Original Research Article

COMPARATIVE EVALUATION OF METHANE YIELD FROM CONTINUOUS AND BATCH FERMENTATIVE PROCESSING OF SELECTED AGROWASTE

ABSTRACT

This study investigated the influence of different agrowaste compositions on methane yield in batch and continuous operational modes, highlighting the significance of substrate characteristics in determining the efficiency of methane production. It comparatively assessed the methane yield derived from continuous and batch fermentative processing of the following agrowaste; Cassava peels (A), Maize husks (B), Pig Slurry (C), and composite (D) that represents the co-digestion of the aforementioned A, B & C. Eight digesters were used in all, two anaerobic systems for each substrate, [ie, one operating in a batch mode (1) and the other in a continuous mode (2)]. The proximate properties of the substrates were determined and gas production rates were monitored over the experimental period of 45 days. Gas analysis of the generated gas revealed mainly Methane and CO_2, with concomitant organic compounds like; Ethanol, Methanol, Acetic Acid, Acetone, etc. Minute quantities of Phenol and Lactic Acid were mainly found in the gas generated from Cassava peels. The average percentage value of Co-digested substrates (D) yielded higher gas volume of 78.263±4.54, followed by C (74.263±4.65), B (70.240±4.38), and A (56.090±3.50). The results also revealed that the continuous fermentative process demonstrated a more stable and consistent methane production rate compared to the batch system, attributed to its steady-state operational mode and continuous substrate feed input. However, modeled graphical results showed that batch fermentation system produced higher gas yield (for all the substrates) between days 29-39 before it recorded a sharp decline curve, attributed to the reduction in substrate availability.

KEYWORDS; Anaerobic Digestion (AD), Agrowaste, Co-Digestion,Methane Yield, Batch, Continuous.

1. INTRODUCTION

The world is facing two vital challenges, energy crisis and environmental pollution. Energy is a key component for all sectors of a modern economy and plays an elementary role in improving the quality of life [1]. Currently, approximately 75-80% of world energy supplies rely on rapidly exhausting nonrenewable fossil fuels. More over-dependence on these fossil fuels is domiciled in Africa [2]. At the current consumption rate, crude oil reserves, natural gas, and liquid fuels were estimated to last for around 60 to 120 years, [3]. What will be the faith of this over-dependent energy world if the aforementioned assumption comes to fruition?

Growing global energy needs and the release of environmental pollutants from fossil fuels have increased the quest for clean and renewable fuels as suitable alternative sources of energy. If more research and attention are given to these clean fuels, this century would see a remarkable switchover from fossil-based energy to a bioenergy-based economy, with agriculture and bio-substrates as the main feedstock.

The need for biomethane production also emanates from the fact that some of the feedstocks (e.g., agro and animal waste) end up polluting the immediate environment, and/or reducing environmental aesthetics. Channeling such feedstock into biogas production is a win-win case, as pollution will be abated and the beauty of our environment maintained, with subsequent production of a clean energy source.

Anaerobic digestion is a biological treatment process that recovers valuable products, energy, and nutrients, from organic waste streams in useable forms. Energy is recovered in the form of biogas, typically a mixture of methane (CH_4), and carbon dioxide (CO_2), with few other gases [4]. Small-scale anaerobic digestion in rural developing countries can positively impact the quality of life of its communities or an individual family's quality of life. Anaerobic digestion addresses issues as; energy production in the form of methane, which can be used as a cooking fuel, unsustainable deforestation due to the collection of wood for use as a biomass cooking fuel, mitigation of methane and carbon black emissions into the atmosphere, treatment of animal and/or human waste, reduced amount of biosolids to be disposed, produces nutrient-rich digestate that could be used as a fertilizer [5].

