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Biomethane Recovery for Hermetia illucens Larval Frass Derived from Faecal matter, Swine Manure and Chicken Manure

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Research Article

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Biomethane Recovery for *Hermetia illucens* Larval Frass Derived from Faecal matter, Swine Manure and Chicken Manure

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Abstract

Purpose: The black soldier fly (BSF) offers a transformative approach for food security and organic waste management. However, frass, the residue from larval bioconversion, is biochemically immature and unstable, limiting its direct use for agricultural purposes. This study evaluated the biomethane potential of frass derived from faecal matter, swine manure, and chicken manure using laboratory-scale batch anaerobic digestion reactors.

Methods: Frass samples were characterized for their physicochemical properties before digestion. Biochemical methane potential tests were conducted in triplicate using laboratory-scale batch reactors at a substrate-to-inoculum ratio of 1:1. Methane production continued for 55 days and was fitted using first-order and modified Gompertz kinetic models.

Results: The frass was alkaline (pH 8.1–9.1), with total solids of 87.1–94.3% and volatile solids of 35.3–71.6%. Carbon to nitrogen ratios were below the optimal range for stable anaerobic digestion. Biomethane yields ranged from 100 ± 6.9 to 347 ± 3.6 ml/g volatile solids, with swine manure frass producing the highest yield and chicken manure the lowest. Organic matter removal efficiencies reached 20–55% for volatile solids and 15–36% for Chemical Oxygen Demand. The modified Gompertz model best described methane production from faecal matter and swine manure frass, while the first-order model better fitted chicken manure frass.

Conclusion: These findings indicate that frass, particularly from swine manure, is a promising feedstock for anaerobic digestion, enabling post-harvest stabilization and energy recovery.

Keywords: biomethane potential, black soldier fly, circular economy, frass, organic waste valorisation

Highlights

- BSFL frass was evaluated as a feedstock for anaerobic digestion
- Swine manure frass produced the highest biomethane yield
- Chicken manure frass showed low biodegradability and inhibition risk
- Anaerobic digestion can stabilize frass while recovering renewable energy

Graphical Abstract



1 Introduction

A growing population is typically associated with increasing levels of solid waste, with global annual waste generation projected to rise by 73% by 2050 [1]. The adverse effects of organic waste contribute to environmental pollution through greenhouse gas emissions, unpleasant odours, and leaching of accumulated waste releasing excessive nutrients into soils and water sources [2]. Solid waste management practices, particularly the use of landfills and incineration, have traditionally been favoured for their relative simplicity and low cost; however, they remain fundamentally inadequate in terms of long-term sustainability [3].

The black soldier fly (BSF) offers a transformative solution to the challenges of food security and organic waste management. The larval stage of the BSF is the most valuable for waste management, as it able to bio-convert diverse organic wastes [4]. Beyond waste reduction, the BSFL contributes additional benefits to waste treatment, including pathogen inactivation, particularly of Salmonella species, reduction of fungal diversity, and decreased concentrations of heavy metals such as lead, cadmium, arsenic, and mercury in feed substrates [5-7].

In recent years, there has been a notable surge in research interest and effort from the scientific community in the residues generated after BSFL bioconversion activities, particularly for use for agricultural purposes. With the rapid expansion of BSFL production systems, frass generation has become substantial, accounting for 15–69% of the original feedstock on a dry matter basis, depending on the type of rearing substrate and production systems [8]. The use of the frass as an organic fertilizer has shown potential by improving crop production, producing effects comparable to commonly used inorganic fertilizers [9].

However, the direct application of freshly produced frass to soils presents several challenges. Although the BSFL bioconversion process of organic wastes reduces Salmonella concentrations to acceptable levels, it remains less effective against other common pathogens [6]. Moreover, BSFL frass often displays considerable variability in nutrient composition, high moisture content, a low carbon-to-nitrogen ratio, and phytotoxic properties that can stunt plant growth, thereby limiting its agronomic value as an organic fertilizer [9, 11, 12].

These limitations are largely attributed to the biochemical immaturity and instability of fresh frass, resulting from the rapid nature of BSFL bioconversion process, which does not allow sufficient time for organic matter stabilization [8]. To address these challenges, Song et al. [9] recommends post stabilization of fresh frass through

forced aeration composting techniques, which can significantly enhance its suitability for crop production. However, the increasing volume generated worldwide further necessitates sustainable and safe post processing strategies that extend beyond aeration composting.

Anaerobic Digestion (AD), a widely recognized biological decomposition process occurring in the absence of oxygen, may likewise serve as a promising alternative to post harvest maturation of frass while offering the additional benefit for biomethane recovery. Despite the well-documented stabilization and energy recovery benefits of anaerobic digestion, few studies have investigated BSFL frass as an anaerobic digestion feedstock. To the authors' knowledge, only eight studies have subjected BSFL frass derived from different rearing substrates to the anaerobic digestion process; from human faecal matter [6], swine manure [13], food industry residues [14], corn silage, brewer's spent grain, bran and aquatic plants [15], carrot–beetroot marc [16] , chicken food and food scraps [17], municipal solid waste [18] and agricultural side-streams [19].

Lalander et al. [6] employed anaerobic digestion to support an economic assessment of alternative waste management strategies, whereas Dong et al. [13] investigated the enhancement of anaerobic digestion of swine manure-derived frass through Fe_3O_4 nanoparticle addition and methanogenic community analysis. The choice of BSFL rearing substrate significantly influences the composition of the frass [20] and consequently affect the results of anaerobic digestion. As such, the anaerobic digestion performance of BSFL frass derived from the most abundant manure streams has not been comparatively evaluated under uniform experimental conditions.

This knowledge gap limits the integration of BSFL systems into circular bioenergy frameworks. To address this gap, this present study investigated the biomethane production potential of BSFL frass derived from faecal matter, swine manure, and chicken manure, with the aim to: (i) analyze the composition of the residues; (ii) determine their biomethane production potential; and (iii) model the biomethane production kinetics of these wastes during biomethane formation.

2 Materials and Methods

2.1 Inoculum and Substrate Harvesting, Preparation and Storage

The experiments were carried out at the Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. Fresh faecal matter, swine manure and chicken manure were sourced from neighbouring toilets and farms respectively. Five-day-old BSFL, sourced from an existing colony within the university, were introduced into separate trays (Kenpoly Limited, Kenya) with dimensions of 300mm x 200mm x 60mm containing faecal matter, swine manure, and chicken manure, with frass harvested at larval maturity. In the laboratory, the residues were blended, sieved to 0.42 mm separately to homogenize and reduce the particle size and stored in sterile bottles at 4 °C until use. The residues intended for anaerobic digestion were stored for no longer than one day, allowing sufficient time to obtain the inoculum from an active anaerobic biodigester at the university, which utilized dairy manure as its feedstock.

