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Anaerobic Co-Digestion of Apple Juice Processing Waste with Manure and Corn Stover; Impact on Biogas and Methane Yield

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Abstract

Fruit juice processing generates large volumes of organic waste, including pomace, retentate, and waste apples, that are a challenge to manage. Anaerobic digestion (AD) allows for conversion of these wastes into biogas; however, their high acidity and low buffering capacity limits AD process stability, leading to reduced methane yield. In this study, co-digestion with manure and lignocellulosic biomass (LCB) was assessed. A five-factor mixture design was used to test different combinations on a bench scale, selected based-on seasonal fruit waste availability. Process performance was assessed based-on methane yield and volatile fatty acids before and after AD. Feedstock mixture representing an off-season blend of 20% pomace, 30% retentate and 50% manure, as well as an in-season blends of 20% waste apples, 30% pomace, 30% retentate, and 20% manure, were found to maximise the biomethane yield. Supplementation with at least 20% manure was essential for fruit waste digestion. Replacing a portion of the fruit waste with lignocellulose in the anaerobic digestion significantly improved the methane yield and prevented an "acid crash". It was found that 30% LCB and 20% manure supplementation were the minimum required for anaerobic digestion process stability and yield for both in- and off-season fruit harvesting and processing.

Highlights

- Off- season, 20% pomace, 30% retentate, and 50% manure mix yields 513 ml of Biogas with 51%methane.
- In-season, 20% waste apples, 30% pomace, 30% retentate, 20% manure yields 565 ml of Biogas with 54% methane.
- 30% LCB & 20% manure supplement improves digestibility and AD process stability.

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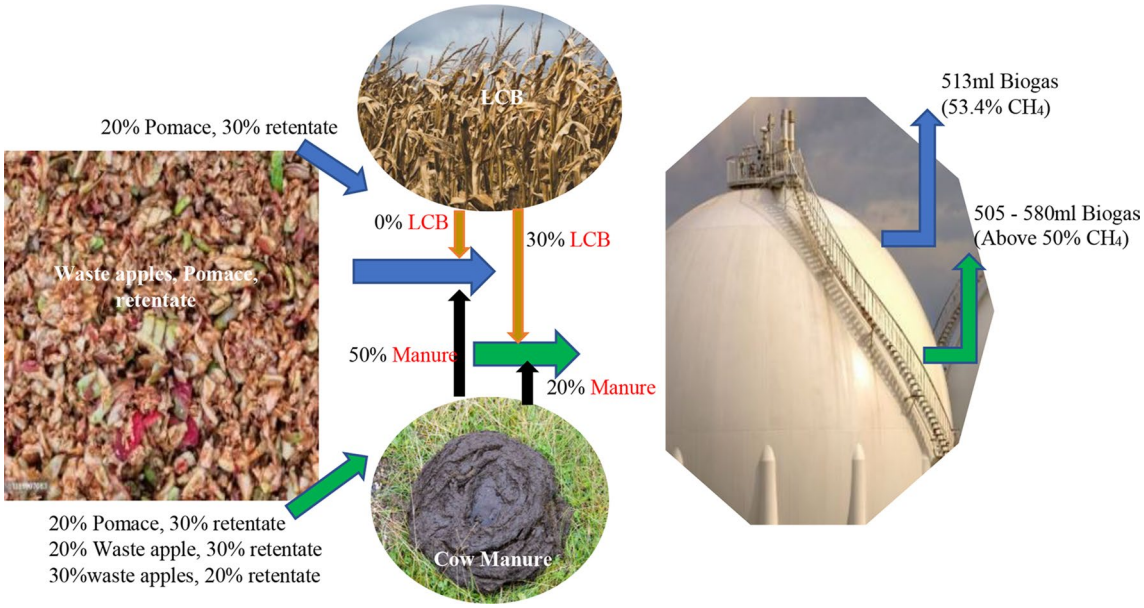
Graphical abstract



Keywords Anaerobic digestion · Fruit waste · Co-digestion · Biogas · Lignocellulose

Introduction

South Africa's fruit processing industry has experienced significant growth in fruit production and processing, growing by over 27% between 2014 and 2021 [1]. This growth has led to a substantial increase in waste generation, with fruit and vegetable waste accounting for up-to 40% of all food waste in South Africa according to recent estimates [2]. Processing of fruits like apple and pears for juice and pulp production generally results in approximately 40 to 50% as waste [3]. Sustainable management of this fruit waste is important for both economic efficiency of industries, the environment and public health.

