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Biogas Production Potential of Mixed Banana and Pineapple Waste as Assessed by Long-Term Laboratory-Scale Anaerobic Digestion

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Abstract: Biogas is a renewable energy source generated through the anaerobic digestion (AD) of organic feedstocks. This study aims to quantify the biogas production potential (BPP) of fruit wastes via semi-continuous lab-scale mesophilic AD over a total of 100 days. The feed was composed of 80% banana peelings and 20% pineapple residues, mimicking the waste composition of a Costa Rican fruit processing facility used as a test case. The average loading rate of volatile suspended solids (VSS) corresponded to 3.6 kg VSS$\cdot$m$^{-3}\cdot$d^{-1}. Biogas yield and composition were monitored, along with the concentration of ammonium, volatile fatty acids, and pH. Discounting the start-up phase, the BPP averaged to 526 L_N (kg VSS)$^{-1}$ with a methane concentration of around 54%, suggesting suitability of the substrate for AD. We calculated that if upscaled to the Costa Rican test case facility, these values translate into a gross average heat and electricity production via AD of around 5100 $MWh_{el}\cdot a^{-1}$ and 5100 $MWh_{th}\cdot a^{-1}$, respectively. Deducting self-consumption of the AD treatment, this is equivalent to 73% of the facility's electricity demand, and could save about 450,000 L of heavy oil per year for heat generation. To circumvent nitrogen shortage, the addition of a co-substrate such as dry manure seems advisable.

Keywords: semi-continuous anaerobic digestion; renewable energy; fruit waste; fermentation test; waste-to-energy

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1. Introduction

Anaerobic digestion (AD) constitutes a multi-step biochemical degradation process performed by microorganisms in the absence of oxygen that is widely employed for biomass treatment. During AD, organic matter is partially transformed into biogas, primarily composed of methane (50–75%), carbon dioxide (25–50%), water vapour, and traces of nitrogen, hydrogen, and hydrogen sulphide [1–3]. Biogas is a potent source of renewable energy, since, upon combustion, it can be converted into carbon-neutral power and heat [4]. Furthermore, residual AD sludge (digestate), if properly managed, holds the potential to be a substitute for mineral fertilisers [5]. A series of organic waste streams may be used in AD, including livestock manure, highly polluted wastewater, and agricultural, agro-industrial, and food waste [6].

In terms of process economics, the substrate's biogas production potential (BPP) is of outstanding importance. It is defined as the maximum achievable volume of biogas in relation to the substrate's organic dry matter content (volatile suspended solids (VSS)), expressed in $L_N\cdot$(kg VSS)$^{-1}$ [7,8], where the subscript N denotes normalisation to standard conditions of 0 °C and 1013 hPa. Besides the BPP, the methane (CH_4) concentration in the biogas also depends on the substrate (Figure 1).

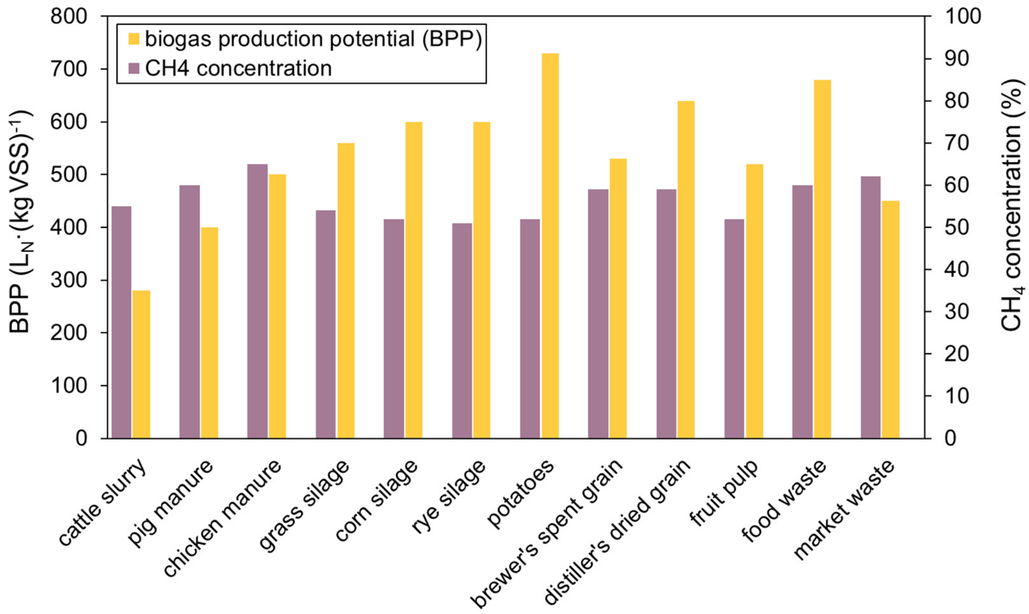

Figure 1. Biogas production potential (BPP) and average CH_4 concentration of substrates commonly used in anaerobic digestion. Data compiled from [9–12].

