,00463	15,257	4,076	4.43
4	−0,01249	18,850	6,273	4.60

Through the mass balance, it was observed that during winter up to Phase 3, there was an increase in the COD consumption reaction rate (rc). In Phase 4, although high gasification was still present (Figure 2), a drastic drop in rc was observed, indicating that introducing a higher amount of biomass could have negative consequences, such as the onset of reactor acidification, excessive biomass accumulation, which could lead to reactor fouling and a rapid reduction in its lifespan. On the other hand, the addition of digestate biomass (DB) had a positive effect on rc up to Phase 3, showing an increase in this rate, which is beneficial for reactor operation, especially in winter. In both winter and summer, the biomass concentration (X) increased following the addition of biomass. More feed leads to more microorganisms.

The study by Qin et al. (2024) analysed the effect of different temperatures on anaerobic co-digestion and showed that mesophilic digestion at 32°C resulted in higher biogas production and process stability, with efficient removal of volatile solids and chemical oxygen demand (COD). These findings corroborate the results of the present study, which also demonstrated efficient removal during the summer.

In summer, however, it was observed that higher biomass addition did not affect rc, with an increase in the rate during Phase 4, indicating the potential to test even larger inputs of material into the reactor. In Phase 4, the highest biogas productivities were identified, coinciding with the highest COD degradation rates.

Conclusion

The addition of 10 tonnes of BM to SWW increases methane yield and biogas production up to threefold, with this quantity being optimal among the tested possibilities for maximising bioenergy production in pig farming systems. The addition of BM enhances biogas production in winter and supports stability in methane production during the colder period of the year. The co-digested material, being of the same type (pig farming), resulted in a rapid increase in biogas production. Coefficients for electricity production after biogas combustion were defined as ranging from 1.67 to 2 kWh m^{-3}, with daily bioenergy productions between 128.8 and 634.8 kWh. Co-digestion of BM with SWW is recommended for increasing bioenergy on the farm. O balanço de massa revelou que há recomendação para aplicação máxima de BM apenas no verão. The addition of BM did not alter the pH of the reactors nor cause VFA accumulation; however, it did increase H_2S concentrations in the biogas, making an efficient removal system for this gas essential to avoid compromising the generator.

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