In South Africa, landfilling remains the primary waste management option for organic waste. However, the available space for new landfills is diminishing, calling for alternative sustainable approaches to disposal. The need is further amplified by the ban on waste exceeding 40% moisture content from entering landfills from 2019 by the South African government [4]. Immediate alternative pathways for waste management such as heat drying and incineration require a lot energy and these are associated with heavy capital/operation costs, making them un attractive [5]. Fruit processors whose waste is often characterised with moisture content as high as 90% need to have immediate sustainable solutions for this growing challenge.

Fruit waste comprises peels, pulp, kernels, seeds, and water in large volumes and are characterised with high quantities of highly digestible organic matter (7.2–43.6% cellulose, 4.26–24.4% hemicellulose, 15.3–23.5% lignin, 3.5-14.32% pectin), macronutrients (48.0-83.8% total carbohydrates, 2.9–5.7% protein and 1.2–3.9% lipids) [2, 3], This makes this waste a resource for biogas production [6, 7]. However, this fruit waste typically contains low quantities of nitrogen and phosphorus, the essential micro-nutrients required to sustain the microbial population in the digester [8]. Furthermore, fruit processing waste offers weak buffering capacity leading to the accumulation of volatile fatty acid (VFAs) during the digestion process, causing digester failure in a so-called "acid crash" [9–11]. Co-digestion with other feedstocks is, therefore, necessary for effective anaerobic digestion of the fruit waste.

Anaerobic co-digestion (Co-AD) of buffered substrates with an appropriate balanced nutrients allows for AD process stability and improves biomethane yield [12; 13]. Moreover, Co-AD is economically attractive for fruit processors with the combination of the various waste streams within a single facility [14]. Combining different waste streams within a particular geographical location in a single digester can also contribute to the development of an integrated waste management system with significant rewards, such as nutrient recycling, energy savings, and reduction of environmental pollution [15].

Earlier studies involving fruit waste focused on mono-digestion and/or co-digestion of fruit and vegetable waste with biochar and sludge with and without pre-treatment [16–18]. In a study Masebinu, et al. 2018 [19] co-digestion

of fruit and vegetable waste (FVW) produced a biogas yield of 0.87 Nm^3/kg (VS) with an average methane content of 57.58% at an optimal fruit-to-vegetable ratio of 2.2:2.8. In another study, fruit and vegetable waste co-digested with anaerobic sludge at a 25:75 ratio produced methane concentrations up to 62%, and microwave pre-treatment increased yield by 10% [16]. A similar study of sewage sludge-derived biochar co-digested with fruit waste digestion boosted methane production by 27% and helped stabilize pH by minimizing volatile fatty acid accumulation [18]. These studies confirm that while mono-digestion of fruit waste is feasible, co-digestion offers considerable advantages in terms of yield and process stability. Limited studies exist on anaerobic digestion with focus on fruit waste from apple juice processing.

Therefore, this present study investigated the anaerobic co-digestion of apple juice processing waste, specifically pomace, retentate, and waste apple, each as a separate stream and as a blend with cow manure; focusing on VFA production and methane yield. The study assessed the potential of replacing a fraction of the processing waste with the abundant lignocellulosic biomass (maize stover) on the AD process performance.

Materials and Methods

Substrate Preparation

Apple fruit processing waste streams (waste apples, apple pomace, retentate) were obtained from a juice processing facility within the Western Cape province, South Africa. These were transported in separate cooler boxes to the laboratory, and macerated upon arrival with a bowl cutter (Tabletop bowl cutter finis). Macerated apple wastes were packaged, sealed and stored at -20 °C in 1 kg aliquots. Maize stover was collected from the Agricultural Research Council (ARC) facilities located in Stellenbosch, South Africa. The maize was harvested at 142 days from planting, placed in the greenhouse to dry for at least four weeks to a moisture content below 12% dry basis. The maize stover was then milled with a Retsch mill SM100 fitted with a 2 mm screen, parked in one kg bags, tightly sealed and stored at room temperature until use. Cow manure was obtained from a dairy farm near Stellenbosch University, South Africa. The manure was screened to remove foreign material and then stored at -20 °C, to limit microbial activity. Manure was thawed before use and stored for not more than three days at 4 °C. The inoculum for AD experiments was collected from active anaerobic digesters at the South African Breweries (SAB) based in Western Cape province, transported in cooler boxes to the lab. On arrival, it was degassed and any residual organic matter removed by preincubation in a 50 L Continuous stirred-tank bioreactor (TF Design (Pty) Ltd) maintained at a temperature of 37 °C for at least 7 days before use.