Biomethane simply means methane obtained from organic sources, which is chemically the same as conventional methane. Biomethanation of fermentable organic materials, such as cattle dung, kitchen waste, poultry droppings, agricultural wastes, etc, is one of the major processes of anaerobic digestion in the presence of methanogenic bacteria. The process occurs inside anaerobic biodigesters. The digested slurry from biogas plants is available for its utilization as bio/organic manure in agriculture, horticulture, and pisciculture as a substitute/supplement to chemical fertilizers [6]. In other words, biogas (anaerobic digestion) plants provide a three-in-one solution for gaseous fuel generation, organic manure production, and wet biomass management [7].

Biogas could also be used in electricity generation, by burning it as a fuel in a gas turbine or steam generator [1]. Comparatively, methane produces less carbon dioxide than other hydrocarbon fuels, for each unit of heat released. In many cities, methane is piped into homes for domestic heating and cooking. In this context, it is usually known as natural gas, which is considered to have an energy content of 39 megajoules per cubic meter [8]. Note that liquefied natural gas (LNG) is predominantly methane (CH_4) converted into liquid form for ease of storage or transport.

2. MATERIALS AND METHODS

2.1 Sample Collection

Selected feedstocks (cassava peels, corn stalk, and pig slurry) were sourced from the University of Nigeria Nsukka (UNN) agricultural science farm. Also, cow rumen contents were obtained from the university market abattoir. Cassava peels and corn stalks were collected using sacks, pig slurry, and cow rumen contents were collected by using surface sterilized air-tight buckets. All were transported to the National Centre for Energy Research and Development Centre laboratory, UNN, for further Processing, analyses, and usage.

2.2 Sample Treatment

Plant substrates were subjected to physical pretreatment by shredding into small sizes of about 2mm, to increase the surface area. For codigestion, the shredded samples were mixed with the animal slurry, and made to have a good slurry composition. This was achieved by addition, with mixing of tap water. Cow rumen (0.5kg) was added for every 10kg of the treated substrate before loading, to optimize methanogens involved in methane production, [9].

2.3 Parameter Measurement

The substrate compositions were determined with effect on gas production. Proximate composition was determined using the standard methods of the Association of Official Agricultural Chemists [10]. pH was measured with a digital pH meter (Metrohm, USA). Temperature was measured and maintained at a mesophilic level (30-40^{0}C), in order to maximize microbial activities. There were intervals sampling of digesters content, to ascertain the levels of these parameters. Adequate hydraulic retention time (HRT) was maintained (45 days), to ascertain the level of methane generated.

2.4 Design of Used Digesters

The digesters used in this research were modified method of Ugwu *et al*. [11]. Digesters were sealed, with a rubber cork, to create an anaerobic environment. A plastic tube was placed through the rubber cork and submerged in the digestate. This tube served as a minor pressure outlet for biogas accumulation between sampling periods; this is referred to as the ‘pressure tube’. The pressure tube was sealed to prevent ambient air from entering the digester when the headspace of the digester was evacuated. Despite the seal, the pressure tube still acted as a form of pressure relief by allowing for some displacement of the digestate in the flask (in which the increasing gaseous pressure would push some of the liquid in the digester into the pressure tube). This in turn will act as a signal of the presence of pressure in the flask.

A flexible plastic tube was attached to the rubber cork via a connector. This was used to collect biogas from the digester (referred to as the ‘biogas line’), into a reservoir, for onward processing. The digesters were filled at 2/3 of their capacity. This was to allow room for the gas and avoid too much pressure build-up.

2.5 Sample Feeding

Prepared 20L of each slurry was carefully fed into the 30L digester capacity (for all substrates), to give room for gas and pressure accumulation. Daily stirring (of 5 minutes) was achieved by a mechanical agitator, after taking the necessary measurements for each day.

2.5 Gas Volume Measurement

Methane yield during digestion was determined by an Aero-qual (500 series) gas analyzer (Model No.: DO-5509). This was done according to the method of Wagentrist*et al.*[12], by inserting the probe for gas detection in the biogas digester nozzle, then unlocked to take records. Readings for both batch and continuous fermentations were subsequently subjected to statistical analysis, to determine the differences.