2.2 Analytical Methods

The characterization of frass derived from faecal matter (FM), swine manure (SM) and chicken manure (CM), as well as the inoculum and feedstock used for the batch reactors, were conducted in triplicates to ensure analytical precision. Substrate parameters analyzed included total solids (TS), volatile solids (VS), pH, and elemental composition (C, N, O, S, H). For the inoculum and adjusted feedstock used for the batch reactor, TS, VS, pH, chemical oxygen demand (COD), and ammonium nitrogen (NH_4^+-N) were measured.

TS and VS were determined according to standard methods in [21]. For TS, the samples were oven-dried at 105 °C in an oven (Memmert UN55, Germany), while VS was measured by igniting the dried samples in a muffle furnace at 550 °C until weight change was <4%. COD was measured using the closed reflux dichromate method, while ammonium nitrogen was analysed using the Nessler method with UV-VIS spectrophotometry (DR 2500, Hach, USA). For the analysis of pH of the substrates, 1 g of the fresh substrates was mixed with 10 mL of distilled water and the pH measured using a compact precision meter (pH meter 3210, Germany). The elemental composition (C, N, O, S, H) of the BSFL frass was obtained using a flash organic CHNOS analyzer (EA 1112, Netherlands).

Prior to analysis, data were tested for normality and homogeneity variance. One-way ANOVA was performed, and statistically significant differences ($p < 0.05$) were further evaluated using Tukey's post-hoc test.

2.3 Biochemical Methane Potential (BMP) Test

In this study, the modified BMP procedure described by Wandera et al. [22] was adopted. The feedstock for the laboratory scale batch reactors were prepared by adjusting the TS of the substrates to match the inoculum concentration by diluting 2.8 g of FM and SM frass, and 2.0 g of CM frass, each with 40 ml of distilled water. For the batch reactor, 125 ml serum bottles which were locally available with a working volume of 80ml were used alongside rubber stoppers. The Substrate Inoculum Ratio (SIR) was maintained at 1:1 to minimize acidification and ensure stable digestion. All the treatments were performed in triplicates.

Table 1: Setup of Laboratory-scale Reactors

Reactor	Reactor Type and Composition	
	Type	Composition of the mixes
R1	Batch	Frass from Faecal Matter + Inoculum
R2	Batch	Frass from Swine Manure + Inoculum
R3	Batch	Frass from Chicken Manure + Inoculum

The headspaces of the serum bottles were flushed with nitrogen gas for 2 minutes to establish anaerobic conditions, then tightly sealed using a rubber cork and parafilm (American National Can, USA). The experiment was carried out under mesophilic conditions and continued until the daily biogas production declined to less than 1% of the cumulative yield which occurred by day 55 across all substrates. Biogas production was measured daily using graduated syringes with capacities ranging from 5ml to 100ml (Tianjin Chengsheng Glass Instrument Co. Ltd, China). The reactors were shaken for two minutes to evenly distribute the substrates and micro-organisms as well as release of the trapped gas bubbles for ease of gas collection. The cumulative yield for the substrate was determined by subtracting biogas produced in the Reactor R4 containing the inoculum only with biogas yield further corrected to standard temperatures and present conditions.

As the biogas produced by the reactors consists of methane, carbon dioxide and trace amounts of other gases in varying quantities, Methane content was determined via gas chromatography using (GC-8A, Shimadzu Corp., Kyoto, Japan) and measuring 1 ml gas samples collected with airtight syringes from the various reactors. Methane yields were then expressed per gram of volatile solids.

The theoretical estimation of the biomethane potential of the substrates was determined using the Buswells equation, derived using the element compositions of Carbon (C), Hydrogen (H), Nitrogen (N) and Oxygen (O) as shows in Equation (1).

$$\boldsymbol{TBMP\ (ml\ CH4\ /g\ VS)} = \frac{22400\ \left(\frac{C}{2}+\frac{H}{8}-\frac{O}{4}-\frac{3N}{8}\right)}{12C+H+16O+14N} \qquad (1)$$

where: TBMP is the theoretical biomethane potential, the constants C, H, O and N represent the molar fraction of Carbon, Hydrogen, Oxygen and Nitrogen.

Statistical differences in both the empirical and theoretical biomethane potential among substrates were assessed using one-way ANOVA in SPSS (version 22.0), with the significance threshold set at $p < 0.05$.

2.4 Kinetic Modelling

The data for the biomethane potential experiments of the three substrates were fitted to both the first-order and modified Gompertz equation model [22] presented in Equations (2) and (3), respectively using nonlinear regression.

$$\boldsymbol{\beta\ (t) = \beta 0(1 - e^{-kt})} \qquad (2)$$

$$\boldsymbol{\beta\ (t) = \beta 0.exp(-\exp(Rmax\ .e(\lambda - t) + 1)} \qquad (3)$$

where: β (t) = cumulative methane yield at digestion time, t (ml/g VS), β0 = biomethane potential of the substrate (ml/g VS), k = biomethane production rate (day-1), Rmax = maximum methane production rate (mL/g VS), λ = lag phase period, t = time in days

The kinetic parameters in the models were determined through nonlinear regression analysis using MATLAB R2025b software (Mathworks, USA). The model performance was evaluated using the coefficient of determination ($R2$) and the root mean square error (RMSE).

3 Results and Discussion

3.1 Physiochemical Parameters of BSFL Frass



Fig. 1 Macroscopic view of BSFL frass derived from faecal matter (1a), swine manure (1b) and chicken manure (1c).

From Fig. 1a, FM appeared dark brown with a granular texture, relatively uniform particle size, and very few visible BSFL exoskeletons. SM had similar colour to FM but displayed greater variation in particle size and more exoskeleton visibility (Fig. 1b). In contrast to the other frass, CM had an irregular, lumpy texture composed of coarse, chunky material with visible bedding residues with an earthy brown colour (Fig. 1c).

Table 2 represents the results of the average values (mean ± SD) of the physiochemical and elemental analysis of the frass samples derived from faecal matter, chicken and swine manure.

Table 2: Physical and Elemental Characteristics of Frass after BSFL Bioprocessing. The different letters as superscript indicate statistically significant differences (Tukey's test; $p < 0.05$).

