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Biochemical methane potential of pumpkin energy crops co-digested with swine wastewater

Edilene da Silva Pereira [a], Ritieli Marostica [a], Jackeline Tatiane Gotardo [a], Jorge de Lucas Junior [b], Mônica Sarolli Silva de Mendonça Costa [a,*]

[a] Research Group on Water Resources and Environmental Sanitation, Western Paraná State University, Agricultural Engineering Graduate Program, Rua Universitária, 2069, Jardim Universitário, 85.819-110, Cascavel, Parana, Brazil

[b] Department of Rural Engineering, São Paulo State University, College of Agricultural and Veterinary Sciences at Jaboticabal, São Paulo, Brazil

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ABSTRACT

Anaerobic co-digestion (ACoD) of livestock waste with energy crops (EC) can increase methane yield and the profitability of biodigesters. The biochemical methane potential (BMP) of two commercial pumpkin species, "Paulista" (Cucurbita moschata) and "Moranga" (C. maxima), was evaluated in a laboratory setting. These pumpkins were either crushed or cooked and mixed with swine wastewater (SWW). The treatments included: AMonoD of SWW (T0) and ACoD of SWW + raw Paulista (T1), cooked Paulista (T2), raw Moranga (T3), and cooked Moranga (T4). The volume and composition of biogas were measured, and the modified Gompertz, Cone, modified First Order, and Logistic models were adjusted. T3 recorded the highest specific productions (1.39 m^3 biogas and 0.91 m^3 CH_4 kg^{-1} VS), surpassing ($p \leq 0.05$) the AMonoD and the other trials, without altering the methane content in biogas. It is concluded that crushed raw moranga is a low-cost EC that can significantly enhance the performance of ACoD with SWW, opening up exciting possibilities for the future of biogas technology. The integration of BMP with cone modelling provides reliable parameters for sizing more compact and economically attractive rural biodigesters.

Introduction

The increasing demand for energy, particularly in agribusiness, drives strategies aligned with the circular economy, which can transform waste into biogas and biofertilizer in an environmentally safe and economically competitive manner. Among the conversion processes, anaerobic digestion (AD) stands out by treating effluents from animal production systems, such as swine wastewater (SWW), generating methane with high calorific value (Cao et al., 2020). Brazil, the fourth largest producer of pork in the world, generates large volumes of SWW, making its energy valorization particularly relevant (ABPA – Associação Brasileira de Proteína Animal, 2025).

To increase methane yield per ton of fresh substrate, anaerobic co-digestion (ACoD), which involves the addition of co-substrates to anaerobic mono-digestion (AMonoD), is employed to balance the carbon-to-nitrogen (C:N) ratio, raise the labile organic fraction, and improve the buffering capacity of the system. This approach results in enhanced productivity and a reduced risk of acidification (Velásquez Piñas et al., 2018; Sillero et al., 2022).

In recent years, there has been a movement towards diversifying the energy crops used as co-substrates. In addition to traditional corn and sorghum, studies from 2022 to 2024 explored silage sorghum on a pilot-plant scale, which exhibited high methanization rates and good adaptability to different reactor configurations (Pasteris et al., 2021). Sugar beet pulp and other byproducts from the sugar industry were found to increase methane potential by diluting inhibitory compounds when mixed with cattle manure (Elsayed et al., 2023). Elephant grass combined with pre-hydrolyzed food waste demonstrated a reduction in lag phase and an increase in cumulative CH_4 production (Kriswantoro et al., 2024). Additionally, perennial grasses with high lignin content, such as Miscanthus giganteus, showed high productivity in marginal areas and excellent performance in ACoD with waste (Egwu et al., 2021). These advances indicate an expanding portfolio of energy crops suitable for ACoD, opening opportunities for underexplored horticultural and regional species.

In addition to operational benefits, the inclusion of energy crops

* Corresponding author.
E-mail addresses: monica.costa@unioeste.br, monicasarollisilva@gmail.com (M.S.S.M. Costa).

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enhances the economic viability of biogas plants. Short-cycle biomass ensures a stable organic load, allows for shorter hydraulic retention times (HRT), and generates excess methane that accelerates the return on investment. Techno-economic studies involving sweet potatoes, cassava, and sorghum have shown increases in Net Present Value (NPV) and reductions in payback periods compared to AMonoD (Agostini et al., 2016; Catherine and Twizerimana, 2022; Montoro et al., 2019).

Within this context, the pumpkin species (*Cucurbita moschata* and *Cucurbita maxima*) deserve special attention. They adapt well to various regions and have short crop cycles (Nick and Borém, 2017), along with a high content of easily hydrolysable carbohydrates. Brazilian experiments with sweet potatoes, cassava, and sugarcane juice have demonstrated the potential of horticultural and tuberous plants in ACoD (Damaceno et al., 2019; Montoro, 2020; Restrepo et al., 2022). However, literature involving Cucurbita primarily focuses on Telfairia occidentalis peels with poultry manure (Dahunsi et al., 2016, 2018, 2019). More recently, Moghadam and Zareei (2021) optimized the ACoD of pumpkin residue, generally cultivated for seed extraction, which leaves most of its pulp as waste, by combining it with cattle manure using response surface methodology (RSM). Their study indicated an ideal mixing ratio of 10:90 (pumpkin: manure), achieving 93.5 mL CH_4 per day, thus reinforcing the technical–economic potential of the Cucurbita genus. However, the methane yield was not reported based on total solids (TS) or volatile solids (VS) in the available abstract, highlighting a scientific gap that requires further investigation into commercial varieties of pumpkin in ACoD using SWW along with various pre-treatments.

Additionally, simple pre-treatments such as grinding and mild cooking have been widely studied as strategies to improve the biodigestibility of lignocellulosic and starch-rich substrates. Grinding reduces particle size, thereby increasing the surface area available for microbial action and accelerating the hydrolysis rate. In this study, cooking treatment was specifically applied to pumpkin biomass to break down cell walls and promote starch gelatinization, increasing the soluble fraction of organic matter (Ariunbaatar et al., 2014; Pagliaccia et al., 2019; Zhou et al., 2018). Both processes are characterized by low technical complexity and cost-effectiveness for rural applications, potentially aiding in the reduction of the microbial adaptation phase (lag) and improving the kinetic parameters of AD.

A crucial aspect of BMP studies is kinetic modeling. Models such as the modified Gompertz, Cone, First Order, and Logistic translate time series of biogas production into parameters, including lag phase (λ), maximum rate (Rm), maximum accumulated potential (P), and degradation constants (k). These parameters standardize comparisons among co-substrates, guide reactor sizing by indicating viable HRT, feed scale simulations with the Anaerobic Digestion Model No. 1 (ADM1), and anticipate operational risks by revealing issues within the system.

In light of these gaps, this study evaluates, for the first time, two commercial pumpkin cultivars subjected to physical (grinding) and thermal (cooking) pre-treatments in ACoD with SWW. The biochemical methane potential (BMP) was determined according to VDI (2006) and analyzed using the five cited models, providing inputs for the technical–economic optimization of future rural biodigesters in tropical and subtropical regions.

Materials and methods

Obtaining substrates and inocula

The energy crops used in co-digestion with swine wastewater were acquired from the Supply Centre (CEASA), consisting of two varieties of pumpkins: "Paulista" Squash (*Cucurbita moschata*) and "Moranga" Squash (*Cucurbita maxima*).

The experiment was conducted on a bench scale in the Laboratório de Análise de Resíduos Agroindustriais (LARA) at the Universidade Estadual do Oeste do Paraná (UNIOESTE), Cascavel Campus. Swine wastewater was collected from a Piglet Production Unit (UPL) located near Cascavel, PR. The inoculum used in the experiment was sourced from the International Renewable Energy Centre – Biogas (CIBiogás) in Foz do Iguaçu, Paraná.