2.6 Gas Sampling and Methane Separation

This was done according to the method of Wagentrist*et al.*[12]. A representative sample of individually generated biogas was carefully collected from the storage system, to avoid contamination or alteration of the gas composition. The gas samples were injected into a gas chromatograph, and the individual gases were separated as they passed through a column. The detector at the end of the column identified each gas and measured its concentration.

3. RESULTS AND DISCUSSION

3.1 The results of proximate characteristics of the substrates are presented in Table 1.

For ash content, the highest value of 3.50±0.22% suggests that cassava peels have higher concentrations of inorganic minerals and non-combustible material compared to others. Moisture content is the proportion of water present in a material, and it is an important parameter in various applications, including bioenergy production [13]. Crude fiber is an important indicator of the plant material's structural components that contribute to dietary fiber. The highest value (3.98±0.25%) suggests that B2 has a higher concentration of structural components such as cellulose, hemicellulose, and lignin, compared to others (lowest at C1). Crude fat, also known as crude lipid, refers to the total fat content in a sample. The highest value (3.40%±0.21) suggests that C2 can provide more energy than A1 and A2 with a value of 1.20±0.07.

Methane is primarily produced through methanogenic archaea in the final stages of anaerobic digestion. The availability of substrates, including those derived from protein breakdown, can influence the activity of methanogens and the pathways through which methane is produced. Pig slurry has a higher protein content of 4.51±0.28, as against the least value of 1.52±0.9, recorded for cassava peels. Adequate carbon availability is essential for sustaining the activity of methanogens. According to Molino *et al*. [14], substrates with higher carbon content generally provide more carbonaceous compounds, serving as favorable substrates for methane generation. In this regard, corn husks recorded the highest level of 6.38±0.28, against pig slurry (3.91±0.17).

Table 1. Proximate Results of Sample Contents at 24hrs of setup

PARAMETERS	**A1**	**A2**	**B1**	**B2**	**C1**	**C2**	**D1**	**D2**
Ash	2.80 ±0.17	2.79 ±0.17	3.50 ±0.22	3.50 ±0.22	1.89 ±0.12	1.89 ±0.12	2.77 ±0.17	2.79 ±0.17
Moisture	84.39 ±5.27	84.56 ±5.28	80.36 ±5.02	80.24 ±5.01	82.00 ±5.12	81.94 ±5.12	82.35 ±5.14	82.70 ±5.16
Crude Fibre	3.49 ±0.22	3.47 ±0.22	3.89 ±0.24	3.98 ±0.25	1.40 ±0.09	1.39 ±0.09	2.48 ±0.15	2.48 ±0.15
Crude Fat	1.20 ±0.07	1.20 ±0.07	2.00 ±0.12	2.05 ±0.13	3.39 ±0.21	3.40 ±0.21	2.19 ±0.14	2.20 ±0.14
Protein	1.53 ±0.10	1.52 ±0.9	3.06 ±0.19	3.09 ±0.19	4.51 ±0.28	4.51 ±0.28	3.01 ±0.19	3.03 ±0.19
Carbon	4.79 ±0.21	4.69 ±0.20	6.38 ±0.22	6.38 ±0.28	3.99 ±0.14	3.91 ±0.17	4.79 ±0.30	4.79 ±0.21

Values are means of duplicate determinations with standard deviations (Mean±SD).
Note that the values of ash, Moisture, Fibre, Fat, Protein, and Carbon are in percentage (%).

A = Cassava Peel, B = Maize husks, C = Pig Slurry, D = Equal combination of A, B, & C1 = Batch Process, 2 = Continuous Process.