	Frass derived from various substrates		
Parameters	FM (n=3)	SM (n=3)	CM (n=3)
pH	8.2 ± 0.0^{b}	8.1 ± 0.0^{b}	9.1 ± 0.0^{a}
Total Solids (%)	88.3 ± 0.2^{b}	87.1 ± 0.1^{c}	94.3 ± 0.3^{a}
Volatile Solids (%)	69.4 ± 1.8^{b}	71.6 ± 0.1^{a}	35.3 ± 3.0^{c}
% VS/TS	78.6	82.3	37.4
Carbon (%)	52.66 ± 0.01^{c}	61.77 ± 0.02^{a}	56.11 ± 0.01^{b}
Nitrogen (%)	5.38 ± 0.01^{a}	3.98 ± 0.03^{b}	3.08 ± 0.04^{c}
C/N Ratio	9.79 ± 0.01^{c}	15.54 ± 0.01^{b}	18.24 ± 0.02^{a}
Oxygen (%)	37.65 ± 0.01^{b}	44.07 ± 0.02^{a}	33.88 ± 0.01^{c}
Hydrogen (%)	4.08 ± 0.01^{c}	7.10 ± 0.01^{a}	5.11 ± 0.01^{b}
Sulphur (%)	0.018 ± 0.001^{a}	0.004 ± 0.010^{c}	0.10 ± 0.01^{a}

Though the pH values of frass residues for all the substrates ranged between 8.1 - 9.1, CM was significantly more alkaline than SM and FM. The alkaline nature of the frass in this study was consistent with previous studies indicating alkalinity in frass produced after BSFL is reared on different feeds [5, 24, 25]. The optimal pH environment for BSF production spans slightly acidic to basic conditions of 6.0–10.0 [26]. Although the alkaline pH values observed are suitable for BSFL production, such conditions may influence the initial buffering capacity of anaerobic digesters.

The Total Solids (TS) ranged from 87.1% - 94.3% and different significantly among the frass, with chicken manure frass being the driest. The Volatile Solids (VS) content varied from 35.3% - 71.6%, showing significant variability in degradable organic matter. Moisture content regulation of the rearing substrate is especially critical for ensuring higher larval survival rates, but excessive moisture complicates the separation of the frass from the biomass during the harvesting stage [27]. The frass was harvested in stages after a considerable portion of the larva had advanced to the prepupal stage, likely contributing to higher TS values due to sustained aeration. Similarly, variations in TS among frass has also been attributed to differences in rearing methods, harvesting practices, and post-processing [20]. High total solids coupled with reduced volatile solids in chicken manure frass indicate limited readily biodegradable organic matter, consistent with its lower methane yields.

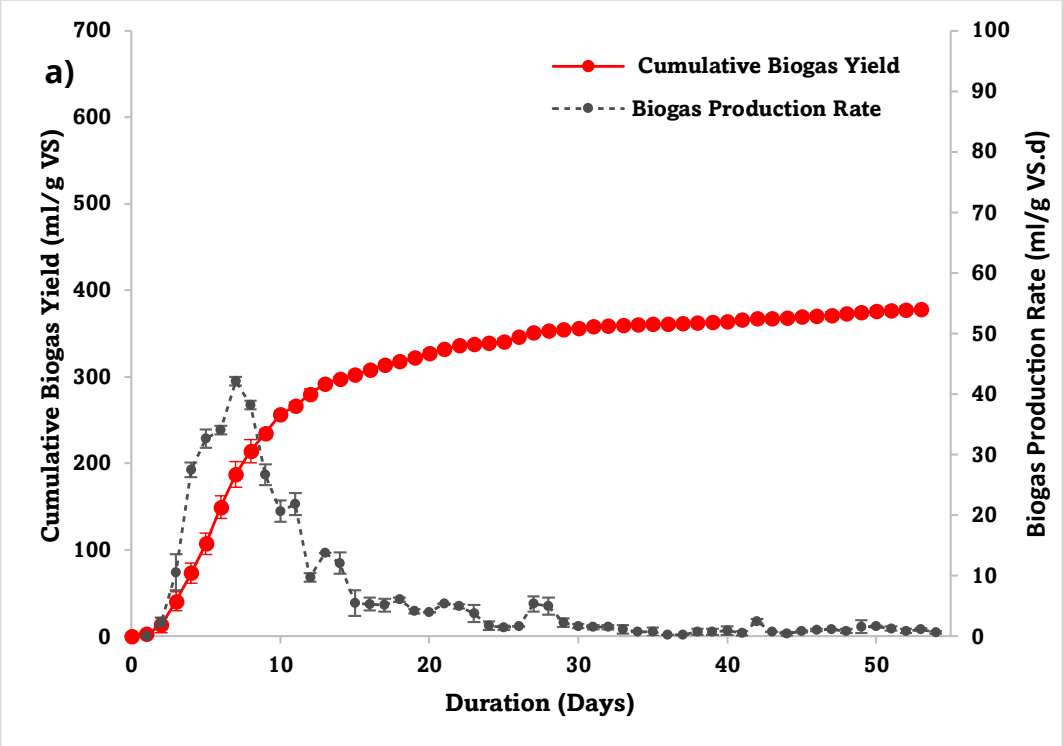
Comparison to chicken and swine manure derived frass values reported in the literature, Liu et al. [28] reported lower mean TS values of 37.6% ± 0.24 but higher mean VS values at 50.96% ± 1.28 for CM while overall lower TS and VS values at 41.0% ±0.18 and 57.96% ± 0.49 respectively for SM.

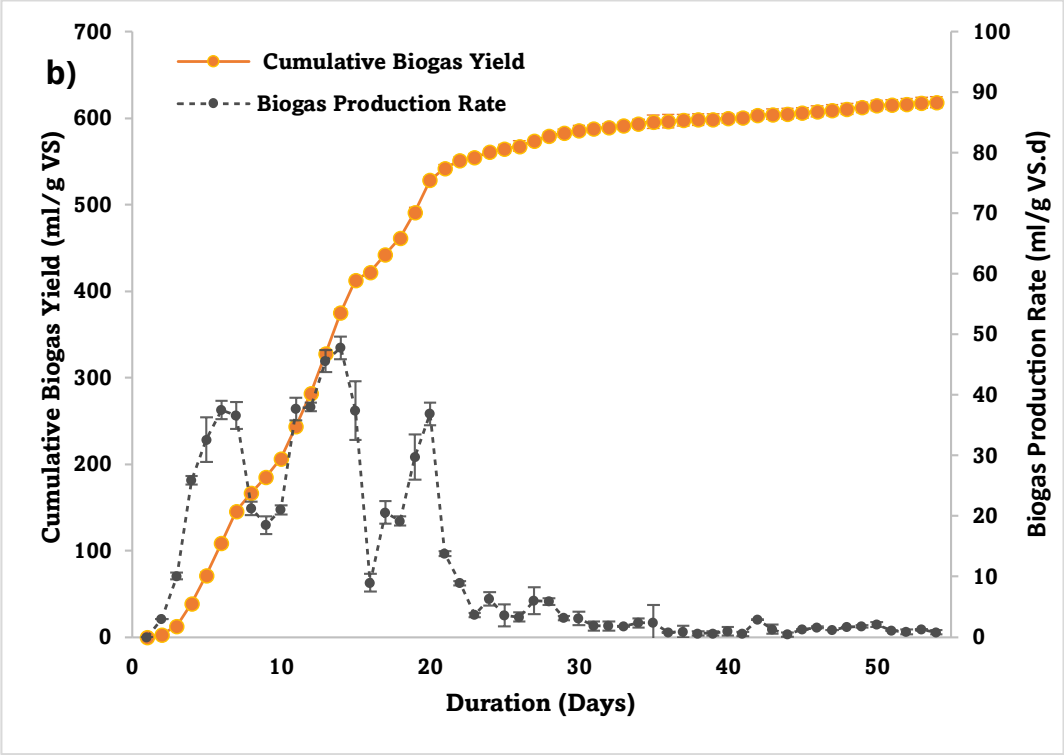
Elemental analysis revealed that all substrates contained high concentrations of carbon and oxygen relative to other elements. The carbon-to-nitrogen (C/N) ratio was highest in CM, followed by SM and FM respectively. A high C/N ratio promotes carbon utilization, whereas a low ratio favours nitrogen accumulation, which can lead to ammonia formation resulting in inhibition of anaerobic digestion [29]. All values obtained in this study were below the optimal C/N range of 20–30 reported in the literature for stable and efficient anaerobic digestion [30]. However, the C/N ratios for CM and SM in this study align with the general average reported by Gärttling and Schulz [20], who reported mean values around 15.73 ± 0.36 for frass for a diverse range of residues. Similarly, Liu et al. [28] reported C/N ratios in the range of 15–19 for CM and SM frass, findings that agree with those reported in this study.