For co-digestion, two varieties of pumpkins were obtained from the Supply Centre (CEASA): "Paulista" Squash (*Cucurbita moschata*) and "Moranga" Squash (*Cucurbita maxima*). The pumpkins were ground to an approximate particle size of 2 mm in diameter, including the peel and seeds but excluding the stalks. This was accomplished using an organic waste grinder (TRAPP, model TR200). After grinding, part of the pumpkins was left raw, while the other portion was cooked at 70 °C for 29 ± 5.8 min without the addition of any substances. Both fractions—raw and cooked—were stored frozen in polyethylene bags until needed. Any liquid released during the grinding process was incorporated into the substrate.

The chemical composition of the inoculum, swine wastewater, and the two pumpkin varieties (Paulista and Moranga) was analyzed. The parameters assessed included pH, electrical conductivity (EC), alkalinity fractions, volatile acidity (VA), total carbohydrates, total Kjeldahl nitrogen (TKN), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). The results of these analyses are summarized in Table 1.

Biochemical methane potential test (BMP)

The Biochemical Methane Potential (BMP) test was conducted using anaerobic digestion in batch reactors. This experiment was carried out in triplicate, utilizing amber glass reactor bottles, each with a total capacity of 1000 mL, which includes approximately 500 mL of useful volume and 500 mL of headspace for biogas storage. The following treatments were applied:

– T_0: anaerobic mono-digestion of swine wastewater (AMonoD SWW);

– T_1: anaerobic co-digestion of swine wastewater + raw Paulista (ACoD SWW + raw Paulista);

– T_2: anaerobic co-digestion of swine wastewater + cooked Paulista (ACoD SWW + cooked Paulista);

– T_3: anaerobic co-digestion of swine wastewater + raw Moranga (ACoD SWW + raw Moranga);

Table 1
Chemical characterization of the inoculum, swine wastewater, and pumpkin varieties (Paulista and Moranga) used in the BMP assays.

Parameter	Inoculum	SWW	Paulista	Moranga
EC ($mScm^{-1}$)	4.98 ± 0.03	4.87 ± 0.14	5.75 ± 0.0	5.93 ± 0.0
pH	8.65 ± 0.10	7.55 ± 0.22	4.37 ± 0.04	4.31 ± 0.04
Partial Alkalinity (mgL^{-1})	12072 ± 392	952 ± 88	nd	nd
Intermediate Acidity (mgL^{-1})	656 ± 154	1392 ± 63	nd	nd
Total Alkalinity (mgL^{-1})	12728 ± 416	2344 ± 67	nd	nd
Volatile Acidity (mgL^{-1})	90 ± 9	1754 ± 40	nd	nd
VA/TA	0.01 ± 0.0	0.75 ± 0.02	nd	nd
Total Carbohidrate (gkg^{-1})	0.27 ± 0.03	1.12 ± 0.04	103.11 ± 1.1	125.25 ± 4.8
TKN (gkg^{-1})	17.93 ± 1.17	42.1 ± 0.63	30.1 ± 0.79	29.1 ± 0.71
P (gkg^{-1})	16.26 ± 1.1	28.73 ± 1.6	4.26 ± 0.4	4.24 ± 0.0
K (gkg^{-1})	4.1 ± 1.1	1.75 ± 0.2	0.6 ± 0.0	0.8 ± 0.0
Ca (gkg^{-1})	77.8 ± 12.3	75.4 ± 5.5	41.0 ± 0.5	92.1 ± 0.6
Mg (gkg^{-1})	17.7 ± 2.4	17.4 ± 1.4	2.5 ± 0.0	3.9 ± 0.0

nd = not determined.

– T_4: anaerobic co-digestion of swine wastewater + cooked Moranga (ACoD SWW + cooked Moranga).

In addition to these treatments, three reactor bottles were utilized to evaluate the biological activity of the inoculum. Microcrystalline cellulose (20 μm in diameter) was used as a reference sample to validate the effectiveness of the inoculum employed in the tests. Another three reactor bottles were filled only with inoculum to measure endogenous biogas production.

Characterisation of substrates and inoculum

An initial characterization of the swine wastewater, pumpkin varieties, and inoculum was conducted separately, as well as for the various mixtures at the beginning of the process. This characterization focused on total solids (TS) and volatile solids (VS), utilizing the gravimetric technique with a precision balance (0.001 g) from the Tecnal® brand, Model 210 A. The analysis was performed according to the methods outlined in APHA (2005) to establish the composition of the reactor substrates. The results are presented in Table 2.

For the composition of the substrate, it was assumed that the TS content in each reactor was less than 10 %. The VS of the inoculum ranged from 1.5 % to 2.0 % of the total test content, with the proportion of VS in the inoculum to the substrate being greater than or equal to 2.0, as outlined in Table 3 and in accordance with VDI 4630 (2006).

It is important to note that the C:N ratio of the mixtures was not determined in this study. The experimental design was based on the percentage of TS and maintained the inoculum-to-substrate ratio on a VS basis ($VS_{inoc}/VS_{subs} \geq 2.0$), following the VDI 4630 (2006) guidelines. While the C:N ratio is a critical parameter for AD, this limitation should be considered when interpreting the results, and it will be addressed in future research. All assays were conducted at a mesophilic temperature of 37 °C for a duration of 47 days.

Mono-digestion was performed only with SWW (T_0). The pumpkin varieties, whether raw or cooked, were not subjected to mono-digestion, as the study's aim was to evaluate their influence when co-digested with SWW. All treatments were compared on a VS basis to ensure consistency (see Table 3).

It is important to highlight that the mixing ratios of SWW and pumpkin biomass used in this study were not optimized. The goal was not to determine the optimal ratio, but rather to compare the performance of the two pumpkin species (raw and cooked) under fixed conditions. The ratios were established based on preliminary trials and previous research conducted by our group, ensuring an appropriate C:N balance and feasible digestion performance.

Sample addition and setup

After adding the sample, each flask was sealed and equipped with a screw-type sealing system. This system included a needle connected to a silicone hose with an on/off valve, followed by two catheter-type branches with a closure mechanism. This setup facilitated the measurement of biogas production.

Once the samples were sealed, the flasks were incubated for 24 h before commencing daily biogas measurements. These measurements were conducted using a glass syringe specifically designed for this purpose, along with a NEDA 1604 IEC auto-off manometer (6F22) to account for internal and external pressures within the reactor flasks. The volume of biogas produced was monitored daily and standardized under normal temperature and pressure conditions using Eq. (1).

$$V_0 = V.\frac{(P_L - P_W).T_0}{P_0.T} \quad (1)$$

In which:

– V_0 – standardised biogas volume (mL);
– V – recorded biogas volume (mL);
– P_L – atmospheric pressure at the time of recording (mbar);
– P_W – water vapour pressure (mbar);
– T_0 – normalised temperature (273 K);
– P_0 – normalised pressure (1.013 mbar);
– T – ambient temperature (K).

The assay was conducted at a mesophilic temperature of 37 °C for a total of 47 days. However, the period of interest was specifically defined as the duration during which daily biogas production exceeded 1 % of the accumulated biogas volume (VDI, 2006).

Biogas analysis

The composition of the biogas, specifically the concentrations of methane (CH_4) and carbon dioxide (CO_2), was determined using a gas chromatograph (model GC-2014, Shimadzu Scientific Instruments, Columbia, MD, USA). The instrument was equipped with a Carboxen® 1000 Plot column (4.5 m, 2.10 mm), as adapted from the methods described by Penteado et al. (2013).

Statistical analysis

For the statistical analysis, a completely randomized experimental design (DIC) was employed, and the data were evaluated using the free software Statistica®, Stat Soft, version 10.0.0 (1984). The normality of the data was assessed using the Shapiro-Wilk test. Following this assessment, analysis of variance (ANOVA) was conducted, along with multiple comparisons of means using the Tukey test at a 5 % significance level.