The experimentally derived BPPs range from 280 to 730 L_N·(kg VSS)$^{-1}$, with an average CH_4 concentration of 50–65%. Fruit pulp, which is of particular interest in this study, has a reported BPP of 520 L_N·(kg VSS)$^{-1}$ and a CH_4 concentration of around 52%, placing it in the mid-range compared to other substrates.

In addition to direct experimental investigations, the BPP of a specific substrate may also be theoretically derived employing empirical values for the three main substrate components, namely crude fat, crude protein, and carbohydrates [13]. According to the German Association of Water, Wastewater, and Waste (DWA), the AD of crude protein yields the highest methane concentration of 71%, whereas the degradation of crude fat and carbohydrates results in values between 68% and 50%, respectively [14]. Regarding the BPP, crude fat accounts for 1250 L_N·(kg VSS)$^{-1}$, while crude protein and carbohydrates show lower BPPs between 700 and 790 L_N·(kg VSS)$^{-1}$, respectively [10,14]. This theoretical approach does not consider components, such as lignin or starch, that are more difficult or easier to degrade, nor cumulative or antagonistic effects. Therefore, practical fermentation tests complemented with a thorough process monitoring should be conducted to improve reliability and to obtain the operating values for large-scale AD applications [11]. Monitored indicators of process stability could include biogas composition, pH, ammonium (NH_4-N), and total volatile fatty acid (TVFAs) [13,15].

The bacterial groups involved in AD have individual pH optima. Specifically, hydrolysing bacteria require a pH of 6.0–8.0, while acidogenic bacteria rely mostly on an acidic pH range between 5.5–6.5. The activity optimum of acetogenic bacteria was reported as 6.0–6.2, and for methanogenic bacteria as 7.0–7.2 [13,16,17].

Therefore, on the one hand, monitoring of pH is crucial to controlling process stability. On the other hand, AD systems are buffered by dissolved CO_2, carbonate, and ammonia, which delays noticeable pH changes. Consequently, pH measurement does not ideally serve for the early detection of process imbalances.

VFAs, such as acetic (C2), propionic (C3), isobutyric, butyric (C4), isovaleric, and valeric (C5) acid, are formed as intermediate metabolites by acidogenic bacteria. Upon conversion into acetic acid (acetogenesis), Archaea complete the transformation into CH_4 and CO_2 [15,18]. Under normal operating conditions, VFA levels are stable, with production approximately equal to the conversion into CH_4. Otherwise, accumulation of VFA beyond values of 1000 mg HAc·L^{-1} may indicate hampered methanogenesis [3,15]. In addition to VFA accumulation, the accumulation of excess NH_4-N can also inhibit the AD process. Ideally, NH_4-N concentrations should range between 1000 and 2700 $g \cdot L^{-1}$ [19,20].

The global food industry faces the challenge of efficiently managing significant amounts of fruit processing waste (FPW), including peel fractions, pulp, pomace, and seeds [21,22]. Traditionally, FPW is used for livestock feeding or is either composted, incinerated, or landfilled. Referring to its high organic matter content and optimal moisture levels, several studies have also emphasised that FPW, either individually or combined with a co-substrate, could also be used for AD [8,23–28].

As a major tropical fruit producer, Costa Rica plays a significant role in the global production of banana and pineapple, ranking fourth in global banana exports after Guatemala, the Philippines, and Ecuador [29]. In addition to being the third-leading supplier of banana to the European Union, Costa Rica is also the world's largest pineapple exporter, with a market share of nearly 70% [29,30].

