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Research Article

Anaerobic Codigestion of Tuber Waste and Fruit Waste: Synergy and Enhanced Biogas Production

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Increased urbanization and consumerism have resulted in the excessive release of food waste and municipal solid waste. Such wastes contain abundant organic matter that can be transformed into energy, addressing the twin challenges of waste management and energy insecurity. In recent years, different studies have investigated ways of producing biogas through the codigestion of organic wastes. In this work, different food wastes were codigested and the biogas yield was determined. The effect of feedstock mixing ratios, temperature, and pH was studied. A mixing ratio of 1 : 1 produced the highest biogas yield (2907 ± 32 mL), nearly twice, which was obtained at a ratio of 1 : 4 (1532 ± 17 mL). The biogas yield increased with the temperature rise. The lowest yield of 2907 ± 32 mL was obtained at 20°C, while the highest yield of 4963 ± 54.6 mL was obtained at 40°C. Regarding pH, the yield was 2808 ± 31 mL at pH 6.5 and 7810 ± 86 mL at pH 7.3. This indicated a 178.1% increase in the biogas yield. The CN ratio for tuber waste and fruit waste was 18 and 28, respectively, while the corresponding pH was 6.7 and 6.9. A positive synergy index of 4.5 was obtained, which is higher than what is reported in the literature of codigested substrates. Irish potato peels and banana peels produced the highest biogas yield and are recommended for use as codigested feedstock.

1. Introduction

Energy insecurity and municipal solid waste management (MSWM) are among the most challenging problems globally. Rapid urbanization leads to a rise in municipal solid waste (MSW) generation that has created big problems regarding waste management and disposal. Globally, municipal solid waste production per annum exceeds 2 billion tons, which threatens the environment. Developing nations produce 109.5–525.6 kg per individual annually, while developed countries generally produce about 521.95–759.2 kg of MSW per individual annually [1]. In Kenya, according to Muniafu and Otiato, the total solid generated in the city of Nairobi was about 2,680 tons per day in 2002, equivalent to 0.714 kg per single person per day [2]. The analysis of municipal waste generated in Thika (a town in Kenya) for six months in 2014 shows that organic solid waste was about 68% [3]. All these wastes are biodegradable and therefore can be transformed into renewable and sustainable energy products, thus providing a solution to waste disposal and management.

The organic part of solid municipal waste (SMW) can be treated in a digester to release biogas and natural bioliquid fertilizers [4]. The substrate in the biodigester passes through four stages to release biogas, namely, hydrolysis, acidogenesis, acetogenesis, and lastly methanogenesis [5–7]. Biogas constituents vary depending on what was used in the digester and mainly consist of CH_4

(55–77%) and CO_2 (30–45%), although they contain a small number of some other gases such as ammonia (NH_3), nitrogen (N_2), hydrogen sulfide (H_2S), and some siloxane compounds [6].

The CN ratio, biodegradability index, and alkalinity among others are important parameters that should be considered in biogas production [8, 9]. Nitrogen is a vital constituent for the establishment of the cell structure, while carbon acts as energy-giving for microbes [10]. Zhou [11] reported that a CN ratio of 20–30 : 1 is favorable for microorganisms to work on the food substrate, and therefore, a low CN ratio substrate needs codigestion with high CN ratio feedstock. Some published work has discussed and summarized the composition of lignocellulose [12]. The composition of lignocellulose plants varies according to the level of maturity, species, and growth conditions [13]. Lignin, hemicellulose, and cellulose comprise more than 80% lignocellulosic material, and therefore, lignocellulose has a high CN ratio which results in low biogas production [14]. One of the perspectives for improving the biogas yield in the digester is through the codigestion of high and low CN ratio feedstock for synergetic effects. This may intensify the AD process due to superior nutrient stability, supporting microbial growth [15]. Codigestion of fruit waste, dung, and vegetable waste in a continuous digester at 35°C increased production from 230–450 L/kgVS [16], while batch codigestion of molasses and cow manure rise the yield from 60–230 L/kgVS [17]. Numerous factors contributed to an increase in the biogas yield including the temperature [18], carbon-to-nitrogen ratio [19], pH [20], organic loading rate (OLR), hydraulic retention time (HRT) [21], totally solid and particle size of the substrate [22], and digester configuration [23]. The utilization of wastes for the biogas yield is a crucial aspect of reducing greenhouse gas emissions, reducing odor related to the natural decomposition of organic wastes in landfills, and power production.