This study contributes to the limited body of research on frass derived from faecal matter, swine manure, and chicken manure. Given the variability observed and the growing interest in these residues, further investigation into frass composition remains necessary.

3.2 Biogas and Biomethane Potential of BSFL Frass

From Fig. 2, it is apparent that biogas production commenced on the first day for all substrates, with the highest total biogas yield relative to the volatile solids (VS) observed in SM (619 ± 6.5 ml/g VS) followed by FM (378 ± 4.7 ml/g VS) and CM frass (185 ± 2.2 ml/g VS). The peak production rate for FM, SM and CM was 42.1, 47.8 and 13.5 mL/g VS.d occurring at 6, 13 and 4 days, respectively, after start of digestion. By day 38, 90% of the total biogas potential for all the substrates had been achieved with production declining thereafter. At the end of the experiment on the 55th day, the daily biogas production had declined to less than 1% of the cumulative production for all substrates.





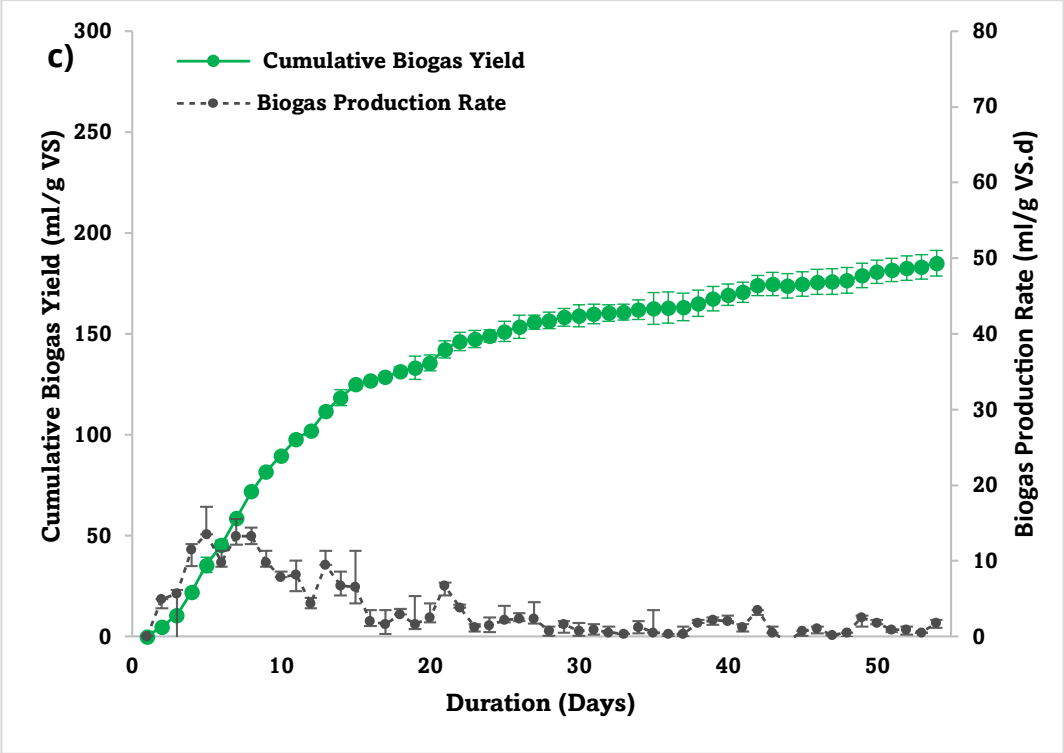


Fig. 2 Daily and cumulative biogas production of frass obtained from BSFL reared on a) faecal manure b) Swine manure and c) chicken manure

As shown in Table 3, experimental biomethane potential followed a similar trend, with SM producing the highest value (347 ± 3.6 ml/g VS) followed by FM (205 ± 2.6 ml/g VS) and CM the lowest (100 ± 6.9 ml/g VS). Statistical analysis showed significant differences ($p < 0.05$) in both biogas and biomethane production potential

among the three substrates. These variations can be attributed to differences in frass composition, which is strongly determined by the BSFL rearing substrate [20] that consequently influence the biomethane potential [31].

Table 3 presents the experimental biogas potential, experimental and theoretical biomethane potential, biomethane concentration, and biodegradability index of frass derived from faecal matter, swine manure, and chicken manure.

Table 3: Biogas and Biomethane Potential (Experimental and Theoretical)

Parameters	Frass derived from faecal matter, swine and chicken manure		
	FM (=3)	SM (n=3)	CM (n=3)
Biogas Potential (ml/g VS)	378 ± 4.7	619 ± 6.5	185 ± 2.2
Experimental Biomethane Potential (ml/g VS)	205 ± 2.6	347 ± 3.6	99.9 ± 6.9
Theoretical Biomethane Potential (ml/g VS)	442 ± 0.04	510 ± 0.01	539 ± 0.05
Biomethane Concentration (%)	54.2	56.02	54
Biodegradability Index (%)	46.4	68.0	18.5

Based on the characterisation results (Table 2), SM contained the highest organic matter and therefore exhibited the greatest biodegradation potential, whereas BSFL frass derived from chicken manure (CM) frass had the lowest organic matter content. The poor biogas yield of BSFL frass derived from CM (Fig. 2c) can further be attributed to several factors. Its structural complexity, with visible bedding residues that are typically associated to be high in lignocellulose content has been shown to limit its biodegradability [32]. Frass from chicken manure also had elevated pH values beyond the recommended range of 6.7–7.5 for optimal biomethane production [33], as well as the highest sulphur concentration among the substrates. Sulphur levels are of critical importance in AD systems, as sulphate reduction during digestion generates hydrogen sulphide, a toxic compound that increases process toxicity and inhibits biomethane production [34].