This case study focusses on a Costa Rican facility specialised in the manufacturing of juices, purees, and concentrates, as well as liquid banana and pineapples flavours. The annual FPW generation amounts to 52,000 t (80% banana peelings and 20% pineapple core and peelings). In the following Sections, these are denoted as BW and PW, respectively. Presently, the FPW is used as feedstock in meat production. For the future, the plant operator is considering an economically more feasible waste-to-energy valorisation pathway based on AD and biogas combustion in a combined heat and power plant. This would reduce external electricity and heating demand and avoid waste transportation costs. Previous research has reported on the AD of BW and PW as separate substrates [27,28] over timescales of up to 40 days. Suhartini et al. (2021 [8]) conducted a batch lab scale test over 30 days to evaluate the specific biogas potential of both banana and pineapple peelings. The anaerobic treatment under mesophilic conditions revealed that pineapple peelings have a higher biogas potential (817 $L_N \cdot (\text{kg VSS})^{-1}$) compared to banana peelings (595 in $L_N \cdot (\text{kg VSS})^{-1}$). However, data on longer timescales and with a co-feeding of BW and PW are lacking. This has so far impeded a reliable projection of the energetic benefit that would come along with an AD implementation at the test case site.

Therefore, this study focused on the BPP and methane yield from the mixed substrate over a total duration of 100 days. A semi-continuous substrate lab-scale test was conducted under mesophilic temperature conditions. The experiment involved an inoculation phase, a start-up phase, and a steady-state feeding phase. Based on the latter, the suitability of the mixed waste for AD processing was assessed, and the potential energy yield was balanced against the plant's demand.

2. Materials and Methods

The BPP of the mixed fruit waste was evaluated over a steady-state feeding period of 69 days, during which daily gas production and composition were determined. The pH of the liquid digestate along with the concentration of ammonium (NH_4-N), and volatile fatty acids (VFA) were monitored as indicators of process stability.

2.1. Fruit Processing Waste

Taking the waste generation of the Costa Rican test case facility as a reference, the FPW consisted of BW and PW (banana peelings and pineapple cores and peelings, respectively). It was obtained from customary banana and pineapple, with no distinction between organically and conventionally grown fruits. The BW was crushed with a mincer, whereas the PW were shredded using a mixer to reduce the particle size and increase the access of bacteria to the substrate, and samples were stored at 4 °C for 1–2 days. At the beginning of the test, the substrates were first frozen and then thawed in the fridge and mixed. From day 73 onward, only fresh FPW was used.

2.2. Experimental Setup and Sampling

The AD was conducted in a lab-scale reactor (Figure 2) made of stainless steel with an effective volume of approximately 7 L. The reactor was placed in a water bath and held at 38 °C by an immersion thermostat. Substrate feeding was performed every working day through a manhole at the reactor top, simultaneously removing an equivalent volume of the digested sludge. The biogas was collected in a 50-L aluminium-laminated gas sample bag (Tesseraux, Bürstadt, Germany) attached to the reactor via a gas extraction nozzle.