In Kenya, the Irish potato contributes to a third of overall energy consumption and is the second major crop [24]. It grows better in elevated areas than grain crops. The production of Irish potatoes in Kenya was 2.1 million tons in 2021, which is a 40% increase from 1.5 million tons in 2017 [25]. The increase in demand for Irish potatoes in Kenya has forced consumption to rise from 35 kg per single person in 2019 to 63 kg in 2021 [24], which indicates that waste is highly generated as consumerization increases. The production of bananas in 2012 constituted 38% of all the fruit produced in Kenya [26]. It generates income for households, especially in Tharaka (19%), Kirinyaga (21%), and Mt. Kenya (40%), and at the same time achieves food security [27]. Therefore, banana and Irish potatoes are widely grown and utilized in Kenya; their peels are readily available and hence were used in this study.

Banana and Irish potato peels contain high volatile solids and low ash content and are locally available in abundance for biogas production. Banana peels contain excessive nutrients [28], while Irish potato peels do not release excessive VFA. The anaerobic codigestion of fruit waste and tuber waste accelerates the hydrolysis process, dilutes the inhibitory substance as it balances nutrients, maintains the reactor equilibrium, and improves the yield. The synergistic effect of codigested food waste has also been reported [29, 30]. It is determined by dividing the yield obtained from codigestion by the yield obtained from individual substrates during monodigestion under the same conditions. A synergy index below 1 indicates an antagonistic effect, while that above 1 shows a synergistic effect [31]. Few studies have looked at the energy potential of banana peels and Irish potato peels; further investigations need to be conducted to address the enormous amount of organic waste in the substrate for the biogas yield. The present work codigested different food wastes and municipal solid wastes. The current work studied the effect of various parameters affecting the biogas yield during the codigestion of Irish potato peels and banana peels and resulting synergy. The novelty of the work is that, to date, no available literature has reported on the codigestion of Irish potato and banana peels and the resulting synergistic effect. The study assesses the outcome of the substrate mixing ratio, temperature, and pH for Irish potato peels codigested with banana peels. It contributes to renewable energy generation and the reduction of environmental pollution, as well as climate change, which is now an agenda worldwide.

2. Materials and Methods

2.1. Substrates and Inoculum. Five varieties of kitchen waste (KW) were collected from the Moi University cafeteria. These were ugali (UG), cooked rice (CR), cooked Irish potatoes (CIPs), cooked beans (CBs), and cooked banana (CBN). Municipal solid wastes obtained from the Moi University market included Irish potato peel (TW), banana peels (FrW), kale (SWW), cabbage leftover (CBG), and spinach leftover (SW). The feedstock was blended uniformly using an electrical blender for size reduction to increase the surface area to volume ratio. The quartering and sampling techniques were applied to obtain representative samples of the feedstock for anaerobic codigestion and were performed following the procedures analyzed by Campos-M and Campos-C [32]. The inoculum used for biogas production experiments in this study was collected from one of the sewers on Moi University's main campus. It was watery with a pH value of 7.4, showing a higher buffering ability that will help maintain the digester's pH and abstain from the accumulation of volatile fatty acid.