3.2 Methane and CO_2 Generated

The variation between methane (CH4) and carbon dioxide (CO_2) production during anaerobic digestion is a key indicator of the efficiency and stability of the process. Table 2 shows that an increase in one is almost proportion to a decrease in the other. Methane values range from 54.187±3.38 (for A1) to 83.946±5.24 (for D2), indicating variability in the total methane production among the substrates.
Analysis of the percentage contents present in the generated biogas in Table 3 and Fig. 2, proved that continuous processes generated higher methane yield than batch, for all the substrates. This is in line with the work of Yusuf &Ify[15], they attributed it to a steady flow of substrate into the digester. This consistent supply of organic material ensures that the microbial community remains active and can maintain a fairly continuous level of biogas production, resulting in higher overall gas yields compared to intermittent batch feeding [16]. Research works of Li *et al*. [13], Wagentrist, *et al*. [12], and Ofoefule*et al*. [17] also validated the aforementioned claim.
Codigestion, the process of digesting multiple substrates together, often results in a higher gas yield compared to monodigestion, where a single substrate is used [18]. Table 2 proved that substrate D, a composite of A, B, and C, co-digested together yielded the highest gas amongst others. However, D2 which is the continuous process of substrate D recorded the overall highest methane yield of 83.946 (in percentage). From the above, one can conclude that continuous fermentation and co-digestion are necessary to maximize biogas yield in anaerobic fermentation. According to Karakashev*et al.*[19], the combination of different substrates in codigestion can result in synergistic degradation, where certain compounds in one substrate can facilitate the breakdown of complex components in another. This synergistic effect enhances the overall degradation efficiency, leading to increased gas production.

Table 2. Percentage Mathane and CO_2 Generated

CONTENTS	A1	A2	B1	B2	C1	C2	D1	D2
Methane	54.187 ±3.38	57.992 ±3.62	69.373 ±4.31	71.107 ±4.44	69.057 ±4.33	79.468 ±4.96	72.580 ±4.53	83.946 ±5.24
CO_2	38.742 ±1.69	36.636 ±1.60	25.743 ±0.93	25.383 ±1.11	26.588 ±0.90	16.426 ±0.72	23.120 ±1.44	13.847 ±0.60

Values are means of duplicate determinations with standard deviations (Mean±SD).
CO_2 = Carbon dioxide. A = Cassava Peel, B = Maize husks, C = Pig Slurry, D = Equal combination of A, B, & C, 1 = Batch Process, 2 = Continuous Process.

3.3 Other Organic Components in the Generated Biogas

Note that Ethanol and methanol are typically not significant components of biogas produced through anaerobic digestion. While they are not common in biogas, it's important to note that the specific composition of biogas can vary depending on the feedstock and process conditions [20]. Trace amounts of other compounds like acetic acid, acetone, and acetonitrite, were found present (Table 3). Ward *et al*. [21] opined that these compounds are generally not significant components of biogas and do not contribute substantially to its energy content.

Also, negligible values of phenol were recorded for substrate A. Ahring *et al*. [22] noted that cassava contains natural phenolic compounds, including hydroxycinnamic acids, flavonoids, and tannins, which are part of the plant's defense mechanisms against pathogens and pests. These phenolic compounds can be released from the cassava biomass during the breakdown process in the anaerobic digester. They were also of the opinion that the complex structure of these phenolic compounds in cassava can make it resistant to complete degradation during anaerobic digestion.

Table 3. Other Organic Compounds Present in the Generated Biogas

CONTENTS	**A1**	**A2**	**B1**	**B2**	**C1**	**C2**	**D1**	**D2**
Ethanol	2.311 ±0.14	1.840 ±0.11	3.414 ±0.15	2.560 ±0.18	2.409 ±0.21	3.071 ±0.19	2.957 ±0.15	1.182 ±0.07
Methanol	3.246 ±0.14	2.582 ±0.11	0.567 ±0.04	0.334 ±0.02	1.196 ±0.02	0.752 ±0.03	0.380 ±0.07	0.775 ±0.03
Acetic acid	0.163 ±0.01	0.129 ±0.01	0.338 ±0.00	0.061 ±0.01	0.095 ± 0.01	0.033 ±0.00	0.244 ±0.01	0.047 ±0.00
Acetone	0.246 ±0.02	0.148 ±0.01	0.379 ±0.01	0.212 ±0.03	0.197 ±0.02	0.098 ±0.01	0.484 ±0.01	0.102 ±0.01
Acetonitrile	0.170 ±0.01	0.165 ±0.01	0.185 ±0.02	0.303 ±0.01	0.458 ±0.01	0.149 ±0.01	0.235 ±0.03	0.097 ±0.00
Lactic acid	0.002 ±0.00	0.001 ±0.00	--- ---	--- ---	--- ---	0.002 ±0.00	--- ---	0.003 ±0.00
Phenol	0.934 ±0.04	0.507 ±0.02	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---