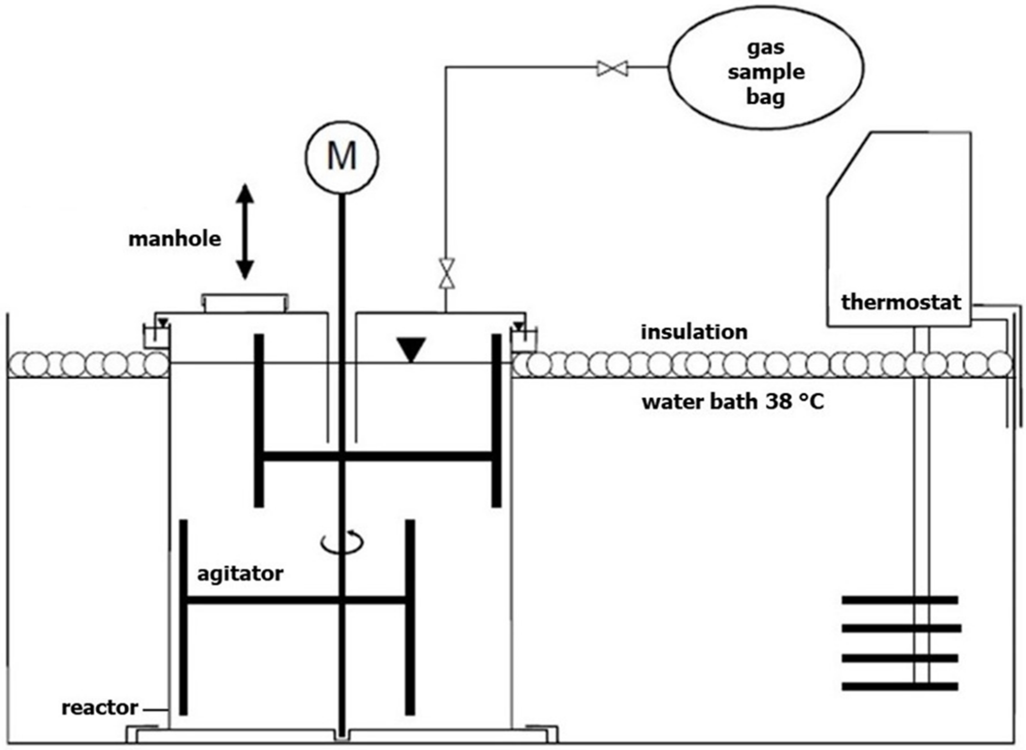

Figure 2. Experimental setup.

A total of 6.6 L anaerobically stabilised activated sewage sludge from the Giessen municipal wastewater treatment plant served to inoculate the reactor. The sludge was kept for six days at 40 °C to release gases that could potentially interfere with biogas production from the mixed FPW. Following this pre-conditioning, the fermentation test was started up by adding approximately 100 g crushed BW, equivalent to an organic loading rate (OLR) of 1.6 kg VSS·m^{-3}·d^{-1}. Before introducing PW, the BW feeding varied between 100 and 150 g·d^{-1}. In response to a pH decrease to 7.1 on day 9, 6 g of urea were introduced into the reactor, resulting in a pH increase to 7.7 on the following day. On day 13, a mixture of BW (150 g) and PW (50 g) was added to the fermenter increasing the OLR to 3.1 kg VSS·m^{-3}·d^{-1}. The mix was chosen to gradually increase the proportion of PW to accurately represent the waste generation data at the test case site. From day 31 onward, the rate of BW and PW was constant at 200 g d^{-1} and 50 g d^{-1}, respectively, giving an OLR of 3.7 kg VSS·m^{-3}·d^{-1}. Gas production was measured on workdays, excluding Mondays to account for the ceased feeding during the weekends. The fermentation test was terminated on day 100, resulting in a total stationary feeding period of 69 days.

2.3. Sample Analysis

Before and during the fermentation test, organic dry matter content of the samples, expressed as volatile suspended solids (VSS), was determined weekly by measuring the total and volatile solids (TS and VS, respectively) following DIN EN 12880:2001-02 and DIN EN 15935:2021-10 standards [31,32]. Briefly, samples of either BW or PW were filled in beakers, dried until weight constancy at 105 °C, and cooled down to room temperature in a desiccator before obtaining the sample's TS by weighing [31]. The samples were then combusted in a muffle oven at 550 °C for 2 h, cooled down as described above, and weighed to determine their VS content [32]. The TS content within the digester was measured according to following DIN EN 12880:2001-02, as mentioned above [31].

The concentration of VFA (mg $HAc \cdot L^{-1}$) was monitored according to DIN 38414 S 19. Therefore, samples of the digestate were centrifuged (10 min, 18,000 rpm), membrane filtrated (0.45 µm), and the supernatant was acidified to pH < 2 with 40% phosphoric acid to ensure protonation of the VFA. The concentration of acetic (C2), propionic (C3), isobutyric, butyric (C4), isovaleric, and valeric (C5) acid was determined using gas chromatography (Varian CP-3380) with flame ionization detection (Column, stationary phase: 15% SP 1220, 1% H_3PO_4 on 100/120 Chromosorb WAW Column: $6' \times 1/8''$ G.S.; temperature program: 90 °C (hold 2 min—2°/min—end 120 °C); Inj. Temp.: 200 °C, flow rate: 40 mL min^{-1} He. The concentrations of the individual VFA were converted into acetic acid equivalents (mg $HAc \cdot L^{-1}$) considering the molar ratios and the molar mass of the respective VFA, and were summed up to represent the total VFA (TVFA) concentration [33].

The NH_4-N concentration (mg $NH_4\text{-}N \cdot L^{-1}$) in centrifuge supernatants was determined according to DIN 38406-5:1983-10. In summary, the samples underwent steam distillation (Type B-323, Büchi distillation unit). The distilled ammonia was absorbed in 50 mL of boric acid (20 $g \cdot L^{-1}$) and titrated to pH of 4.6 with an automated titration system (TitraLab 840, Radiometer Analytical) for quantification [34].

The biogas volume produced through AD was measured using a Drum-Type Gas Meter, Ritter, size 0.5, Series TG (Wet-Test). For comparability, the measured gas volumes were converted to standard volume conditions, accounting for the air temperature and pressure records. A multi-gas analyser (Multitec 540, SEWERIN) served to determine the biogas composition in terms of CH_4, CO_2, O_2, and H_2S.