2.2. Analytical Methods. The pH was measured using a digital pH meter (Tecnal, Brazil), moisture content was obtained through an air oven-drying method using a laboratory oven (model LDO-150), and total solids were acquired through an air oven-drying method using a laboratory oven (model LDO-150) [33]. Similarly, volatile solids were obtained gravimetrically through the gravimetric valorization method using a muffle furnace (model ELF11/14B 220–240 V 1PH + N) [33]. The analytical determination of electrical conductivity and total dissolved solids (TDSs) was performed using a multiparameter meter (model HQ40d), while nitrates were quantified by HATCH 8039 through a cadmium reduction method using a spectrophotometer (model DR-900) [34]. Chemical oxygen demand (COD) was determined by the close reflux through the calorimetric method [35] using a spectrophotometer (model DR-900), and BOD was determined by using a BOD incubator (model WTW™ 208432) [36]. Substrates were weighed using an electronic precious balance (model HZT–A200), while the biodegradability index was obtained by the ratio between BOD and COD [37].

2.3. Experiment. Experiments were performed in a batch system to evaluate biogas production on a laboratory scale. Anaerobic codigestion experiments were conducted using plastic bottle reactors with a working volume of 1.5 L. Different food wastes (FWs) and some selected municipal solid wastes (MSWs) were codigested in separate reactors. The codigested feedstock that gives the highest yield was tested for other parameters. The effect of the substrate mixing ratio, temperature, and pH was studied. Typically, four different ratios of codigested substrates were tested, 1 : 1 ($TW : FrW_{1\&2}$), 1 : 2 ($TW : FrW_{1\&2}$), 1 : 3 ($TW : FrW_{1\&2}$), and 1 : 4 ($TW : FrW_{1\&2}$), and a range of temperature 20–40°C, with an increment of 5°C, and a pH of 6.5, 6.9, and 7.3 were investigated in this study. Substrates were fed into airtight digesters under anaerobic conditions, and biogas was measured by the water displacement method. Production was started within the first 8 hours (Figure 1), research run design as indicated in Table 1. One end of the plastic pipe was connected to the digester, while the other end was connected to the inverted cup-like apparatus, which was immersed in a container, and contained water. The displaced water was measured and was equal to the amount of biogas produced. The biogas was collected in a sampling gasbag for analysis. The HRT for this experiment was 15 days; thereafter, production was stopped.

2.4. Synergy Index (SI). The SI was obtained as the fraction of methane produced by the codigestion feedstock to that of individual substrates. Codigestion of the feedstock initiates an interactive effect that may be synergistic or antagonistic [38]. Kim et al. [39] described that the synergy index normally reflects the synergistic effect of numerous substrates. The following equation was applied in calculating the SI:

$$SI = \frac{\text{yield obtained from codi gestion of TW and FrW}}{\text{yield from TW + yield from FrW}}. \tag{1}$$

The SI greater than 1 shows that the codigestion process has positive synergy, results while the SI less than 1 indicates antagonistic results [38, 40].

3. Results and Discussion

3.1. Characterization of Feedstock. The characterization results of inoculum, tuber waste, and fruit waste are shown in Table 2. The pH of tuber waste, fruit waste, and inoculum was found to be 6.7, 6.9, and 7.4, respectively. The pH range of thermophilic anaerobic digestion is 6.5–7.6 [41]. The moisture content of fruit waste was found to be 78.3 ± 0.2%, total solid 21.7 ± 0.2%, and volatile solid 94.00 ± 1.9%, and these were in agreement with the literature [42–44]. Meanwhile, the moisture content, total solid, and volatile solids of Irish potato peels were found to be 72.00 ± 0.2, 28.00 ± 0.2, and 92.00 ± 1.7%, respectively, which was in agreement with the literature [45–47]. The total dissolved solids (TDSs) for fruit waste (banana peels) was 32.5 ± 0.4 g/L. The TDS increases the electrical conductivity of the feedstock and is important in the survival of microbes. The inoculum used had high alkalinity content and pH that provides buffering conditions that maintain the pH of the feedstock in the digester and hence will avoid the accumulation of VFA. The biodegradability index values range from zero to unity; for complete biodegradation, BI must be above 0.3 [37].