Values are means of duplicate determinations with standard deviations (Mean±SD).
A = Cassava Peel, B = Maize husks, C = Pig Slurry, D = Equal combination of A, B, & C1 = Batch Process, 2 = Continuous Process.

3.4 Bar Representation of Contents Present in the Generated Biogas

Figure 1 presents the relationship that existed between methane (CH_4) and carbon dioxide (CO_2) concentrations in the generated biogas. In anaerobic digestion, CH_4 and CO_2 are the two primary gases produced, and their proportions can vary depending on several factors, including the feedstock. As observed in other works of Igoni[23] and Mondal & Chatterjee [24], this relationship between CH_4 and CO_2 in biogas is typically inversely proportional. In other words, as the CH_4 concentration increases, the CO_2 concentration tends to decrease, and vice versa. The ratio of CH_4 to CO_2, often referred to as the methane content or methane yield, is an essential indicator of biogas quality. From Fig. 1, while other constituents maintained fairly equal values, methane seemed to have gained every loss of carbon dioxide.

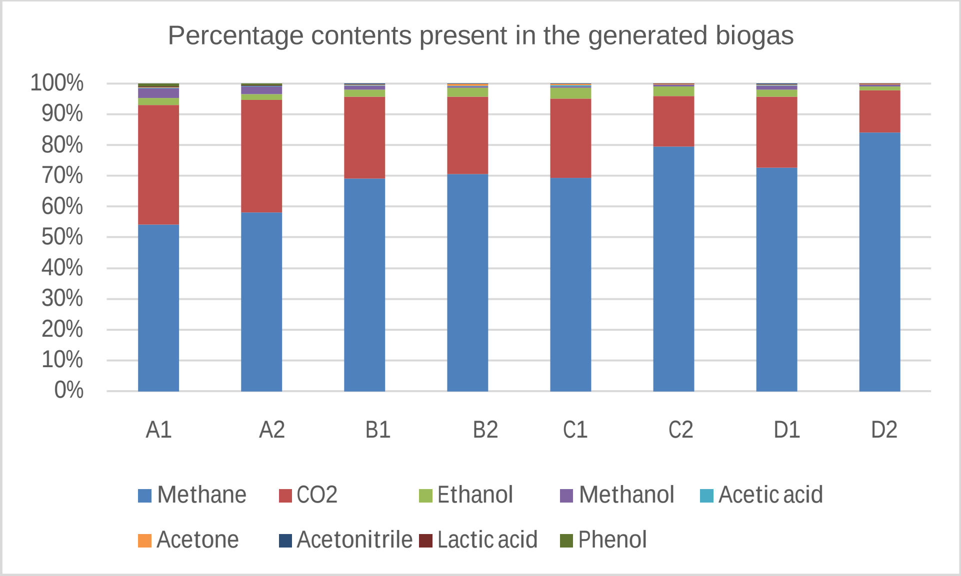


Fig. 1. Bar chart of percentage components in the generated biogas.

A = Cassava Peel, B = Maize husks, C = Pig Slurry, D = Composite.
1 = Batch Process, 2 = Continuous Process.

3.5. Comparison of Methane Generated by Batch and Continuous Processes

Figure 2 shows the overall methane yield compared between batch and continuous processes. The highest values were recorded for substrate D, followed by C, B, and A. This shows that codigestion of the substrates outperformed others, followed by pig slurry (C), Corn husks (B), and lastly Cassava Peels (A). However, for all the substrates, accumulated gas production was higher in continuous systems, due to its steady-state operation with a constant inflow of substrate (feedstock) and effluent removal [14]. This steady inflow of organic material provides a stable environment for methanogenic microorganisms, which produce methane. **Also,** Continuous systems often maintain consistent nutrient availability, including carbon sources and trace nutrients, which are essential for methanogenesis. This can support sustained methane production [25].