For the methane content data, which did not exhibit a normal distribution, a non-parametric ANOVA was performed using the Kruskal-Wallis test. This involved multiple comparisons of independent sample rankings based on the median, as well as the 1st and 3rd quartiles as references.

Kinetic analysis

For the kinetic analysis of biogas and methane production results

Table 2
Determination of solids, organic matter, and volume of pig farming wastewater and energy crops for the BMP test, corresponding to an organic loading equivalent to 4.8% of total solids (TS).

Treatments	SWW and EC		Batch reactor feed loading					
	TS (%)	VS (%)	TS (%)	FM (g)*	SWW (mL)	Subs. (mL)	Inoc. (mL)	Total (mL)
SWW	0.8	66.8	0.8	–	250	250	200	450
Raw Paulista	15.9	90.2	4.0	12.6	37.4	50	200	250
Cooked Paulista	17.3	90.2	4.0	11.5	38.5	50	200	250
Raw Moranga	8.2	87.8	4.0	24.3	25.7	50	200	250
Cooked Moranga	9.4	89.4	4.0	21.3	28.7	50	200	250

SWW and EC: swine wastewater and Energy Crops; TS: total solids; VS: volatile solids; FM: fresh matter of the EC; SWW (mL): volume of SWW; Subs. (mL).: volume of substrate; Inoc (mL).: volume of inoculum; Total (mL): total volume, regarding substate (SWW + EC) and inoculum; FM (g)*: the determination of the fresh matter was carried out in grams (g), and a density of 1 was assumed for the calculation of the total volume of the reactor in mL.

Table 3
Experimental setup of the BMP assay.

Treatments	TS (%)	VS (%)	Inoculum Mass (g)	TS (g)	VS (g)	Substrate Mass (g)	TS (g)	VS (g)	VS_{inoc} / VS_{subs}	Reactor TS (%)
T_0 − AMonoD SWW	0.8	66.8	200	6.2	3.9	250	2.0	1.3	2.9	1.8
T_1 − ACoD SWW + Raw Paulista	3.5	88.6	200	6.2	3.9	50	1.8	1.6	2.5	3.2
T_2 − ACoD SWW + Cooked Paulista	3.9	88.8	200	6.2	3.9	50	1.9	1.7	2.3	3.2
T_3 − ACoD SWW + Raw Moranga	2.9	86.8	200	6.2	3.9	50	1.5	1.3	3.1	3.1
T_4 − ACoD SWW + Cooked Moranga	3.0	87.9	200	6.2	3.9	50	1.5	1.3	3.0	3.1

SWW and EC: swine wastewater and energy crops; TS: total solids; VS: volatile solids; Inoc: inoculum; Subs: substrate; VSinoc/VSsubs: ratio between inoculum VS and substrate VS; Reactor TS: total solids in the reactor.

from the BMP assay, the software Statistica, developed by StatSoft, was utilized. The advanced tool for estimating nonlinear regression models was applied, using least squares estimation via the Gauss-Newton method with 10,000 iterations and 10 convergence criteria. Over the years, simpler and more applicable mathematical models have been developed, operating under the assumption that the biogas production rate is equivalent to the specific growth rate of methanogenic microorganisms within the reactors (Liew et al., 2021).

Although there are various existing mathematical models, a kinetic model is particularly effective for understanding key parameters related to anaerobic digestion and for accurately predicting the performance of a reactor. This makes it a valuable tool for pilot-scale studies (Liew et al., 2021). Depending on the specific model used, it is possible to extract crucial information, such as the specific biogas production over time, the maximum potential for biogas generation, the duration of the lag phase, the maximum biogas production rate, the kinetic constant, and the relationship between biogas production and microbial activity (Egwu et al., 2021; Karki et al., 2022; Liew et al., 2021; Meneses-Quelal et al., 2021; Santos et al., 2022; Sillero et al., 2022; Silva et al., 2021; Vanarath and Thalla, 2022).

To select at least one model that adequately fits the experimental observations, this study utilized five conventional simplified mathematical models that are commonly employed in Anaerobic Monod kinetics (AMonoD) and Anaerobic Codigestion (ACoD). The models included are: the modified Gompertz model (Sillero et al., 2022) (Eq. (2), the Cone model (Karki et al., 2022) (Eq. (3), the modified First Order model (Santos et al., 2022) (Eq. (4), the Logistic model (Liew et al., 2021) (Eq. (5), and the modified Logistic model (Karki et al., 2022) (Eq. (6). The specific equations for each model are provided below.

$$H(t) = Pexp\left\{-exp\left[\frac{R_m.e}{P}.(\lambda - T) + 1\right]\right\} \quad (2)$$

$$\mathrm{H(t)} = \left[\frac{\mathrm{P}}{1 + (\mathrm{KT})^{-\mathrm{n}}}\right] \quad (3)$$

$$H(t) = P[1 - exp(-KT)] \quad (4)$$

$$H(t) = \left[\frac{P}{1 + bexp(-KT)}\right] \quad (5)$$

$$H(t) = \left[\frac{P}{1 + exp\left(\frac{4Rm}{P}(\lambda - T\right) + 2)}\right] \quad (6)$$

In which:

H(t): specific biogas production (cumulative) over time (t) (mL.g VS^{-1});

P: maximum biogas generation potential (mL.g VS^{-1});

Rm: maximum biogas generation rate (mL.g VS d^{-1});

e: Euler's constant (2,718282);

b: constant (dimensionless);

λ: lag phase during biogas generation (d);

T: time required for cumulative biogas production (d).

K: kinetic constant (1/day);

n: shape factor (dimensionless).

Model evaluation

To determine the most suitable model for the experiment, validation metrics were employed, which consist of various quantification measures. Depending on the experimental variables, one model may demonstrate greater viability than another for the specific treatment, even within the same experiment. This is because different variables have a direct relationship with the anaerobic digestion process, including factors such as the lag phase, the potential for cumulative biogas production, and the maximum biogas production rate, all of which can influence the chosen model.

Therefore, the decision-making process for selecting the most appropriate model for each treatment was based on a comprehensive set of metrics, with each metric assessing different aspects of the modelling. While some metrics are more robust than others, it is crucial to avoid relying on a single metric as the sole criterion for analysis (Karki et al., 2022).

The analyses of the quality of the fits and the evaluations of how well the kinetic models describe the anaerobic digestion processes were conducted based on model parameters and the values of the residual functions (errors). The focus was on minimizing the differences between experimental and predicted results (Karki et al., 2022). The metrics used for this evaluation included the difference in cumulative biogas production, absolute percentage difference (% difference P), ANOVA (p-value ≤ 0.05), coefficient of determination (R^2), adjusted coefficient of determination (R^2adjust), and root mean square error (RMSE).

The % difference P metrics and the variance analysis through the F-test were designed to assess how well the model results aligned with the experimental data, enabling a focused evaluation of each model. In contrast, the R^2, adjusted R^2, and RMSE metrics were used for general comparative analyses between models, assisting in the selection of the model that provided the best fit (Karki et al., 2022).

Results and discussion

The Biochemical Methane Potential (BMP) test was conducted over a period of 47 days for all treatments. However, biogas production stabilized more quickly in certain treatments, with production accounting for less than 1 % of the accumulated volume within the following timeframes: 13 days for T_2 (ACoD with food waste and cooked Paulista), 20 days for T_3 (ACoD with food waste and raw Moragna), 22 days for T_4 (ACoD with food waste and cooked Moranga), 25 days for T_1 (ACoD with food waste and raw Paulista), and 29 days for T0 (AMonoD with food waste).