Substrate Characterisation

Fresh homogenised samples of each feedstock were subjected to macronutrients, nutrients, proximate, and ultimate analysis. Macronutrient analysis involved assessing for crude fibre, crude protein, lipid, and carbohydrates content. This was done at the Quantum Analytical lab in Malmsbury, Western Cape, South Africa. Protein analysis was done following Dumas method as describe by Serrano et al. (2013) [20]. The ANKOM XT15 extraction system as described by Seenger et al. (2008) [21] was used to determine crude fat content. Crude fibre analysis was conducted following the AOAC 962.09 standard method for crude fat content analysis [22]. The total available carbohydrates were calculated as the difference between the total mass and the mass of all other measured micronutrients of the substrate.

Proximate analysis of the substrates for moisture content (MC), total solid (TS), and volatile solid (VS) was done following the standard methods from American Public Health Association for analysis of (waste) water [23] methodology using a Barnstead Thermolyne 6000 furnace. For ash content, a known weight of the oven dried sample from moisture content determination was incinerated to ashes in the furnace at 550 °C for 8 h. The weight of the resultant ash was weighed. The ash content was expressed as the wight of the ash to the weight of the dried sample. Ultimate analysis was conducted following homogenisation on TS basis to determine the carbon (C), and nitrogen (N), contents; with an Elemental Analyzer, Elementar Analysensysteme GmbH.

Batch Anaerobic Digestion Experiments

Biomethane potential (BMP) tests were carried out following the standard protocol as described by [24] Angelidaki et al. (2009), using 100 ml Serum bottles with a 70 ml working volume. The BMP tests were carried out on individual substrates, and different substrate combinations. The substrate combinations were set-up to mimic seasonal variation in the fruit waste availability over the year, including the

availability in abundance (at peak production) and off season (limited production).

For the BMP test set -up, a sample of the individual or blended substrates was transferred to the 100 ml serum bottle and inoculated with previously degassed inoculum. Distilled water was added to bring the total solids loading to 10% of the working volume. For blended substrate BMP tests, a solution containing 1% calcium carbonate was used to provide for both buffering and as a top- up to make up to the 10% solids loading. Blended samples were mixed for homogeneity and their pH adjusted to 7 using 1 M sulphuric acid or a solution of 1 M potassium hydroxide solution. Using a butyl rubber and an aluminium crimp, the serum bottles were plugged and sparged with nitrogen gas in the head space to drive out any oxygen and create anaerobic conditions. The serum bottles containing the individual or blended substrates were incubated at 37 °C in an incubator for a total of 30 days. For blends, substrate replacement of between 20 and 50% and 0–30% for manure and LCB, respectively, were investigated with different fruit waste proportions as a percentage of the total solid loading.

BMP tests for individual substrates were conducted in triplicates. For blends, a five-factor, five-level, constrained mixture design was developed using Statistical 13.2 with independent variables as pomace waste apples, retentate, cow manure, and LCB and response variables as total biogas and methane yield, as shown in Table 1. The design considered that; no individual fruit waste exceeded more than 30% w/w of the total substrate mixture (so as no fruit waste combinations exceed 60% to lead to acid crash). In addition, the LCB addition did not exceed 30% of the substrate mixture and that no combination of manure and LCB exceeded 80% of the total substrate mixture. Because of the bulky of runs, BMP tests for blended substrates were done as single

Table 1 BMP test substrate combination experimental design at different concentrations of manure and LCB supplementation, and measured biogas and methane yield for each combination and the resultant C: N ratio