Relative to experimental results, TBMP was 1.5 times higher for SM, 5.4 times higher for CM, and 2.2 times higher for FM (Table 3). Interestingly, however, while experimental biomethane potential (BMP) mirrored the biogas yield trend, theoretical biomethane potential (TBMP) displayed a different trend entirely, particularly for CM with the substrate having the highest values (Table 3). Overall, the consistently higher theoretical values align with previous studies with the values being based on theoretical stoichiometric equations assuming that all organic constituents are fully degraded and overlooking process inhibition, which is often not the case for complex substrates [35].

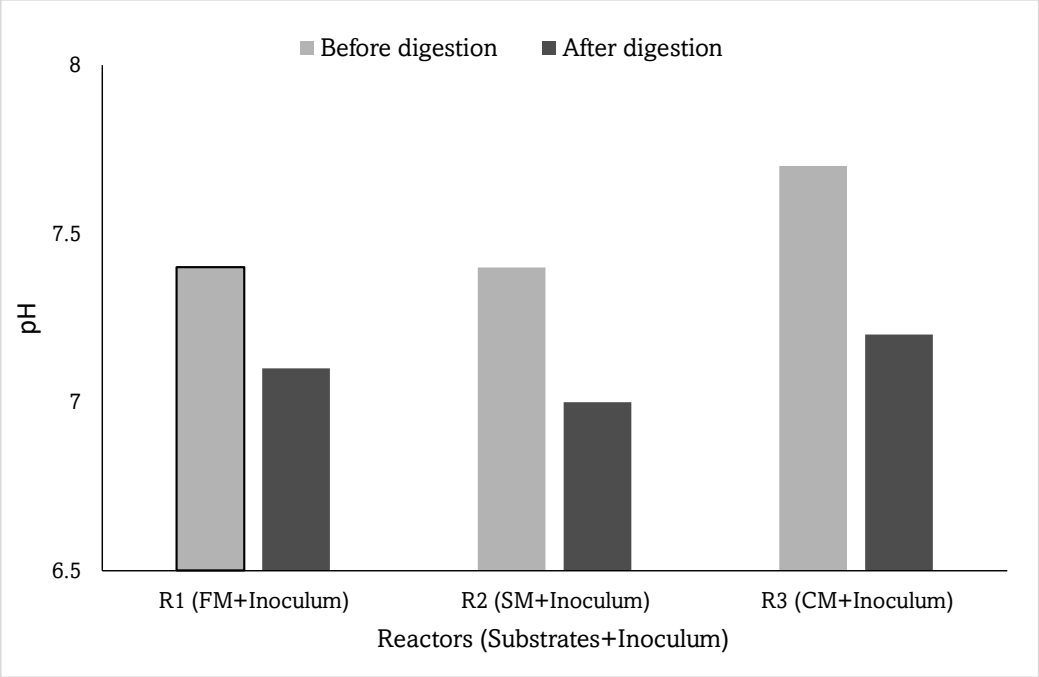
Similarly, Labatut et al. [36] demonstrated that the accuracy of biomethane potential estimates using Buswell's equation decreases as substrate biodegradability declines. Among the tested substrates, BSFL frass derived from swine manure (SM) exhibited the highest biodegradability at 68%, whereas CM frass showed the lowest at 18.5% (Table 3). The large discrepancy between CM frass experimental and theoretical BMP values is likely due to the very low biodegradability of the substrate.

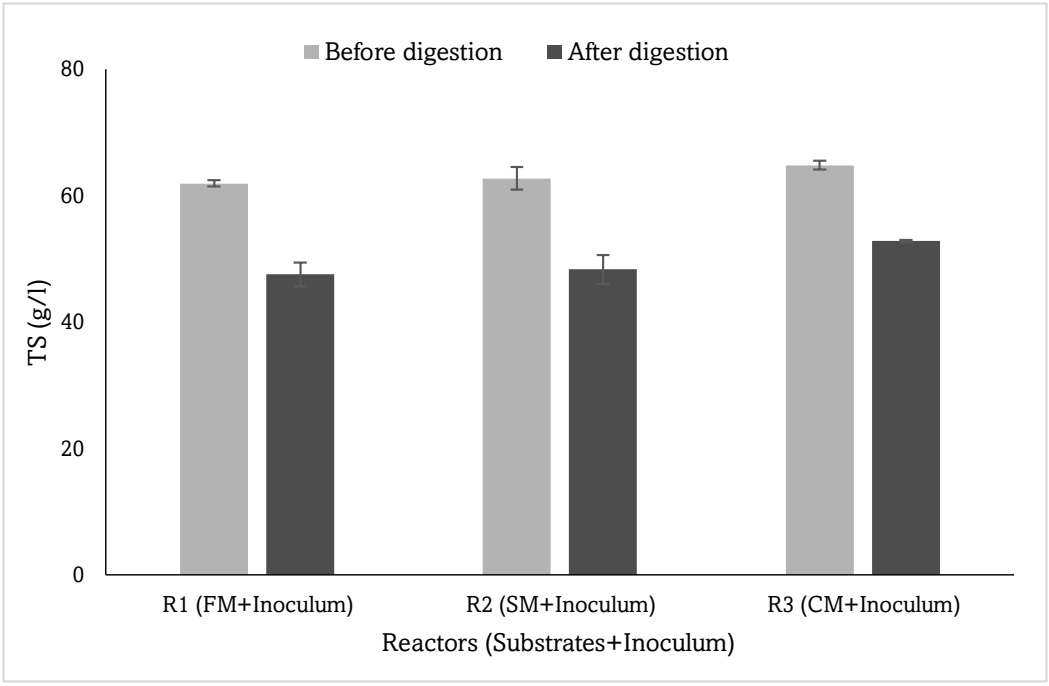
Although research on insect residues as substrates in BMP tests remains limited, several studies have investigated the BMP of BSFL frass. Of these, only two studies by Lalander et al. [6] for FM and Dong et al. [13]