Accumulated volume and specific production of biogas and methane

The results presented in Table 4 indicate that treatment T_3 (AcoD SWW + raw Moranga) significantly outperformed treatment T_0 (AMonoD SWW) across nearly all volumetric parameters. There was a notable 78.8 % increase in the accumulated volume of biogas and an 86 % to

Table 4
Biogas and methane production from T_0 (AMonoD SWW), T_1 (ACoD SWW + raw Paulista), T_2 (ACoD SWW + cooked Paulista), T_3 (ACoD SWW + raw Moranga), and T_4 (ACoD SWW + cooked Moranga).

Treat.	Accumulated volume Biogas (L)	Specific Production Biogas (L $kgVS^{-1}$)	Specific Production Biogas (L $kgTS^{-1}$)	Specific Production Methane (L $kgVS^{-1}$)	Specific Production Methane (L $kgTS^{-1}$)	Methane (%)
T_0	$1.0^{B\pm}0.3$	$746.0^{B} \pm 226.8$	$499.8^{B} \pm 152.0$	$554.8^{B} \pm 174.5$	$371.8^{B} \pm 119.9.$	$74.2^{A} \pm 1.4$
T_1	$1.2\ ^{AB\pm}0.2$	$740.0^{B} \pm 150.8$	$655.7^{B} \pm 133.7$	$473.8^{B} \pm 97.8$	$419.9^{B} \pm 86.7$	$64.0^{AB} \pm 1.5$
T_2	$1.4\ ^{AB\pm}0.2$	$837.0^{B} \pm 117.3$	$743.3^{B} \pm 104.1$	$527.1^{B} \pm 78.8$	$468.1^{B} \pm 70.0$	$62.9^{BC} \pm 0.8$
T_3	$1.8\ ^{A\pm}0.2$	$1389.9\ ^{A\pm}189.2$	$1205.7\ ^{A\pm}164.1$	$914.7\ ^{A} \pm 122.1$	$793.5\ ^{A\pm}105.9$	$65.8^{AB} \pm 1.1$
T_4	$1.2\ ^{AB\pm}0.1$	$939.1^{B} \pm 0.88.7$	$825.1^{B} \pm 78.0$	$611.3\ ^{AB} \pm 52.4$	$537.1^{B} \pm 46.0$	$65.1^{AB} \pm 0.6$
CV (%)	15.5	17.4	14.1	13.2	13.8	1.7

Treat.: treatments; CV: coefficient of variation; different letters = statistically different means at 95 % significance.

113 % increase in specific methane production according to VS and TS. This demonstrates a strong synergy between the soluble carbohydrates in the pumpkin and the nitrogen in the SWW. Although the methane content (CH_4 %) was higher in T_0 (74.2 %), the volumetric gain achieved in T_3 led to an additional 360 L of CH_4 per kilogram of VS. This highlights that the isolated percentage does not accurately represent overall energy performance.

The treatment with cooked Paulista (T_2) showed an intermediate response that was statistically similar to most of the other treatments. This indicates that cooking does not impede digestion, but it also does not offer an advantage comparable to the simple grinding used for pumpkins. These findings support the use of low-cost mechanical pretreatments for cucurbits.

The substrates used in the test had varying percentages of VS, as presented in Table 3. Values above 60 % indicate high biodegradability, reflecting a greater proportion of organic matter suitable for conversion into biogas (Silva et al., 2021). In the mono-digestion of SWW (T_0), the highest percentage of methane was observed, which is attributed to its protein- and lipid-rich composition, along with the high ammoniacal alkalinity that keeps a portion of the CO_2 dissolved as bicarbonate. When pumpkins are added, the carbohydrate content increases, resulting in additional CO_2 generation during the acidogenesis phase and consuming part of the alkaline buffer. As a consequence, the percentage of CH_4 decreases; however, the absolute volume of energy obtained from the co-digestion treatments significantly increases.

When comparing the two pumpkin varieties, differences in methane yields may be attributed to their biochemical composition. *Cucurbita moschata* is known for its high fiber content, with variable proportions of soluble carbohydrates, reporting between 14.8 % and 22.8 % fiber in the pulp (Men et al., 2021). In contrast, *Cucurbita maxima* shows compositional differences in fiber fractions, such as neutral detergent fiber (NDF) and acid detergent fiber (ADF), which can vary depending on the cultivar (Kulaitienė et al., 2014). These differences in the carbohydrate-to-fiber balance could explain the superior performance of T_3 (raw Moranga), which exhibited higher biodegradability. Although we did not analyze specific fractions like proteins, lipids, or carbohydrates, it is likely that the varietal composition influenced the efficiency of anaerobic digestion.

In addition, the pretreatments applied to the pumpkins should be taken into account. Grinding the pumpkins reduced their particle size to approximately 2 mm, which increased the available surface area for microbial action. Meanwhile, cooking promoted starch gelatinization and facilitated the breakdown of cell walls, resulting in a greater soluble organic fraction (Bekele and Emire, 2023). Interestingly, cooking did not enhance performance compared to using raw substrates. This suggests that the soluble fraction released during cooking may have led to rapid acidogenesis and a partial depletion of buffering capacity, as indicated by the lower methane percentages observed in treatments T_2 and T_4. Nonetheless, the overall volumetric production in these treatments remained higher than that achieved with mono-digestion, highlighting the potential of simple, low-cost mechanical pretreatments to improve co-digestion with swine wastewater.

Although this study did not measure parameters such as alkalinity, protein, and lipid content in the residues, the observed trends align with existing literature on the co-digestion of animal manure and carbohydrate-rich substrates. Future research will include a more detailed chemical characterization and monitoring of alkalinity to confirm these hypotheses and further clarify the mechanisms involved.

These findings suggest that the superior performance of *C. maxima* (Moranga) in treatment T_3 is likely due to its biochemical composition, which features higher soluble carbohydrates and lower fiber fractions. These characteristics favour faster hydrolysis and subsequent methanogenesis compared to *C. moschata* (Paulista). In terms of pretreatments, grinding increased surface area exposure and microbial accessibility, while cooking was expected to enhance digestibility through starch gelatinization. However, cooking may have also led to rapid acidification and partial consumption of buffers, which could explain the lack of further gains in methane yield for treatments T_2 and T_4. Despite these variations, all co-digestion treatments (T_1–T_4) performed better than mono-digestion (T_0), indicating that both pumpkin varieties are effective co-substrates for SWW. Although the absence of detailed biochemical analyses (such as proteins, lipids, and alkalinity) prevents a definitive understanding of the underlying mechanisms, the observed outcomes align with previous studies that utilized carbohydrate-rich residues as co-substrates alongside livestock manure (e.g., Montoro et al., 2019; Silva et al., 2021). This underscores the practical potential of incorporating locally available vegetable residues into anaerobic digestion systems.

In Fig. 1, the efficiency of AD is observed in terms of specific biogas production (Fig. 1a) and methane production (Fig. 1b), which ranged from 740 to 1,389.9 L/kg VS^{-1} and 473.8 to 914.7 L/kg VS^{-1}, respectively (Table 4).

The findings indicate that the organic materials in the substrates are efficiently converted into biogas, as evidenced by the chemical characterization of both the pumpkins and swine wastewater (see Table 1). The elevated levels of total carbohydrates and nitrogen compounds contribute to the swift biogas production, aligning with the findings from Silva et al. (2021). This illustrates that the crops utilized, particularly raw pumpkin, exhibit synergistic effects on anaerobic digestion, similar to the results observed by Montoro et al. (2019) in their study with sweet potatoes used as an energy crop in co-digestion with dairy cattle manure.

Kinetic analysis

For the BMP test results, the modified Gompertz, Cone, modified First Order, Logistic, and modified Logistic kinetic models adequately described the cumulative biogas production, as shown in Fig. 2.