Supplement replacement (%)		Assay No	Fruit substrate Blend (% weight)			Yield (ml)		Yield (mL. gVS^{-1}_{fed})		CH_4 (%)	C: N
Manure	LCB		Waste apples	Pomace	Retentate	Biogas	CH_4	Biogas	CH_4		
20	-	1	30	30	20	235	105	127	57	49.2	31.3
		2	30	20	30	406	151	217	81	48.5	32.1
		3	20	30	30	565	232	302	124	50.5	31.2
40	-	4	30	30	-	217	48	118	26	22.1	36.9
		5	-	30	30	455	161	240	85	42.5	36.2
		6	30	-	30	599	222	317	118	45.3	40.3
20	20	7	30	30	-	144	42	79	23	38.8	31.3
		8	-	30	30	495	212	262	112	50.9	30.9
		9	30	-	30	541	221	287	117	51.1	33.7
50	-	10	20	-	30	536	211	282	111	47.1	44.4
		11	-	20	30	513	212	269	111	53.4	41.0
		12	20	30	-	595	240	321	130	50.8	40.4
		13	30	-	20	673	267	357	142	47.7	44.8
		14	-	30	20	467	272	247	144	49.7	39.7
		15	30	20	-	673	279	364	151	49.2	42.0
20	30	16	20	-	30	505	201	267	106	50.2	33.5
		17	-	20	30	506	196	267	103	50.8	31.6
		18	20	30	-	463	166	251	90	41.1	31.2
		19	30	-	20	580	241	310	129	50.3	33.7
		20	-	30	20	656	281	349	150	49.4	30.9
		21	30	20	-	407	159	221	87	49.3	32.1
40	30	22	-	30	-	412	147	221	79	48.5	36.1
		23	-	-	30	573	189	299	99	40.3	39.2
		24	30	-	-	605	245	326	132	41.8	40.1
50	20	25	-	30	-	772	307	413	164	47.4	39.6
		26	-	-	30	592	215	308	112	45.4	43.4
		27	30	-	-	446	152	239	82	46.2	44.5
50	30	28	-	20	-	679	233	362	124	43.1	40.7
		29	-	-	20	783	319	410	167	46.4	43.3
		30	20	-	-	916	155	490	83	43.8	44.0

LCB- Lignocellulosic biomass – Corn stover used **Off-season Blends**: When fruit waste is available in limited quantities at 50% and below requiring manure/LCB supplementation above 50%. **In-season Blends** When waste is available in abondance at 60% and above, requiring manure/LCB supplementation of below 50%

Table 2 Physio-chemical composition of the individual substrates

Parameter	Substrate				
	Manure	LCB (Maize stover)	Waste Apples	Pomace	Retentate
TS (% w/w)	9.8±1.0	91.1±0.3	13.1±2.7	18.1±3.0	5.3±3.3
VS (% of TS)	84.5±1.7	91.7±0.2	98.5±0.0	98.2±0.2	89.7±0.2
Ash (%TS)	15.5±0.3	8.3±0.2	1.5±0.0	1.8±0.2	10.3±0.2
Moisture (% w/w)	90.2±1.0	8.9±0.3	86.9±2.7	81.9±3.0	94.6±3.3
Crude protein (%TS)	9.9±0.4	11.5±0.3	4.5±0.14	10.6±0.8	14.5±0.6
Crude fats (% TS)	5.3±0.3	0.7±0.1	3.6±0.0	8.1±0.5	2.8±0.7
Carbohydrates (%TS)	33.2±3.2	52.1±1.7	77.6±1.3	41.3±0.8	45.0±1.4
Total Crude Fibre (%TS)	29.2±1.6	27.5±1.3	12.7±1.2	38.3±1.8	27.4±1.7
Cellulose (% fibre)	19.5±0.1	31.7±0.1	19.0±0.3	29.2±0.7	N/A
Hemicellulose (% fibre)	21.7±0.3	11.4±0.2	14.3±0.1	12.4±0.7	N/A
Lignin (% fibre)	32.6±0.2	20.7±0.0	29.1±0.2	26.3±0.7	N/A
Pectin (% TS)	N/A	N/A	4.3±0.3	3.0±0.5	2.9±0.2
C: N	28.9±1.2	23.4±0.2	101.4±22.6	29.0±0.5	30.1±2.1
pH [-]	7.17	5.75	3.94	3.37	3.43

runs. The mixture design (Table 2) was analysed using an ANOVA for both methane (mL.gVS) and biogas (mL.gVS) as outcome variables to ascertain the experimental design robustness.

For the individual substrates, the total volatile fatty acids (VFA) production for each experimental run was determined before and at the end of the BMP digestion experiment. For the VFA analysis, aliquots were taken from the digestate and centrifuged at 8000 rpm for 2 min. The supernatant was analysed for VFA using the High-performance liquid Chromatograph (HPLC) (HP series 1100, Germany) equipped with a Biorad Aminex HPX-87 H column and a UV detector. The temperature was set at 65 °C and 0.6 ml/min 0f 0.005M H_2SO_4.