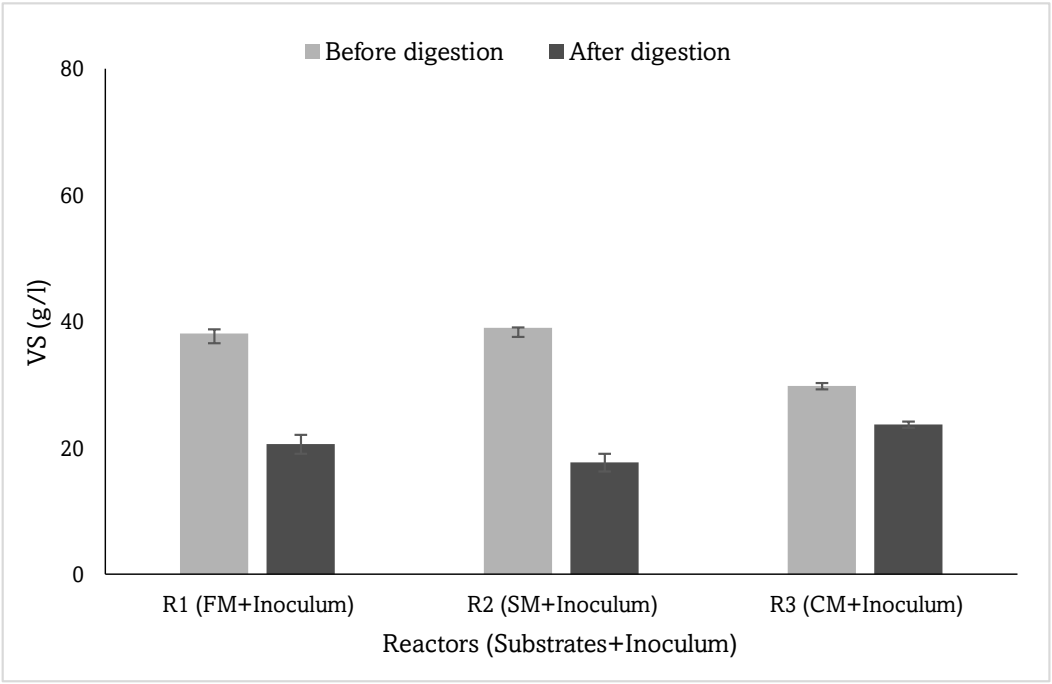
for SM allow for direct comparison with the results of this experiment due to the similarity of the substrates. In comparison with these studies, the findings from our study established 15% and 70% higher BMP values for FM and SM frass, respectively. However, the biomethane concentrations in the biogas produced were reported to range from 47% to 64%, this being generally within the same ranges reported in our study.

When compared more broadly with studies using frass from a range of different BSFL rearing substrates, the reported mean BMP values include 165 mL/g VS for food industry residue frass [14], 201–287 mL/g VS for frass from corn silage, brewer's spent grain, bran, and aquatic plants [15], 207.9 mL/g VS for carrot–beetroot marc frass [16], and 264 mL/g VS for agricultural side-stream frass [19]. The highest BMP value reported in these studies (502 mL/g VS) was observed for frass derived from mixed food waste [17].

Fig. 3 illustrates the removal efficiencies of TS, VS, and COD. VS and COD indicate the organic matter content and can be used to assess treatment efficiency and biodegradation extent in the AD process [37].




Before digestion
After digestion
80
60
40
20
0
TS (g/l)
R1 (FM+Inoculum)
R2 (SM+Inoculum)
R3 (CM+Inoculum)
Reactors (Substrates+Inoculum)


Before digestion
After digestion
80
60
40
20
0
VS (g/l)
R1 (FM+Inoculum)
R2 (SM+Inoculum)
R3 (CM+Inoculum)
Reactors (Substrates+Inoculum)

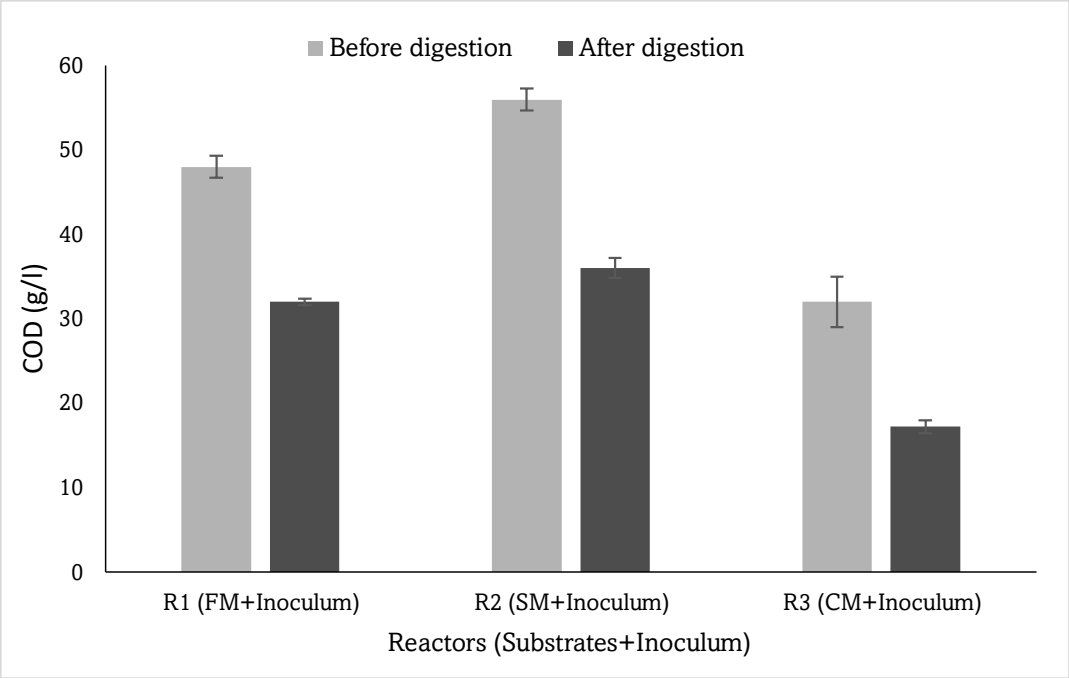


Fig. 3 Changes in the pH, TS, VS and COD in each reactor

As methane production is directly linked to VS degradation, higher VS reduction in the AD process indicates higher extent of degradation and biogas yield. In view of this, the trend in the reduction of the TS, VS and COD were aligned with those of the biogas production from the frass derived from the three substrates. The SM achieved the highest removal rates, with values of 23% for TS, 55% for VS, and 36% for COD. This was followed by the reactor with FM, which recorded a reduction of 23%, 45.9%, and 33% for TS, VS, and COD, respectively. The CM reactor reported the lowest performance, with removal efficiencies of 18% for TS, 20% for VS and 15% for COD. The initial pH values of all reactors decreased before stabilizing within the range of 7.4–7.7, indicating progression through acidogenesis and the associated production of volatile fatty acids (VFAs).

3.3 Modelling Biomethane Production Kinetics

The kinetic parameters for biomethane production, using the first order model and modified Gompertz equation are presented in Table 4.

Table 4: Kinetic Parameters for the Frass using the first-order model and modified Gompertz model.