However, modeled graphical representation of gas volume production per time, in days (Fig. 3), revealed that batch processes outperformed the continuous processes between days 25-39. While the latter tended towards a steady state, the former recorded a sharp decline from day 40, probably due to exhaustion of nutrients [9].

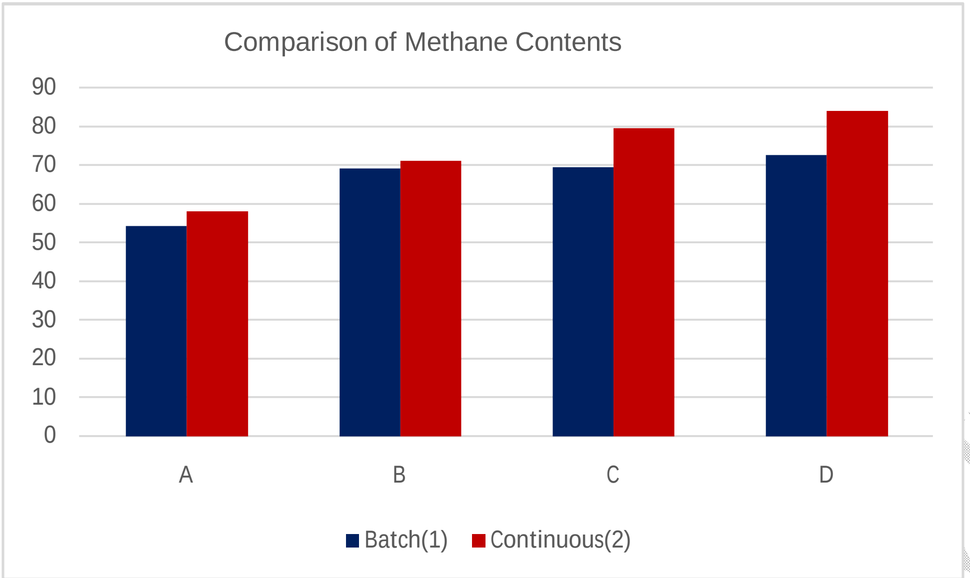
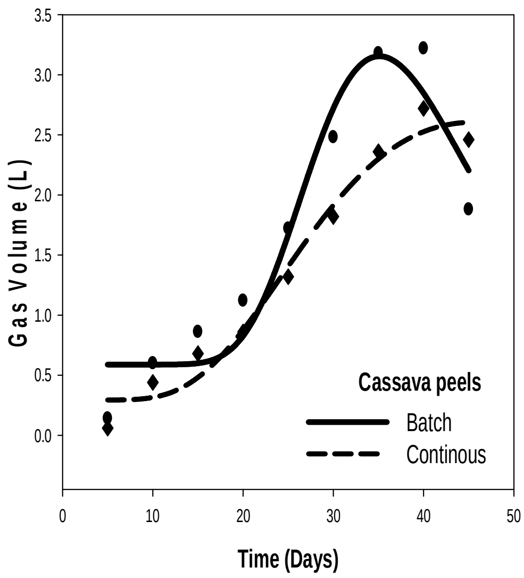
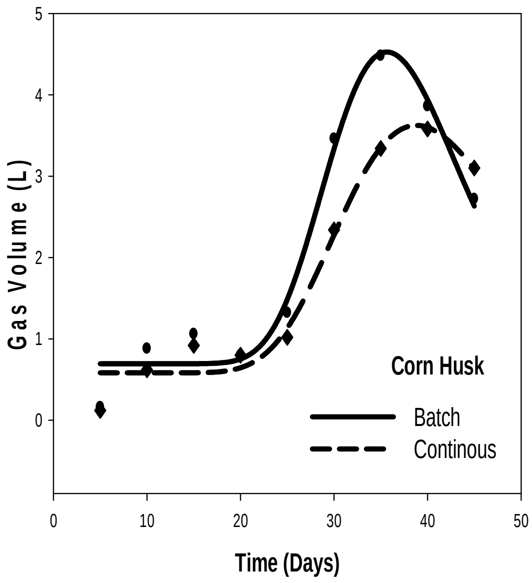