3.2. Codigestion of Different Substrates. Figure 2 indicates the biogas production from the codigestion of different feedstock. The codigestion of vegetable waste (VW) and fruit waste (FrW) produced the lowest yield (95 ± 1.1 mL) which may have been caused by the decomposition of easily digestible materials that leads to the production of more volatile fatty acids that hinder the methanogenesis process [48]. The highest yield (2907 ± 32 mL) was observed in the digester composed of tuber waste (TW) and fruit waste (FrW) due to the high biodegradability index (BI) of banana peels and tuber waste [49]. The CN ratio of banana peels was observed to be 28 : 1, while for Irish potato peels, it was 18 : 1, which are in line with [46, 50], respectively. The CN ratio of Irish potato peels was found to be less than recommended 20–30 : 1 [51], which implies that it is the nitrogen-rich substrate, and therefore, codigestion with the carbon-rich compound is required.

3.3. Effect of Substrate Mixing Ratios. Irish potato peels and banana peels were mixed in four ratios of 1 : 1, 1 : 2, 1 : 3, and 1 : 4. The mixing ratio acts as synergism to expand the existence of an adaptable and dynamic microbial community and balance nutrients, whereby pH for both reactors was decreased as production proceeded. Codigestion of banana peels and Irish potato peels is very crucial as it balances nutrients, maintains the reactor equilibrium, accelerates the hydrolysis process, and improves the yield. There was no thermal pretreatment performed for both substrates; biogas production commences within the first 8 hrs after setup for all the mixing ratios. On the 15^{th} day, the pH of the reactors decreased from 6.8 to 6.2, and this was due to the accumulation of VFA, which leads to the cessation of the product after 15 days. Volatile fatty acid accumulation resulted from banana peels, as shown in the literature [28], compared to Irish potato peels. Figure 3 shows the daily biogas production for different mixing ratios. The cumulative biogas yield increased progressively throughout the process.

Production decreases with an increase in mixing ratios as it can be observed that a mixing ratio of 1 : 1 displays the highest yield of 472 ± 5.2 mL on day 8 and that a mixing

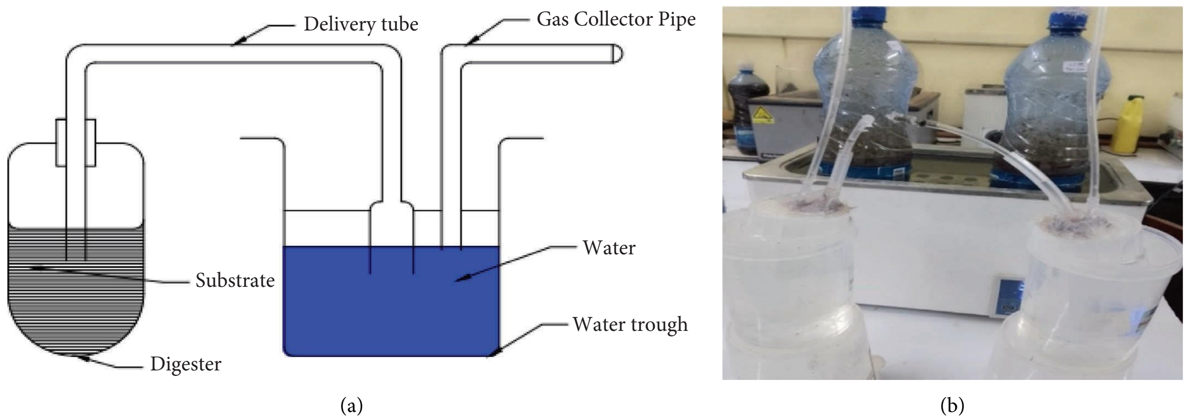

Figure 1: (a) Schematic diagram; (b) lab-scale setup for codigestion of Irish potato peels and banana peels in duplicate.