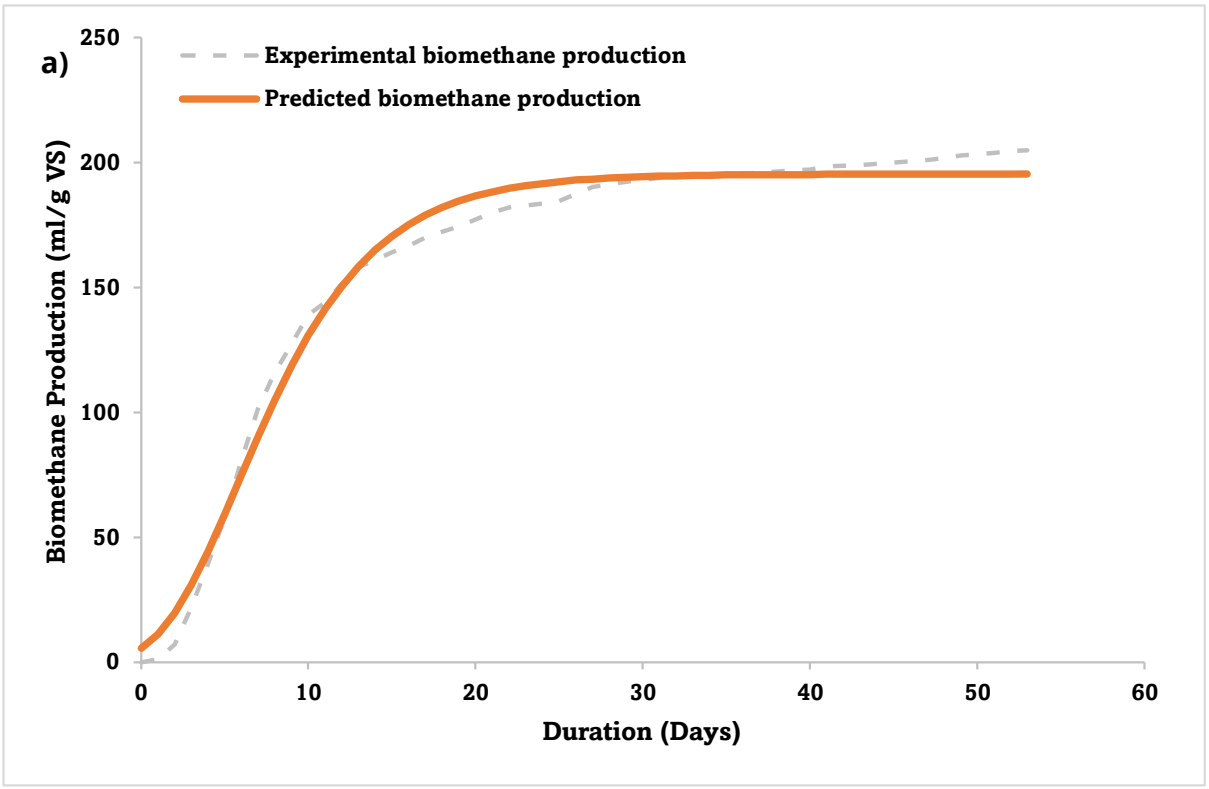
Parameter		**BSFL Frass Substrates**		
	Units	**FM**	**SM**	**CM**
Lag phase (λ)	days	1.221	2.949	-0.582
Maximum production rate (R_{max})	ml/g VS	15.65	21.09	4.636
R^2		0.9871	0.9975	0.9831
RMSE		6.656	5.764	4.636
Predicted biomethane	ml/g VS	195	341	93
Experimental biomethane	ml/g VS	205	347	100
Variance	%	4.7	1.7	7

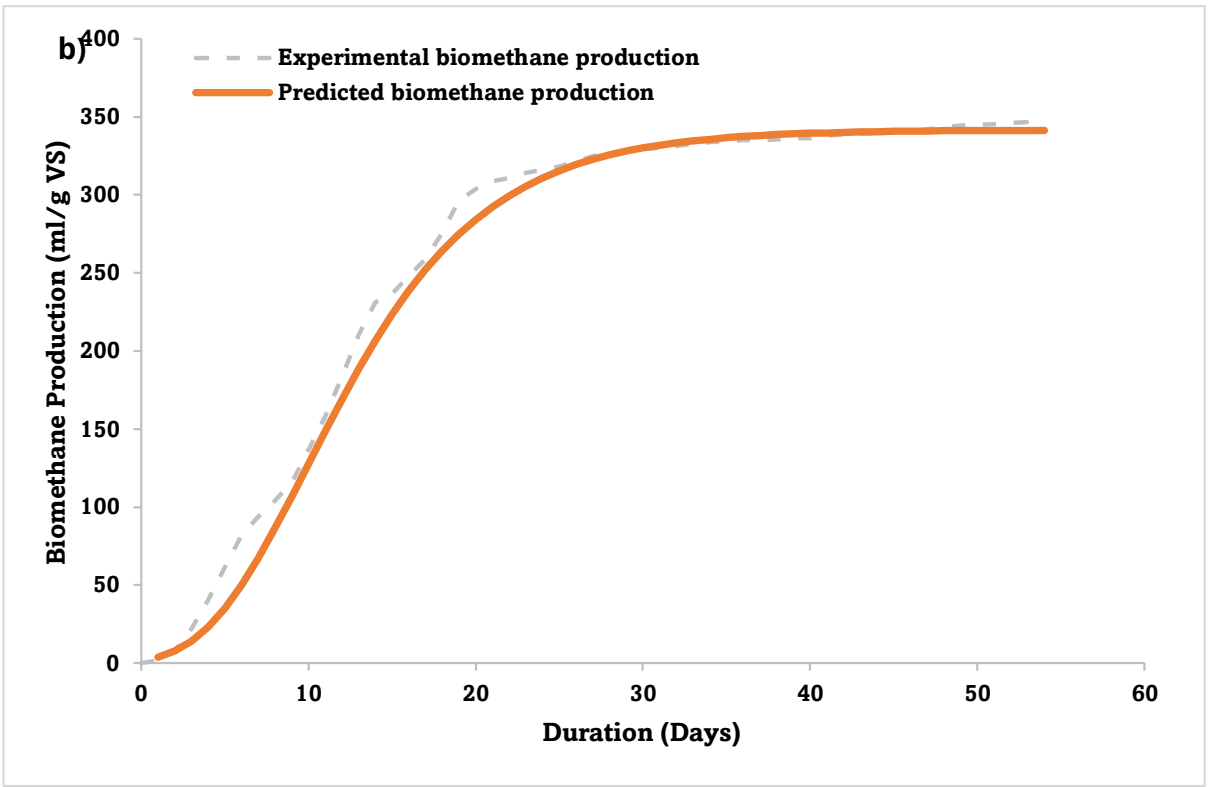
Parameter		BSFL Frass Substrates		
	Units	FM	SM	CM
First Order Hydrolysis Constant (k)	1/day	0.097	-	0.072
R^2		0.9762	-	0.9896
RMSE		8.94	-	2.652
Predicted biomethane	ml/g VS	204	-	97
Experimental biomethane	ml/g VS	203		100
Variance in biomethane Potential	%	0.5	-	3

For all BSFL frass substrates except that derived from swine manure, both kinetic models showed a good fit with the experimental biomethane values. For FM and SM, however, the modified Gompertz model provided better accuracy, with higher $R2$ values of 0.9871 and 0.9975, respectively, confirming its reliability in predicting biomethane potential for these substrates. In contrast, although the CM substrate provided a relatively high $R2$ value of 0.9831, the modified Gompertz model estimated a negative lag phase (λ), suggesting it may not be suitable for describing biomethane production in this case. Instead, the first-order kinetic model offered a better fit for CM, with positive kinetic parameters and a slightly higher $R2$ value of 0.9896 compared to the Gompertz model.