It was observed that a similar trend in cumulative biogas production, both experimental and predicted, occurred among the treatments, with a rapid increase in biogas output during the initial days. Following this peak phase, production gradually declined and stabilized, which aligns

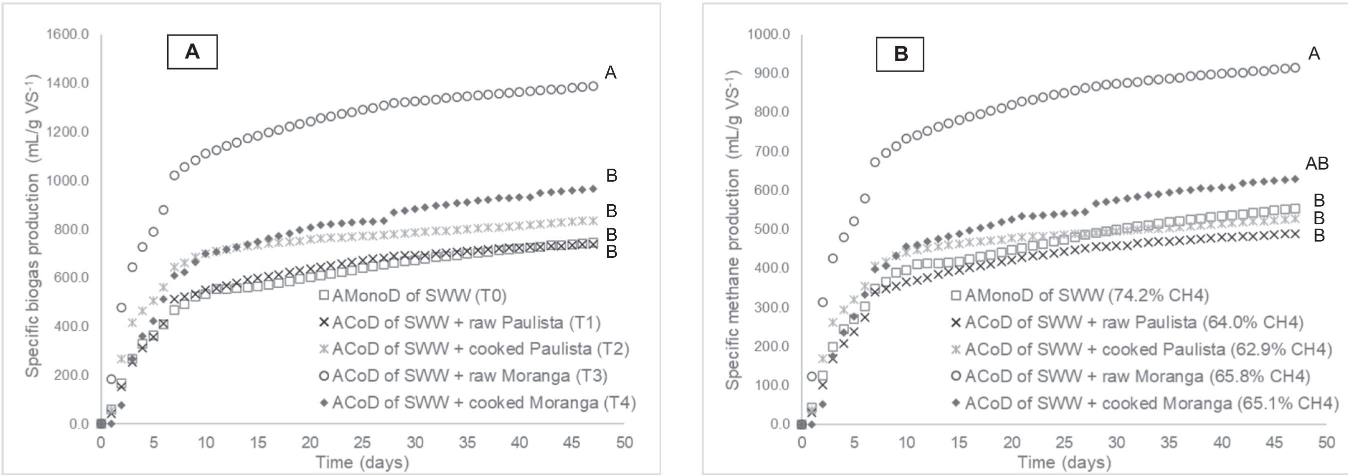

Fig. 1. Specific production of biogas (a) and methane (b), in mL.g VS^{-1}, during the 47 days of the experiment.

with the findings of Meneses-Quelal et al. (2021) and Sillero et al. (2022). The batch feeding system played a critical role in this dynamic, as it led to the depletion of biodegradable complexes in the medium. This depletion ultimately reduced microbial activity, slowing down the biodegradation process and resulting in a decrease in biogas generation, as noted by Liew et al. (2021). Table 5 provides a summary of the parameters and metrics from the kinetic models used to evaluate these adjustments.

In the models developed for this study, the percentage difference in biogas yield (% difference P) between the experimental and the estimated cumulative potential production (mL.gVS^{-1}) was found to be below 9.5 % for AMonoD and 8.3 % for ACoD. Existing literature suggests that a smaller deviation indicates a better fit, with deviations not exceeding 10 % being ideal, as anything beyond this threshold might invalidate the model (Khatun et al., 2023). Therefore, the observed differences in yield between the experimental results and the model estimates in this study indicate a good model fit, as the deviations remained under the 10 % threshold.

A comparable deviation was reported by Vannarath and Thalla (2022), which emphasizes the importance of using this alongside other modeling metrics for proper validation of the adjustments made. Similar findings were also noted by Karki et al. (2022) and Meneses-Quelal et al. (2021), where the observed differences were considered adequate as well. This consistency across multiple studies reinforces the reliability of the modeling approaches used in evaluating biogas production.

Two models emerged as the most accurate in terms of yield differences: the Cone model, which showed percentages of 3.75 % (T_1), 1.32 % (T_2), 3.95 % (T_3), and 1.28 % (T_4), and the modified Gompertz model, which had a deviation of 6.18 % (T_0) (see Table 4). These findings suggest that the Cone model performed particularly well in ACoD, while the modified Gompertz model was more effective in AMonoD. Similar results were observed by Sillero et al. (2022), who reported modified Gompertz values ranging from 2.48 % to 2.52 % in treatments that included sewage sludge and agricultural residues (ACoD). Additionally, Karki et al. (2022) noted in their kinetic study of organic waste that the Cone model produced values ranging from 1.7 % to 10.9 % for both AMonoD and ACoD, respectively.

In this study, the kinetic constants (K) varied from 0.16 to 0.30 d^{-1} using the Cone model, while values ranged from 0.12 to 0.21 d^{-1} with the modified First Order model. The highest rates were recorded in treatment T_2, while T_0 exhibited the lowest rates. Higher kinetic constants indicate quicker degradation rates (Khatun et al., 2023), which are influenced by factors such as biodegradability, test temperature, and the presence of inhibitory substances (Morais et al., 2021).

The results, with values between 0.1 and 0.2 d^{-1}, confirm that the highest biogas and methane production occurred within a span of less than 30 days, assuming adequate hydrolysis of degradable organic compounds took place, as noted by Silva et al. (2021) and Karki et al. (2022). In the logistic model, K values ranged from 2.62 to 5.21 d^{-1}, again with T_4 showing the highest value and T_0 the lowest.

In the sigmoidal representation of the models (Fig. 2), the K parameter reflects the slope trend, indicating the initiation of biogas and methane production, at which point the conversion of organic matter to biogas occurs more swiftly. A higher kinetic constant corresponds to greater hydrolytic activity (Karki et al., 2022; Khatun et al., 2023), which implies a reduced demand for hydraulic retention time (HRT). This reduction is beneficial on an absolute scale, as it allows for smaller reactor dimensions while accommodating the same feed load (Silva et al., 2021).

Favorable K values suggest that the lignocellulosic materials present in the substrate were in a labile form, which enhances synergistic effects for biogas production at an accelerated rate (Vannarath and Thalla, 2022). This condition was likely supported by the physical and thermal pre-treatment applied to the energy crops, optimizing the substrate for efficient degradation and biogas generation.

Zhou et al. (2018) emphasized the significance of pre-treating organic substrates, as it enhances critical stages of the AD process, particularly hydrolysis and acidogenesis. Pre-treatment facilitates an increase in the production of soluble compounds, which can have a direct positive effect on the yield of volatile fatty acids (VFAs).

It's also important to note that none of the treatments achieved K values lower than 0.1 d^{-1}. Such values could suggest a prolonged adaptation period for the microorganisms to acclimate to the substrate, as well as initial acidification and possible inhibition of methanogenesis, as observed by Karki et al. (2022) in their research.

The maximum biogas production rate (Rm) was particularly noted in T_3, presenting the highest values in both the Cone and Modified Logistic models. In the Cone model, Rm values were recorded as 38.09 (T_0), 50.93 (T_1), 90.54 (T_2), 104.18 (T_3), and 67.12 (T_4) mL.g VS d^{-1}, indicating that the maximum production in the ACoD treatments exceeded that of AMonoD by a factor of 1.3 to 2.7. Similarly, in the modified logistic model, Rm values were 31.74 (T_0), 44.72 (T_1), 79.80 (T_2), 89.15 (T_3), and 61.23 (T_4) mL.g VS d^{-1}, with ACoD again outperforming AMonoD by 1.4 to 2.8 times. These findings align with the results from Pan et al. (2019), who also reported higher Rm for ACoD compared to AMonoD in studies involving sewage sludge and food waste, thereby reinforcing the enhanced suitability of ACoD substrates for hydrolytic activity, attributed to their superior biodegradability and conversion rates.