The gas volume, composition, and pH of the fermenter digestate were determined daily, whereas all other parameters were examined once a week. The fermentation test was evaluated in terms of BPP and the methane concentration.

The specific biogas production (L_N $m^{-3} \cdot d^{-1}$) was determined using the ratio of the daily gas volume ($L_N \cdot d^{-1}$) to the fermenter volume (m^3), show in Equation (1). Therewith, the BPP ($L_N \cdot (kg\ VSS)^{-1}$) was derived according to Equation (2), where the total OLR (kg $VSS \cdot m^{-3} \cdot d^{-1}$) refers to the sum of the organic loading rates (OLR) of BW and PW.

$$\text{Specific biogas production} = \frac{\text{daily biogas produced}}{\text{fermenter volume}} \tag{1}$$

$$\text{BPP} = \frac{\text{biogas production}}{\text{total OLR}} \tag{2}$$

2.4. Energy Balance

Assuming combustion of the biogas in a combined heat and power (CHP) unit with a 40% power and 45% heat conversion efficiency, we calculated the specific average annual power and heat recovery. This was benchmarked against the annual electricity and heat demand for fruit processing at the Costa Rican test case site. For the assessment of the net production of electricity and heat, a large-scale biogas plant was envisaged.

3. Results

3.1. Fermentation Test

The fermentation test with FPW was conducted over a total period of 100 days. Steady-state feeding conditions were achieved after 31 days, with an average hydraulic retention time (HRT) of 27 days. Results of the process monitoring throughout the testing are presented in Figure 3 with pH, TVFA, and NH_4-N as indicators of process stability.

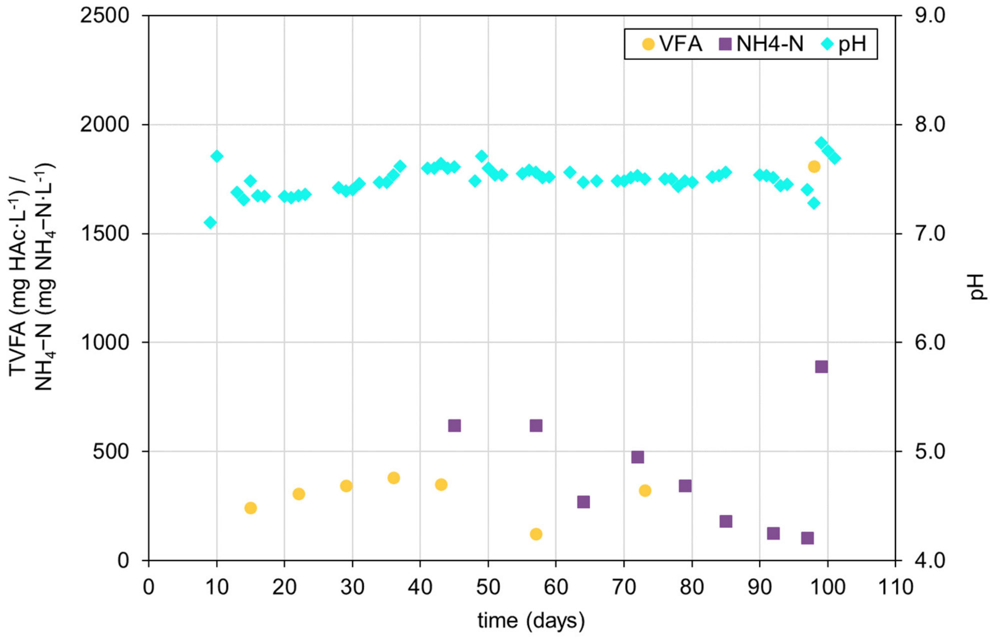

Figure 3. Characteristics of the digestate's liquid phase during the fermentation test.

From start-up until day 97, the pH of the digestate's liquid phase consistently remained within the optimal range of 7.3 to 7.8. Stable process conditions were further evidenced by a TVFA values of <1000 mg HAc·L^{-1} until day 97. The NH_4-N concentration was first measured on day 45. The value of 621 mg·L^{-1} was below the recommended threshold of 1000 mg NH_4-N·L^{-1} [9,35] and decreased over time, reaching 105 mg NH_4-N·L^{-1} by day 97. The NH_4-N minimum coincided with a prominent peak in TVFA concentration (1800 mg HAc·L^{-1}) and with a pH drop to 7.3. To compensate the apparent nitrogen deficiency and avoid further TVFA accumulation, 37 g of urea were added to the fermenter on day 98, yielding a measured NH_4-N concentration of 890 mg·L^{-1} and a recovery of pH on the final days of the experiment. With the deliberate aim of stressing the system, urea was added towards the end of the experiment only.