Based on the kinetic parameters obtained from the modified Gompertz equation model, SM exhibited the longest lag phase (λ = 2.9 days) but the highest maximum methane production rate (Rmax = 21.09 ml CH_4 g^{-1} VS d^{-1}) among all substrates. This indicates the presence of a high portion of readily biodegradable organic matter and, consequently, a high biomethane potential. However, its lag phase suggests the need to prioritize start-up control and process stability in the design and operation of anaerobic digesters treating this substrate. In contrast, FM showed a shorter lag phase (λ = 1.2 days) and a moderate maximum methane production rate (Rmax = 15.65 ml CH_4 g^{-1} VS d^{-1}), which is indicative of rapid microbial acclimation and a more stable and steady anaerobic digestion of the substrate.

For CM, the first-order kinetic model provided a better fit than the modified Gompertz model. The hydrolysis constant (k = 0.072 d−1) indicates a relatively slow hydrolysis rate, consistent with the stabilized nature of the frass and its low biodegradable content. Consequently, hydrolysis emerged as the dominant rate limiting step during anaerobic digestion of this substrate.


a)
Experimental biomethane production
Predicted biomethane production
Biomethane Production (ml/g VS)
250
200
150
100
50
0
0
10
20
30
40
50
60
Duration (Days)


b)
Experimental biomethane production
Predicted biomethane production
Biomethane Production (ml/g VS)
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
Duration (Days)

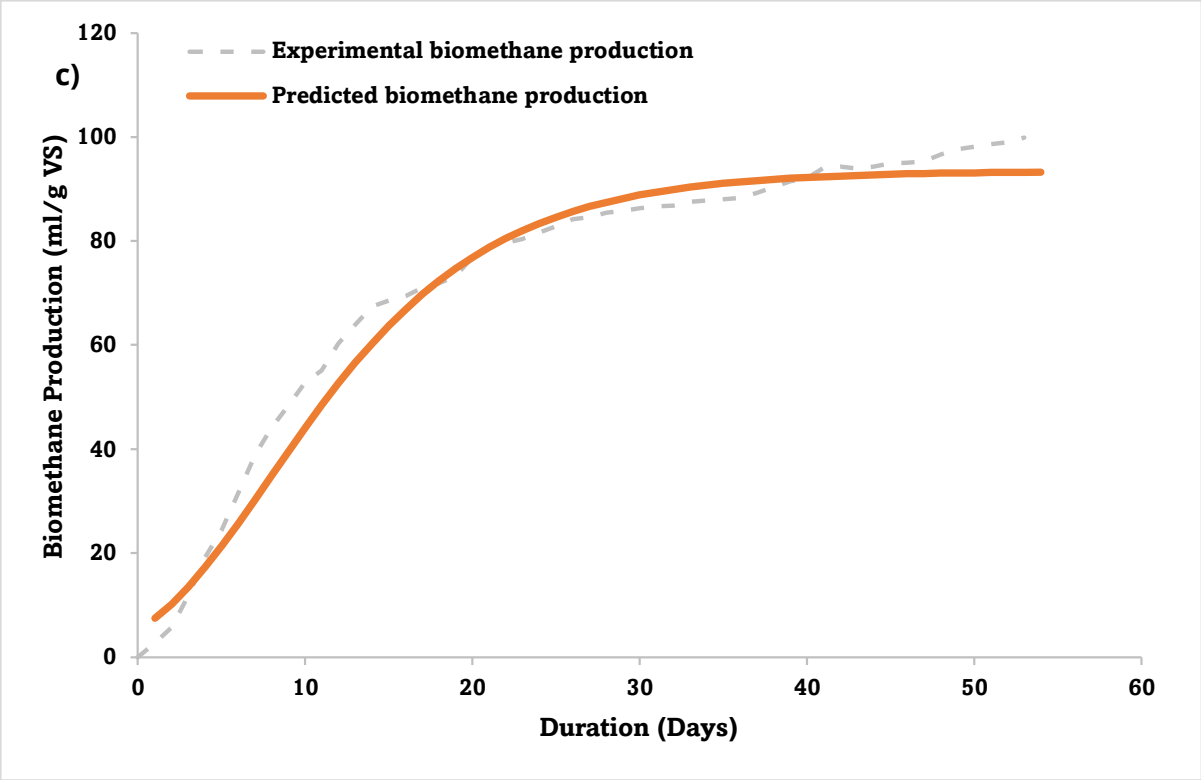


Fig. 4 The predicted and experimental biomethane production from BSFL reared using three substrates a) FM and b) SM using modified Gompertz equation respectively c) CM using first order model

It is noteworthy that both kinetic models predicted biomethane potential values lower than those obtained experimentally. To the best of the authors' knowledge, only one study has applied both kinetic models to fit experimental BMP values for BSFL frass. Wedwitschka et al. [15] reported the first order model as an excellent fit for frass derived from different rearing substrates, with hydrolysis constants (k) ranging between 0.13 and 0.25 d^{-1}. The differences in model performance and kinetic parameter values could be attributed to variations in the initial rearing substrates of the BSFL.

4 Conclusions

The results demonstrated that frass derived from faecal matter and swine manure are a viable feedstock for anaerobic digestion, with swine manure frass exhibiting superior performance, achieving the highest biomethane potential and organic matter removal efficiencies. Given the widespread use of these waste streams as rearing substrates for the BSFL and their local availability, these substrates represent an abundant and practical source of feedstock for biodigesters, while simultaneously contributing to waste management efforts. In addition, biomethane generated from the anaerobic digestion of frass could be utilized for temperature regulation, rearing substrate management, and BSF larva handling and processing within BSFL farms, thereby creating a synergistic integration between BSFL rearing and anaerobic waste digestion.

Anaerobic digestion of BSFL frass not only enables predictable methane production but also enhances biosafety by stabilizing the substrate and reducing pathogen risks, thereby demonstrating its potential as an effective waste-to-energy strategy. Nevertheless, further research is required to determine the extent of specific pathogen inactivation in these substrates, which remains a major limitation for the direct application of fresh frass

to soil. Moreover, as frass composition is highly dependent on the rearing substrate and considering the limited number of studies, additional research is recommended on the co-digestion of frass derived from locally available materials with other suitable substrates as well as understanding the required reactor types and operational digester conditions. The findings of these studies would enhance process stability, improve the nutrient profile of the digestate, and further increase biogas yield.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Author Contributions

All authors contributed to the study conception and design, reading and approving the manuscript. Material preparation, data collection and analysis were performed by Aliyare Mohamed.

Data Availability

All relevant data are available from the corresponding author upon request.

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