For both the individual substrates and the blended substrate BMP tests, the produced gas was measured everyday using a syringe and a needle. The needle attached to the syringe was used to puncture through the rubber stopper, pressure from the produced gas inside the serum bottle would push the plunger, the released gas was measured by the displacement of the plunger in millilitres. Gas samples were analysed using a Compact GC4.0 Gas Chromatograph (GC) using Helium and Argon as carrier gas at a flow rate of 5.0 ml/min and reference gas flow rate of 1.0 ml/min. The GC was fitted with two Thermal Conductivity Detectors (TCD), one detector (at temperature of 50^0C) identified the carbon dioxide composition while the other detector (at temperature of 65^0C identified the amounts of the other gases including oxygen, methane, and nitrogen in the gas sample. An Injection temperature of 60^0C was used for every gas sample. Efforts were made depending on gas quantities collected to measure composition in triplicates and results are reported as average values. The GC was calibrated every 6 months. Calibration involved heating the columns at 50^0C overnight to remove residues and running pure gas samples through to observe the calibration curves. Adjustments were made whenever there were discrepancies.

Results and Discussion

Feedstock Characterisation

The fruit waste had significantly higher levels of carbohydrates compared to manure (Table 2). The high amount of carbohydrates and comparatively little fibre relative to the others, resulted in a very high C: N ratio, given the low nitrogen content (Table 2). Volatile solids (VS) varied between 84-98.5%TS, indicating the substrates were all rich in organic matter and therefore had potential for methane production [25]. Except for pomace (18.1%w/w), the TS for other substrates was within the suitable range of 5 and 15%w/w [26]. All the fruit processing waste had low pH, which represented high acidity and underscored the need for process buffering, specifically alkalinity.

These results demonstrate that the fruit processing waste had multiple nutrient/element deficiencies that could be addressed with substrate proportion optimisation via Co-AD. The performance of a feedstock for methane production is based on the moisture content, biochemical composition, C:N ratio, volatile solids, pH and total solids [26;27]. A feedstock is considered suitable for biogas production if it has adequate moisture between 70 and 90%, optimal Carbon to Nitrogen ratio between 20 and 30, a balanced biochemical composition with moderate carbohydrates, proteins, and lipids [15]. In addition, the volatile compounds of the feedstock should be above 70% TS, with total solids between 5 and 15% and a neutral pH between 6.5 and 7.5 [26].