In wet AD systems, a TS content below 10% is recommended to ensure good mixing [20]. Higher values may hinder bacterial access and may result in incomplete substrate utilisation. Gas production can be reduced even at a TS concentration of approximately 12% [19]. Under the semi-continuous feeding regime employed here, the TS gradually increased until day 72 and then levelled off asymptotically, approaching around 5%. Therewith, good mixing conditions are likely to have prevailed throughout.

3.2. BPP and Biogas Composition

Biogas composition and the volume of gas produced are key indicators of process economics directly linked to the expectable revenues. In addition, sudden changes in either biogas production, CH_4 content, or H_2S level may highlight process imbalances [15,36,37].

Neither the BPP nor the CH_4 concentration were affected by switching the feed from frozen to fresh FPW. The average biogas from our mixed FPW was comprised of 54% CH_4, 46% CO_2, and 8 ppm H_2S. Overall, the CH_4 concentration was within a range of 50 and 57% (see Figure 4). It was highest during the start-up phase and lowest during day 85 and 95. The concentration of H_2S was mostly below 30 ppm and fluctuated slightly. It began to rise on day 92, reaching 35 ppm, peaked at 42 ppm on day 93, then declined again on day 94, stabilising thereafter.

The daily biogas generation varied until day 83, hovering around a mean of 1822 $L_N \cdot m^{-3} \cdot d^{-1}$. Consequently, the BPP fluctuated around an average of 526 ± 198 $L_N \cdot$(kg VSS)$^{-1}$. Considering the steady-state phase, an average BPP of 485 ± 117 $L_N \cdot$(kg VSS)$^{-1}$ was achieved. However, from day 84 onward, biogas production, and hence the BPP, decreased steadily while the H_2S concentration peaked. Please note that the decrease in BPP went along with a decrease in NH_4-N (cf. Figure 3).

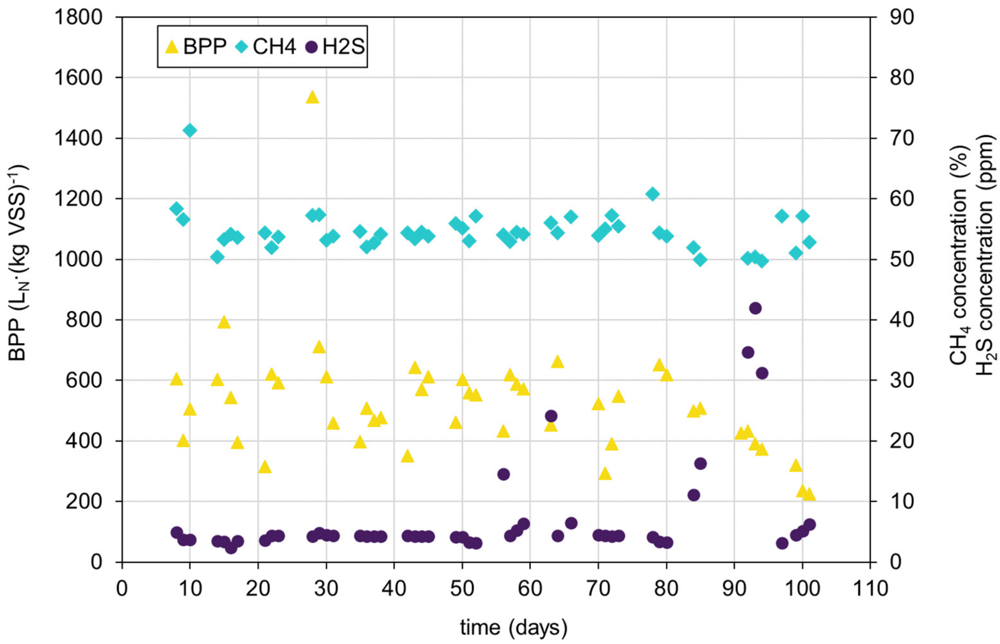

Figure 4. BPP as well as CH_4 and H_2S concentration during the fermentation test.