Fig. 2. Overall methane yield compared between batch and continuous processes
A = Cassava Peel, B = Maize husks, C = Pig Slurry, D = Composite.





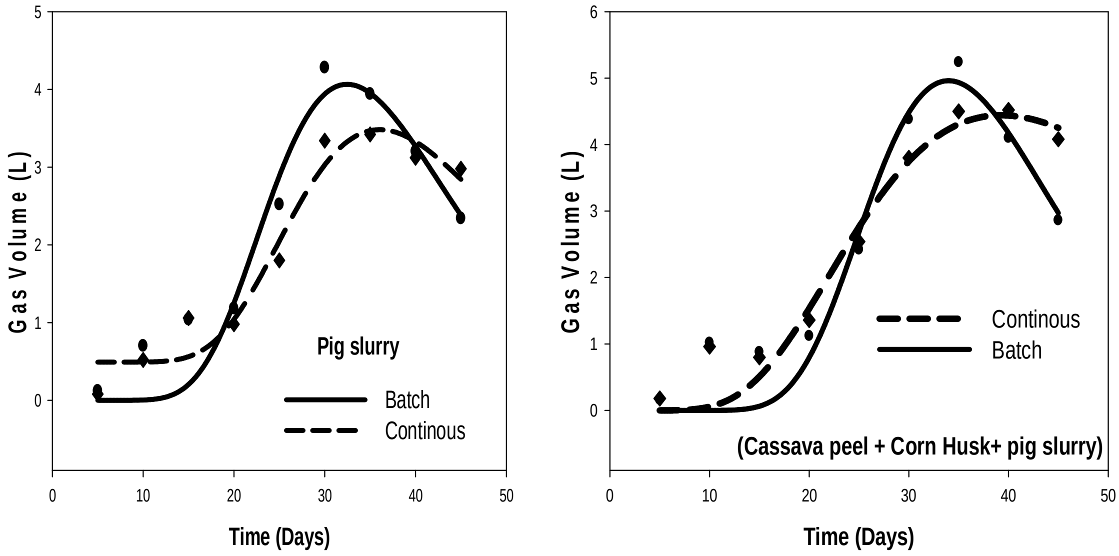


Fig. 3. Gas volume production per time (in days), for batch and continuous processes, using different substrates.

4. Conclusion

This study comprehensively compared the methane yield from continuous and batch fermentative processing of selected agrowaste, shedding light on the distinct advantages and limitations of each operational mode. The findings highlighted that continuous fermentative processing exhibited a more stable and consistent methane production rate compared to batch fermentation, primarily attributed to the continuous substrate feed input and steady-state operation. The higher overall methane yield in the continuous system emphasized its potential as an efficient and reliable approach for sustainable biogas production from agrowaste.

Furthermore, the study underlined the significant impact of agrowaste composition on methane yield in both operational modes, emphasizing the need for tailored substrate management strategies. Codigestion, the process of digesting multiple substrates together, was established as being more effective than monodigestion. It was evident that the combination of codigestion of substrates and continuous fermentative processing not only yielded higher methane but also offered a more viable and consistent approach for large-scale biogas production, making it a preferable choice for industrial-scale waste management.

However, the study recognized the importance of batch fermentation systems for smaller-scale applications and research purposes, allowing for more flexible experimentation and control over the operational parameters. Despite its intermittent operational cycles and potential fluctuations in methane production, batch fermentation remains a valuable platform for understanding the dynamics of microbial processes and biogas generation from agrowaste.

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