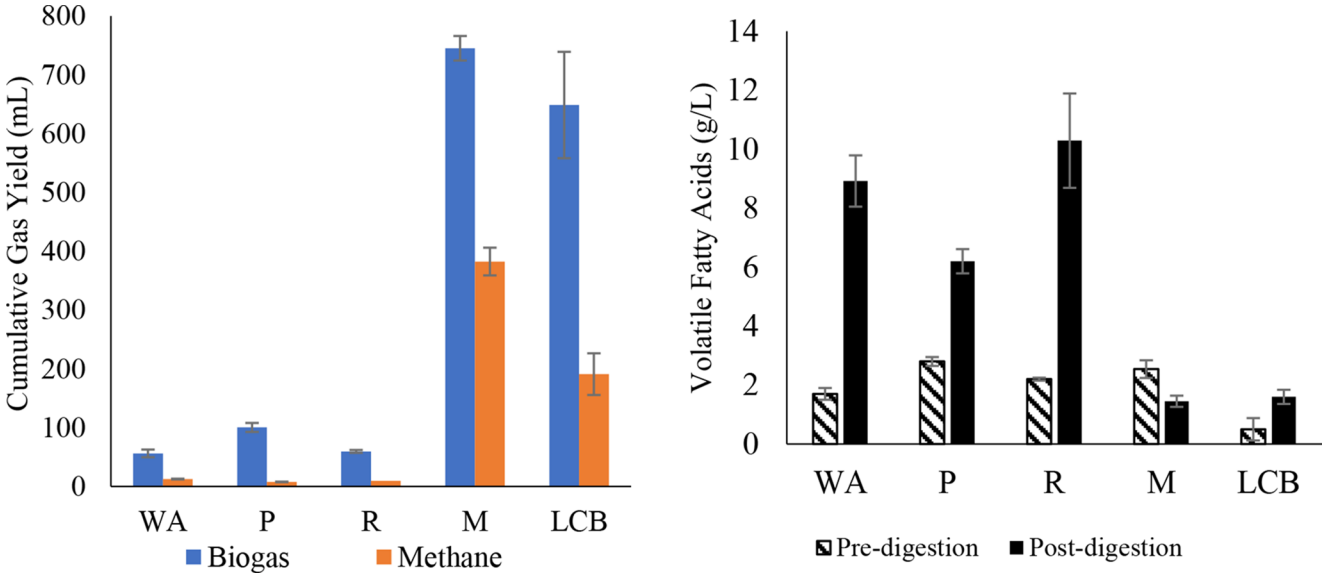


Fig. 1 Biogas, Methane yield and Volatile fatty Acids (VFA) production for Individual substrates, WA- Waste apples, P- pomace, R-Retentate, M- Manure, and LCB- Lignocellulosic biomass. A- Biogas and methane yield, B - VFA pre- and post-anaerobic digestion process for each Individual waste streams

The results suggested that use of significant proportions of the waste apples in any mixture combinations could result in rapid acidification of the AD system due to the high percentage of carbohydrates – 77.6% (Table 2). The fermentation of these high amounts of reducible sugars produces high volumes of VFAs, the rapid accumulation of the VFAs lowers the system's pH leading to a state of acidification [9]. Therefore, a mixture combination involving waste apples would require a significantly high nitrogen source substrate supplementation (LCB and/or manure) in order to prevent acid crash [28].

Similar observations have been reported in several other studies. For instance, Zhang et al. (2013) [29] found that the mono-digestion of food waste rich in carbohydrates led to acidification due to VFA accumulation, negatively affecting biogas yield. Mata-Alvarez et al. (2014) [30] also reported that fruit and vegetable wastes, due to their high sugar content, tend to acidify the digester rapidly, necessitating the use of buffer agents or co-substrates such as cattle manure to maintain optimal pH levels and microbial activity [30]. These corroborating studies highlight the importance of optimising substrate mixtures when utilising fruit processing waste in anaerobic digestion systems. Ensuring an adequate nitrogen supply and buffering capacity is essential for stable and efficient biogas production from such high-carbohydrate organic wastes. A study Zhou et al. (2019) [31] also emphasized the observation that carbohydrate-rich substrates need co-digestion to mitigate the risk of process inhibition.

Biogas, Methane Yield and VFA Production for Individual Substrates

The result of biogas, methane yield and VFA production, (before and after AD) for individual substrates are shown in Fig. 1. The results support the observations from the composition analysis results (Table 2). Manure substrate on average yielded a methane percentage in biogas above 50%. This corresponded to the highest overall biogas and methane yields of 745 mL and 382 mL respectively (Fig. 1A). The AD process for manure also showed a corresponding decrease in post VFA concentration (Fig. 1B). The observed yield with manure digestion represented a stable AD process, since the substate has an array of essential nutrients and elements required for the optimum growth and the metabolic activity of the methanogens during AD as shown in Table 2. Similar observations have been reported with similar studies on swine manure [28]. In other studies, Masebinu, et al. 2018 [19] mono-digestion of fruit and vegetable waste (FVW) produced a biogas yield of 870 ml/kg (VS) with an average methane content of 57.58% at an optimal fruit-to-vegetable ratio of 2.2:2.8.

Manure is followed closely in methane yield by LCB, although LCB showed a 3-fold increase in VFA post-digestion. LCB has a highly complex structure with intertwined polymeric compounds that is known to offer resistance to biodegradation of the LCB, this explains the low biogas yield [31]. The AD process for LCB was however more stable compared to fruit waste. The high level of carbohydrates and low pH measured in LCB (Table 2), indicated that a potential imbalance between the production and

consumption of the VFAs, hence the accumulation and resultant low methane yield. The imbalance arises from the fact that acidogenic bacteria were breaking down the available organic matter faster than methanogenic archaea action on the VFAs to methane.

The fruit processing waste produced low biogas and methane. Methane production from fruit-processing waste is often limited due to the rapid acidification of the high amounts of sugar to VFA (Zang et al., 2022) [29]. Apple waste, retentate and pomace yielded respectively methane content of 22.2, 16, and 7%, (Fig. 1A). The process also produced higher VFA concentration post-digestion in fold increase, 5-, 4- and 2-fold increases post-AD (Fig. 1B). The low methane yield is associated with the high contents of easily-digestible organic polymers, including carbohydrates, proteins and crude fat (Table 2). These were converted to the simple sugars in the hydrolysis stage of the AD process, increasing the sugar concentration in the substrate, and leading to a high concentration of VFAs. For the fruit processing waste, the high VFA production and low methane yield (Fig. 1) support the conclusion that the methanogens in the AD process were not able to convert all of the available VFAs into biogas, resulting in low methane yields similar to those reported for AD of apple pulp [33]. The results support the observation of the instability of the individual waste AD process and underscore the need for Co-AD to improve process stability and methane yield.