4. Discussion

Multiple studies have demonstrated the potential for AD utilisation of FPW [23,25–27,38–41], yet these were conducted over substantially shorter testing periods whereby nutrient shortages may have been overlooked. In this study, we quantified the BPP of mixed FPW (BW and PW) over 100 days, mimicking the FPWs' composition from a test case facility in Costa Rica. The results demonstrate that the mixed FPW has a BPP and CH_4 yield similar to that of other approved substrates. This highlights its potential for an AD-based valorisation. Low levels of H_2S suggest that an additional biogas purification step may not be required.

Nevertheless, extended feeding of BW and PW may result in NH_4-N shortage followed by process instability and reduced yield. Specifically, the NH_4-N concentration was below the advised threshold of 1000 mg NH_4-N$\cdot L^{-1}$ throughout the entire fermentation test and steadily decreased to a minimum of 105 mg NH_4-N$\cdot L^{-1}$. Process instability was indicated by concomitant TVFA accumulation, a drop in pH, a downfall in biogas production, and an increase in H_2S level. Nitrogen could have impaired biogas production in the first place, and it is well known that VFA accumulation inhibits the activity of methanogenic bacteria. As a result of the syntrophic relations among bacteria at various stages, disturbances in one stage can lead to cascading effects on other stages [1].

Based on the substrates' average crude protein content (see Table 1) and the mixing ratio of 4:1, our mixed FPW likely contained 4.8% crude protein, which contains around 16% nitrogen [42]. This gives a theoretical nitrogen content of 0.77% in the mix, which is somewhat below the range of values reported by Bardiya et al. (0.95 and 1.06%), and is low in comparison to other feedstocks, e.g., poultry manure (3–5%) [43], corroborating the nitrogen shortage.

Table 1. Characteristics of BW and PW compiled from the literature data and partially analysed in this study.

Parameter	BW			PW		
	Min.	**Max.**	**References**	**Min.**	**Max.**	**References**
Water content (%)	62.3	85.4	[44–49]	71.1	92.2	[40,50,51]
TS (%)	10.7	18.9	[27,28,46,47,52]	7.8	29.0	[27,28,50,51]
	9.5	18.6	This study	8.7	14.3	This study
VS (% TS)	85.6	92.3	[27,28,46,47]	89.4	96.1	[27,28,40,51]
	82.8	86.6	This study	93.3	96.3	This study
Cellulose (%)	11.1	13.1	[28,46]	11.2	19.8	[27,40,51]
Hemicellulose (%)	5.4	14.7	[28,46]	7.0	11.7	[27,40]
Crude protein (%)	2.0	8.1	[44–46,48,52,53]	3.1	5.0	[40,50]
Crude fat (%)	0.4	12.1	[44–46,48,52,53]	2.4	4.8	[50]
Crude fibre (%)	1.9	14.2	[44,49,52,53]	5.8	42.0	[50]
Carbohydrates (%)	11.8	60.2	[27,44,48,52,53]	35.0	83.0	[27,50]
C/N ratio	30:1	39:1	[27,47]	55:1	77:1	[27,54]

As recommended by Bardiya et al. (1996) and Chulalaksananukul et al. (2012) [27,54], urea solution or livestock manure, such as dry chicken manure or cattle slurry, could be applied as a co-substrate to balance the C/N ratio of the mixed substrate. Both feedstocks are suitable due to an optimal C/N ratio of 10:1 to 12:1.

Zhu et al. (2023) [55] stated that FPW may also contain inhibitory acids that could be managed by co-digestion with high-nitrogen swine faeces. Co-substrates or additives for improved process stability and nutrient balance adjustment should favourably be fed at the very beginning of the anaerobic process [13,49,55,56].

Nitrogen supplementation with urea on day 97 stabilised the system, and H_2S as well as CH_4 recovered. Further investigations on an even longer timescale are required to delineate optimal nitrogen supplementation cycles.

The suitability of our mixed BW and PW for AD is likely due to their high content in carbohydrates, including cellulose and hemicellulose (cf. compilation of the literature data in Table 1). Our own determinations of TS and VS fall within the relatively broad range of reported values, suggesting that our fermenter input was representative. Specifically, BW had an average TS of 12.2% and VS of 84.9%TS, whereas PW showed an average TS of 10.8% and VS of 94.4%TS.

Most biogas plants employ the wet AD technology with a substrate TS of typically below 15% [57,58]. When the feedstock has a higher TS content, it can be slurried with recirculated digestate, process water, or another liquid substrate [56,59,60]. Considering the mixing ratio at the test case facility and the data in Table 1, our FPW had an average TS content of approximately 11.9%. Therefore, an additional mashing process as a pre-treatment step would not be necessary for large-scale applications [14].