In both the modified Gompertz and modified Logistic models, the lag phase is represented by the variable 'λ,' which denotes the time required for methanogenic microorganisms to acclimate to anaerobic conditions

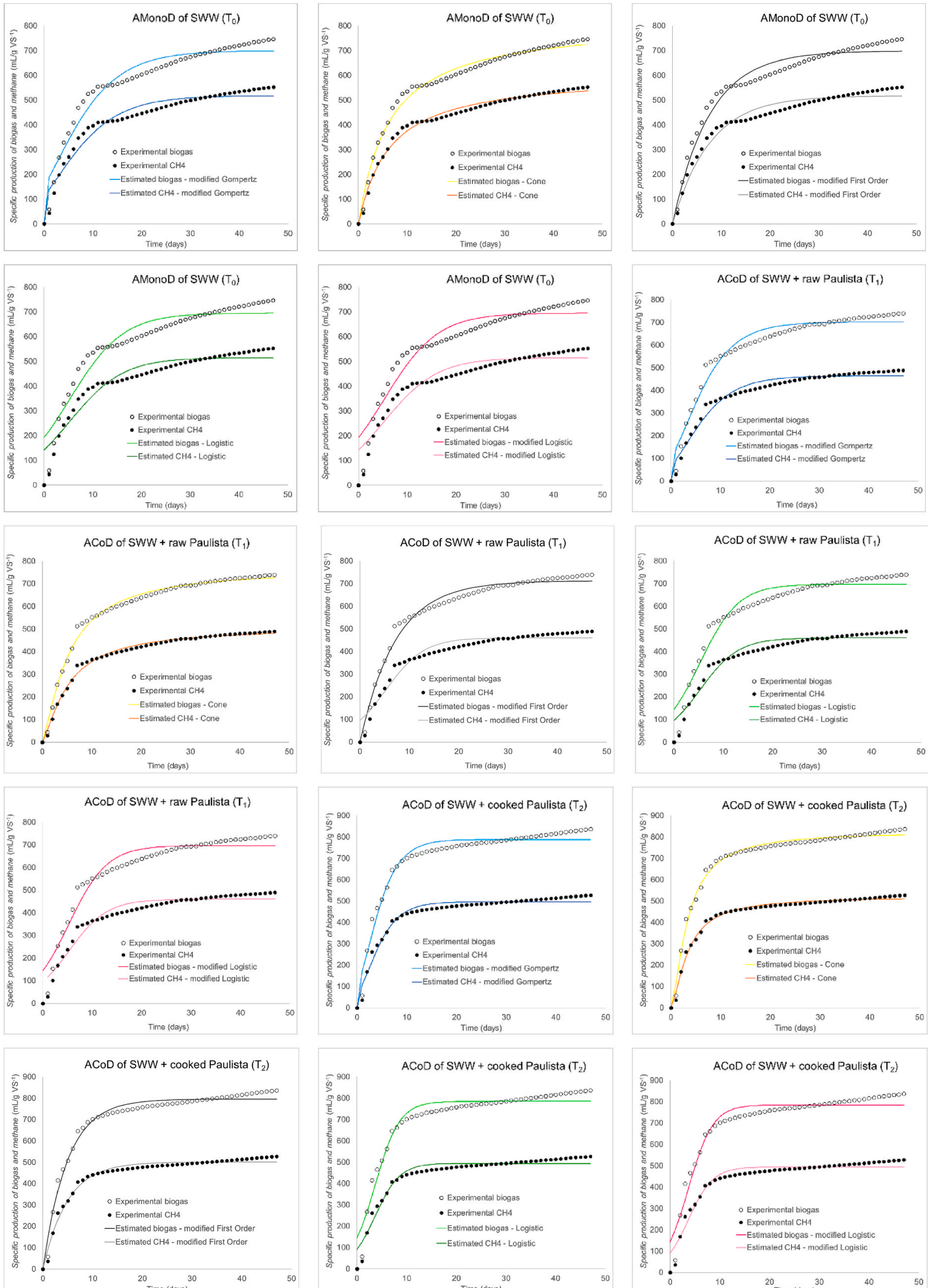

Fig. 2. Specific biogas and methane production (mL.g VS^{-1}) over 47 days, referring to the experiment and modified Gompertz, Cone, modified First Order, Logistic, and modified Logistic models for treatments T_0, T_1, T_2, T_3, and T_4.

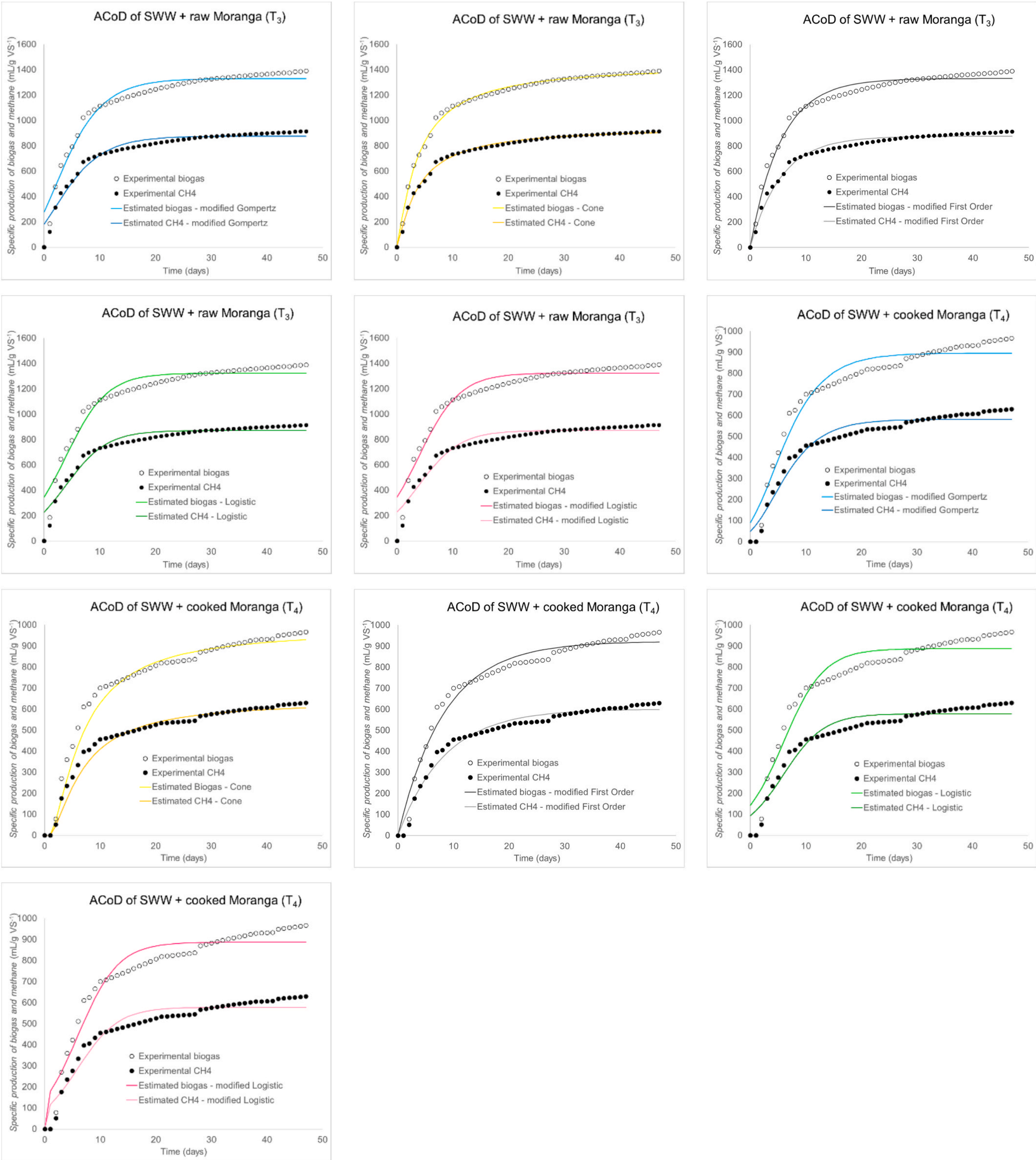

Fig. 2. (*continued*).

before initiating the AD process (Karki et al., 2022; Vannarath and Thalla, 2022). In this study, λ yielded negative time values (days), indicating, as noted by Morais et al. (2021) and Meneses-Quelal et al. (2021), that there was no lag phase observed in the tests. This suggests that biogas production likely began shortly after inoculation, significantly reducing the time needed to reach the exponential phase of production (Morais et al., 2021).