Biogas and Methane Yield for Different Proportions of Fruit Processing Waste, Manure and LCB

From the analysis of the mixture design, biogas and methane yield (mL.gVS) were found to be significant with a p-value of 0.0027 and 0.033 respectively. The total biogas variable yielded an $R^2 = 0.54$ meaning at least half of the observed variation is accounted for by the model.

From the results, Table 1, the overall best methane yield content (513 ml of biogas and 212 ml of methane corresponding to 212 and 111 $mL.gVS^{-1}$ fed respectively) for the whole design matrix of 53.4% (Assay 11) was produced with a substrate blend of 50% manure, 20% pomace, and 30% retentate (Table 1). This point represents the blend with the highest manure content, and the off-season period when fruit waste is in limited quantities. Similar trends in methane yield were observed at 20% and 40% manure addition with minimal addition of waste apples (assay 3 and 22 respectively). The results are similar to those reported by similar studies on the AD process for waste apple pulp juice processing. Li et al. 2017 (34) reports a methane yield of 340 $mL.g/VS_{fed}$ working with chicken manure and apple pulp with blends in ratios 2: 1 respectively. The difference can be attributed to the difference in substrate composition used.

The results suggest that methane yield is maximised when fruit processing waste is Co-AD with manure in proportions of up-to 50%. The presence of large portions of manure in the blend provides a balance in the essential nitrogen and other nutrients for AD process, improves the C: N ratio and thus the high methane yield [35]. However, this is true for when waste apples are included in limited quantities. The reduction in methane yield with inclusion of larger proportions of waste apples (more than 20% of blend) can be attributed to the easily available reducible sugars from the hydrolysis of the significantly high carbohydrate content in the waste apple (Table 2). This causes the rapid acidification of the mixture, limiting the conversion of the VFAs to methane [34]. When proportions of fruit waste were replaced with LCB at fixed manure proportions in the blend, a decrease in methane yield was observed, apparently due to the reduced digestibility of this material. LCB has a highly complex structure with intertwined polymeric compounds that is known to offer resistance to biodegradation of the LCB [32].

For blends with LCB, a slight reduction in methane yield was observed compared to blends with manure alone (Table 1). The maximum percentage yield of 50.9% methane content was observed at 20% manure, 20% LCB, and 30% of pomace and 30% retentate (Assay 8). This is the substrate combination with no waste apple addition, and represents the fruit waste maximisation point and the production season when the waste is available in large quantities. A similar yield for methane was observed when LCB was increased to 30% and pomace reduced to 20% keeping the manure and retentate in the blend at 20% and 30% respectively (Assay 17).

Conclusion

The results of the study suggest that pomace retentate and waste apples requires co-digestion with at least 20% manure addition to have a stable AD process and reasonable methane content in the biogas produced. It was also noted that, blends of the fruit waste with significantly high proportions of waste apples compared to other wastes would require significantly high proportions of manure supplementation beyond the 20%. The addition of LCB as part of the proportion of fruit waste significantly improved biogas and methane yield and minimised the acidity of the fruit waste blend. The results support the conclusion that 30% LCB addition and 20% manure supplementation are sufficient to improve the digestibility and stability of the AD process for fruit juice process wastes in varying proportions.

Future research should focus on optimizing co-digestion ratios of fruit processing wastes, manure, and lignocellulosic

biomass (LCB) to maximize methane yield and process stability. Studies would also explore cost-effective pretreatment approaches to improve on the waste digestibility. Additionally, studying the microbial communities involved in anaerobic digestion and conducting long-term stability tests under various feedstock combinations would provide insights into the process dynamics. Techno-economic and life cycle assessments are essential to determine the feasibility and sustainability of scaling up the process at commercial scale. Finally, investigating the potential use of digestate as a safe and nutrient-rich biofertilizer could support the development of a circular bioeconomy and increase economic viability of juice processing waste to biogas approach the fruit processing industry.

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Declarations

Conflict of interest The authors declare no competing interests.

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