The satisfactory BPP of our mixed FPW may also have benefitted from synergies of BW and PW in terms of mineral nutrients. While BW is richer in iron, calcium, and manganese [49], PW serves as a source of potassium [50].

The share of BW and PW at our test case site may vary over the year due to harvesting and processing specifics. Therefore, knowledge on the contribution of the individual waste streams on the BPP of the mixed waste is needed in terms of biogas yield and revenue projections. In a preliminary 21-day-batch test, the average BPP of pure PW was 726 $L_N \cdot (kg\ VSS)^{-1}$. Considering the BPP of the mixed substrate and the mixing ratio of 4:1 (PW:BW), this suggests a BW-BPP of 476 $L_N \cdot (kg\ VSS)^{-1}$. The lower BPP of BW is attributed to its lower share of carbohydrates compared to PW [27,44,48,50,52,53]. Specifically, the pineapple core is rich in sugar [61]. A higher BPP of PW was also recorded by Bardiya et al. (1996) and Hammid et al. (2019) [27,28]. Direct comparability of the above results to our experiment is, however, impaired by short testing periods.

Combustion of biogas containing H_2S in a CHP unit may require desulphurisation to prevent equipment corrosion and the rapid degradation of lubricants [62]. Biogas produced in this present study had a maximum H_2S concentration of 42 ppm, being lower than the limit values for use in a CHP [60,63]. Therefore, desulphurisation of the biogas generated from our mixed FPW is not mandatory.

In addition to carving into the potential limitations of the AD of mixed BW and PW waste, this study also intends to be a feasibility assessment for the implementation of an AD system for energy recovery at the test case site. Based on the test case site's FPW generation, we suggest a biogas plant consisting of two mesophilic continuously stirred reactors (CSTR) with a total volume of about 5300 m^3. The total own consumption of the biogas plant is estimated as 450 $\pm$ 120 $MWh_{el} \cdot a^{-1}$ and 1100 $MWh_{th} \cdot a^{-1}$. Currently, the fruit processing at the test case site requires approximately 1,400,000 $L \cdot a^{-1}$ of heavy oil for heat production and 7000 $MWh_{el} \cdot a^{-1}$. Assuming the combustion of the FPW-biogas in a CHP unit with a 40% power and 45% heat conversion efficiency, about 5100 $\pm$ 1300 $MWh_{el} \cdot a^{-1}$ and 5100 $\pm$ 1600 $MWh_{th} \cdot a^{-1}$ could potentially be obtained. This results in a net electricity production that covers approx. 67% of the facility's power demand, and a heat equivalent of around 450,000 $\pm$ 143,000 L of heavy oil$\cdot a^{-1}$. To cross-check this projection, an on-site pilot-scale test is currently underway.

5. Conclusions

The mixture of banana peelings and pineapple residues tested in this study appears to be a viable feedstock for AD under mesophilic conditions. To the best of our knowledge, this is the longest fermentation test conducted so far with this food processing waste documenting a BPP of 526 $L_N \cdot (kg\ VS)^{-1}$ and an average CH_4 concentration of 54%. If utilised in a (standard) CHP unit, the FPW of the test case site would potentially provide about 5100 $\pm$ 1300 $MWh_{el} \cdot a^{-1}$ and 5100 $\pm$ 1600 $MWh_{th} \cdot a^{-1}$. Thus, 73% of the Costa Rican facility's electricity demand and approx. 450,000 $\pm$ 143,000 $L \cdot a^{-1}$ of heavy oil for heat production could be replaced with energy derived from biogas production.

Despite these promising results, the NH_4-N concentration decreased steadily during the fermentation test, leading to process instabilities. Therefore, a co-substrate, such as dry chicken dung or urea solution, should be added to compensate for the nitrogen deficiency and adjust the C/N ratio. However, the study was unable to determine whether a sufficient supply of nutrients and trace elements for AD is guaranteed. Hence, further investigations into the substrates' composition, both individually and mixed, are required. To apply the findings of this study to future continuous large-scale applications, additional testing involving daily feeding and digestate removal is recommended.

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Conflicts of Interest: Author Carsten Linnenberg is employed by the company "AD Solutions GmbH". But for purposes of this investigation, there was no financing relationship with the company; therefore, there are no conflicts of interest. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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