In biogas digesters, the lag phase typically varies from 0 to 18 days (Vannarath and Thalla, 2022). Given the adjustments made to the experimental data, both in terms of the metrics and the visual characteristics of the sigmoidal growth curve, it is evident that there was no lag phase. This indicates that the microorganisms in the inoculum were already acclimatized and ready to initiate biogas production, further suggesting that the substrates exhibited high biodegradability of organic compounds (Meneses-Quelal et al., 2021).

In the Cone model, the lag phase is indicated by a constant ($n > 1$)

Table 5
Parameters and metrics of the different kinetic models used in the BMP test, referring to anaerobic monodigestion with swine wastewater (T_0: AMonoD SWW), and anaerobic co-digestion of this with pumpkins ("Paulista" and "Moranga"), with and without heat treatment (T_1: ACoD SWW + raw Paulista), (T_2: ACoD SWW + cooked Paulista), (T_3: ACoD SWW + raw Moranga), and (T_4: ACoD SWW + cooked Moranga).

Models	Parameters and Metrics	Tratamentos				
		T_0	T_1	T_2	T_3	T_4
Gompertz Modificado	P (mL.g VS^{-1})	699.87 ± 9,4	702.02 ± 6,88	788.32 ± 5,8	1330.05 ± 10,18	895.62 ± 10,9
	Rm (mL.g VSd^{-1})	38.09 ± 3,2	50.93 ± 3,5	90.54 ± 6,5	104.18 ± 6,7	67.12 ± 5,5
	λ (d)	−3.92 ± 0,9	−1.76 ± 0,5	−0.81 ± 0,4	−2.57 ± 0,5	−0.82 ± 0,6
	% difference P	6.18	5.13	5.82	4.30	7.41
	p-valor	0.00	0.00	0.00	0.00	0.00
	R^2	0.94	0.96	0.96	0.96	0.94
	R^2_{adjust}	0.93	0.95	0.95	0.96	0.94
	RMSE	37.76	32.01	31.73	49.68	51.80
Cone	P (mL.g VS^{-1})	816.6 ± 20,9	767.7 ± 8,9	826.0 ± 6,0	1444.8 ± 11,5	979.6 ± 16,8
	K (1.d^{-1})	0.16 ± 0,0	0.19 ± 0,0	0.30 ± 0,0	0.26 ± 0,0	0.17 ± 0,0
	n	1.02 ± 0,0	1.31 ± 0,1	1.49 ± 0,1	1.18 ± 0,0	1.43 ± 0,1
	% difference P	9.48	3.75	1.32	3.95	1.28
	p-valor	0.00	0.00	0.00	0.00	0.00
	R^2	0.98	0.99	0.99	0.99	0.98
	R^2_{adjust}	0.98	0.99	0.99	0.99	0.98
	RMSE	19.19	14.96	16.85	19.65	29.64
Modified First Order	P (mL.g VS^{-1})	698.45 ± 7,3	712.07 ± 5,1	796.27 ± 4,8	1332.15 ± 8,0	922.72 ± 9,7
	K (1.d-1)	0.13 ± 0,0	0.14 ± 0,0	0.21 ± 0,0	0.18 ± 0,0	0.12 ± 0,0
	% difference P	6.37	3.77	4.87	4.15	4.60
	p-valor	0.00	0.00	0.00	0.00	0.00
	R^2	0.96	0.98	0.97	0.97	0.97
	R^2_{adjust}	0.95	0.98	0.97	0.97	0.97
	RMSE	31.67	22.94	25.33	40.54	39.69
Logistic	P (mL.g SV^{-1})	694.86 ± 10,0	696.73 ± 7,6	785.31 ± 6,5	1322.99 ± 11,3	886.80 ± 12,0
	K (1.d-1)	2.62 ± 0,4	3.84 ± 0,1	4.43 ± 0,8	2.84 ± 0,4	5.21 ± 1,1
	b	0.18 ± 0,0	0.26 ± 0,0	0.41 ± 0,0	0.27 ± 0,0	0.28 ± 0,0
	% difference P	6.85	5.84	6.18	4.81	8.32
	p-valor	0.00	0.00	0.00	0.00	0.00
	R^2	0.92	0.94	0.94	0.95	0.92
	R^2_{adjust}	0.91	0.94	0.94	0.94	0.92
	RMSE	43.21	38.24	36.48	58.17	60.91
Modified Logistic	P (mL.g SV^{-1} ad)	694.86 ± 10,0	696.73 ± 7,6	785.31 ± 6,5	1322.99 ± 11,3	886.80 ± 12,0
	Rm (mL.gSVd^{-1})	31.74 ± 3,1	44.72 ± 3,9	79.80 ± 7,1	89.15 ± 7,0	61.23 ± 6,3
	λ (d)	−5.68 ± 1,3	−2.55 ± 0,8	−1.26 ± 0,5	−3.54 ± 0,7	−1.27 ± 0,9
	% difference P	6.85	5.84	6.18	4.81	8.32
	p-valor	0.00	0.00	0.00	0.00	0.00
	R^2	0.92	0.94	0.94	0.95	0.92
	R^2_{adjust}	0.91	0.94	0.94	0.94	0.92
	RMSE	43.21	38.24	34.66	58.17	60.91

P: cumulative biogas production; Rm: maximum biogas production rate; λ: lag phase, latency or minimum time for biogas production to start; K: kinetic rate constant; n: shape factor; b: constant; % difference: deviation of predicted biogas production from estimated production; p-value: model significance analysis at $\alpha = 0.05$; R^2: model adjustment coefficient of determination; R^2: adjusted coefficient of determination, discounted about the number of variables in each model; RMSE: root mean square error.

(Morais et al., 2021). The results obtained were 1.0 for T_0, 1.2 for T_3, 1.3 for T_1, 1.4 for T_4, and 1.5 for T_2, confirming the absence of a significant lag phase in these treatments.

Model evaluation

Fisher's statistical test in the analysis of variance (ANOVA) confirmed that all models implemented showed significantly adequate adjustments to the data at a 95 % confidence level (p-value ≤ 0.05). In terms of the coefficient of determination (R2), all five models exhibited R2 values greater than 0.9, indicating an acceptable fit. Notably, the Cone kinetic model achieved the highest accuracy, with R2 values ranging from 0.98 to 0.99 across all treatments, closely approximating R2 = 1.

The coefficient of determination is a crucial metric for validating AD models, as it quantifies the proportion of variance in the dependent variable that can be explained by the independent variable in the experiment (Egwu et al., 2021). In the context of this study, both the First Order and modified Gompertz models yielded R^2 values exceeding 0.96, consistent with findings from Sillero et al. (2022). Additionally, a study by Vannarath and Thalla (2022) on the AD of pre-treated areca nut residues (lignocellulosic) reported R^2 values greater than 0.99 for both the modified Gompertz and modified Logistic models, further underscoring the effectiveness of these modeling approaches.

To account for the differences in the number of parameters across models, which can directly affect R^2, the adjusted R^2 (R^2_{adjust}) is often used. This metric discounts the number of variables in the model equation from the overall R^2, providing a more accurate assessment of model fit. In this study, R^2_{adjust} values ranged between 0.98 and 0.99 for all models. Consistent with the findings of Karki et al. (2022), the Cone model demonstrated one of the best fits, with R^2_{adjust} values particularly noteworthy in the ACoD treatments compared to those of AMonoD.

The lowest root mean square error (RMSE) across all treatments was observed in the Cone kinetic model, with values of 19.19 for T_0, 14.96 for T_1, 16.85 for T_2, 19.65 for T_3, and 29.64 for T_4 (see Table 5). A smaller RMSE indicates that the model predictions are more precise, as it reflects minimal deviations from the experimental data (Egwu et al., 2021).

The kinetic models provided valuable insights, including specific methane yield, lag phase duration, and various kinetic parameters, allowing for the assessment of model adjustments and the optimization of AD processes (Karki et al., 2022; Sillero et al., 2022).

Among the kinetic models applied to mono-digestion and co-digestion in this study, the best fits, based on R^2, R^2_{adjust}, and RMSE metrics, were ranked as follows, from the most adequate to least as follows: Cone, First Order, Modified Gompertz, Logistic, and Modified Logistic models.

Implications for practice

The direct application of the Cone model can be utilized in designing a biodigester for a farm with 1,000 pigs.

Assumptions and load balance

To replicate the conditions evaluated in the BMP test (treatment T_3) on a farm scale, the same proportion of TS in the mixture was adopted, specifically, 4.8 % TS, with 0.8 % derived from SWW and 4.0 % from crushed raw pumpkin. The relevant data can be found in Table 6.

Expected biogas production

Table 7 summarizes the direct application of the Cone model parameters obtained for treatment T_3 (raw “Moranga”) in relation to the daily loads calculated for a farm with 1,000 pigs. Using the specific potential (P), the kinetic constant (K), and the shape factor (n), the specific biogas production was estimated for a hydraulic retention time (HRT) of 25 days. By multiplying this value by the VS load (324 kg VS day^{-1}), we estimate an approximate biogas generation of 440 m^3 per day, which corresponds to 290 m^3 of CH_4 per day (65.8 % v/v). These values serve as an initial reference for sizing the reactor, gas collection system, and energy balance of the unit.

Preliminary dimensioning

A conservative volumetric organic load of 4 kg VS m^{-3} day^{-1} was adopted. Based on a daily mixture of 324 kg VS, the required useful volume is calculated using Eq. (7):

$$Usefulvolume = \ 324 \text{ kg VS day}^{-1} / \ 4 \text{ kg VS } m^3 \text{ day}^1 \approx \ 81 \text{ m}^3 \tag{7}$$

To account for foam, flow variations, and gas space, an additional 15 % slack is added, resulting in a total tank volume of approximately 95 m^3. The feed flow, comprising 8 m^3 of SWW and about 4 m^3 of pumpkin, totals approximately 12 m^3 day^{-1}. Therefore, the projected hydraulic retention time (HRT) is calculated as follows:

$HRT = 95\ m^3 / 12\ m^3\ day^{-1} \approx 8$ *days.*

This HRT aligns with the kinetics described by the Cone model, which predicts that 90 % of the biogas potential is released within 10 days. This ensures high performance without the need to oversize the reactor.

Operational guidelines based on the model

• **Start-up**: Compare the biogas accumulated on days 3, 5, and 7 with the H(t) curve. Deviations greater than 20 % indicate the need for corrections. During start-up, use the Cone equation (Eq. (3) to calculate the predicted accumulated biogas volume on these days. Compare these predicted values with the measurements from the gas meter. Deviations of less than ± 20 % suggest that the reactor is operating according to expected kinetics. Larger deviations may indicate issues such as acidification, heating problems, or failure in mixing, which will require adjustments to pH, alkalinity, or pumpkin dosage.

• **Load adjustment**: Recalculate the mixture if the supply of pumpkin varies.

• **Gas management**: The initial hourly peak should be approximately 7 % of the total volume.

• **Biomass**: The estimated biomass production of 3.9 t day^{-1} requires about 80 ha per year (based on a yield of 70 t ha^{-1} with 2 harvests).

Table 6
Assumptions and load balance (1,000 pigs).

ParAMETER	UniTY	SWW	RAW “Moranga”	TOTAL MIXTURE
Flow/Mass	kg day-1	8 000	3 900	≈ 11 900
Total Solids (TS)	kg day-1	64	320	384
TS Fraction	%	0.8	8.2	4.8
Volatile Solids (VS)	kg day-1	43	281	324
VS/TS Fraction	%	66.8	87.8	—

Table 7
Expected biogas production.

Parameter	Symbol/value	Unity	Observation
Specific Potential	P = 1.44	m^3 biogas kg^{-1} VS	Cone Model T_3
Kinetic Constant	K = 0.26	d-1	
Form Factor	n = 1.18	—	
HRT Considered	t = 25	d	
Specific Biogas	B(25) = 1.35	m^3 kg^{-1} VS	Eq. Cone
Daily VS Load	324	kg VS d-1	Table 4
Daily Biogas	≈ 440	m^3 d-1	
CH_4 Fraction	65.8	% v/v	Average test value
Daily Methane	≈ 290	m^3 CH_4 d-1	

Summary

Using the same total solids ratio as in the test (4.8 % TS, with 4 percentage points from raw pumpkin), a continuous reactor of approximately 95 m^3 (81 m^3 useful volume plus 15 % slack) can support a farm with 1,000 pigs. The daily load consists of 8 m^3 of sewage water (SWW) and 3.9 t of ground pumpkin, equating to about 324 kg of volatile solids (VS) per day. By applying the Cone model parameters obtained for treatment T3 (P = 1.44 m^3 biogas/kg VS, K = 0.26 d^{-1}, n = 1.18), the expected biogas production at a hydraulic retention time (HRT) of 25 days reaches approximately 440 m^3 per day, of which around 290 m^3 is methane (65.8 % v/v). This volume of methane is equivalent to approximately 3 MWh of thermal energy or 150 kW of continuous electrical power, which is sufficient to satisfy the typical demand for ventilation, lighting, and feed grinding on the property.

In addition to providing a clear target value for initial sizing, Cone's equation (Eq. (3) offers several benefits:

• **Adjusting the HRT**: The constant K indicates that 90 % of the biogas potential is released in less than 10 days, allowing for lower hydraulic retention times (HRTs) to be adopted as long as stability is maintained.

• **Monitor start-up**: By comparing the accumulated biogas predicted by H(t) with the measurements taken on days 3, 5, and 7, deviations greater than 20 % will signal the need for operational corrections.

• **Resize loads**: Variations in the availability of pumpkin can be easily recalculated using the equation itself, which eliminates the need for new bench tests.

In summary, the Cone model effectively transforms laboratory results into a practical tool for the pre-design, operation, and optimization of biodigesters that integrate SWW and *Cucurbita maxima* as a co-substrate.

Conclusion

The co-digestion of swine wastewater with the raw Moranga pumpkin variety demonstrated a high technical feasibility for biogas and methane production, achieving 793.5 L CH_4 kg^{-1} TS. This represents a significant increase of 113 % compared to the mono-digestion of swine wastewater, which produced 371.8 L CH_4 kg^{-1} TS. This remarkable improvement underscores the synergistic potential of pumpkin as a co-substrate in enhancing the anaerobic digestion process.

Future studies should explore other pumpkin varieties and different substrate proportions to further optimize methane yield and process stability. Among the kinetic models evaluated, the Cone model provided the best fit to the experimental data ($R^2 > 0.98$), confirming its reliability for predicting methane production and supporting the technical and economic assessment of biogas projects at larger scales.

CRediT authorship contribution statement

Edilene da Silva Pereira: Writing – original draft, Methodology, Investigation, Formal analysis. **Ritieli Marostica:** Methodology, Investigation. **Jackeline Tatiane Gotardo:** Methodology, Investigation, Formal analysis. **Jorge de Lucas Junior:** Conceptualization. **Mônica Sarolli Silva de Mendonça Costa:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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