Table 1: Research run design for codigestion.

Variables	Range of values
Mixing ratio (Irish potato peels and banana peels)	1 : 1, 1 : 2, 1 : 3, and 1 : 4
Temperature	20, 25, 30, 35, and 40°C
pH	6.5, 6.9, and 7.4

Table 2: Characterization of tuber waste, fruit waste, and inoculum used in this study.

Parameters	TW	FrW	Inoculum
Moisture content (%)	72.0 ± 0.2	78.3 ± 0.20	86.2 ± 0.15
Total solid (%)	28.0 ± 0.2	21.7 ± 0.20	13.8 ± 0.50
Volatile solid (%)	92.0 ± 0.17	94.0 ± 1.90	63.4 ± 0.20
Ash content (%)	08.0 ± 0.17	06.0 ± 1.90	36.6 ± 0.35
pH	6.70 ± 0.20	6.9 ± 0.06	7.4 ± 0.06
Chemical oxygen demand (mg/L)	694.0 ± 1.0	2120 ± 2.52	7840 ± 1.53
Biological oxygen demand (mg/L)	408.0 ± 1.15	1134 ± 5.29	4013 ± 9.17
Biodegradability index (BOD/COD)	0.6	0.5	0.5
NO_3 (mg/L)	47.4 ± 0.40	140.7 ± 0.20	20.3 ± 0.3
Total dissolved solids g/L	39.9 ± 0.15	32.5 ± 0.40	3105 ± 1.53
Electrical conductivity (Ms/cm)	53.5 ± 2.0	51.5 ± 0.35	6243 ± 3.51

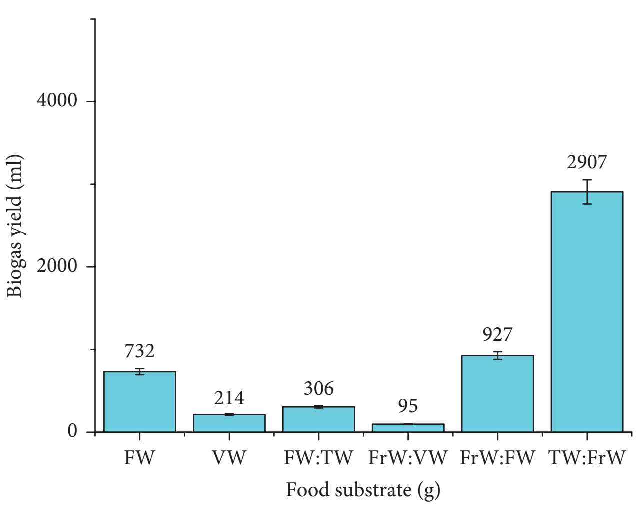

Figure 2: Biogas yield versus codigestion of different feedstock.

ration of 1 : 2 displays the highest yield on day 4 (504 ± 5.5 mL). On the other hand, a mixing ratio of 1 : 3 produced the highest yield on day 5 (455 ± 5.0 mL), and the 1 : 4 reactor displayed the highest yield (240 ± 2.64 mL) on day 7. A cumulative biogas yield of 2907 ± 32 mL was observed in the digester with 1 : 1 (TW : FrW) by the end of 15 days, which is near twice a mixing ratio of 1 : 4 which experienced a low biogas yield of 1532 ± 17 mL. This could have been due to an increase in nutrients (C : N) than the maximum; as a result, the reactor could not be maintained at equilibrium, therefore decelerating the hydrolysis process. Syaichhurozi [52] reported that the maximum biogas production of 114 mL on day 18 from codigestion of rice straw and banana peels resulted in a ratio of 2 : 3, while Barua et al. [28] recorded the highest biogas yield of 170 mL during the 16th day. Tasnim et al. [53] reported methane at 65% and carbon dioxide at 14%, while other gases were reported to be 21% during codigestion of cow dung, sewage sludge, and

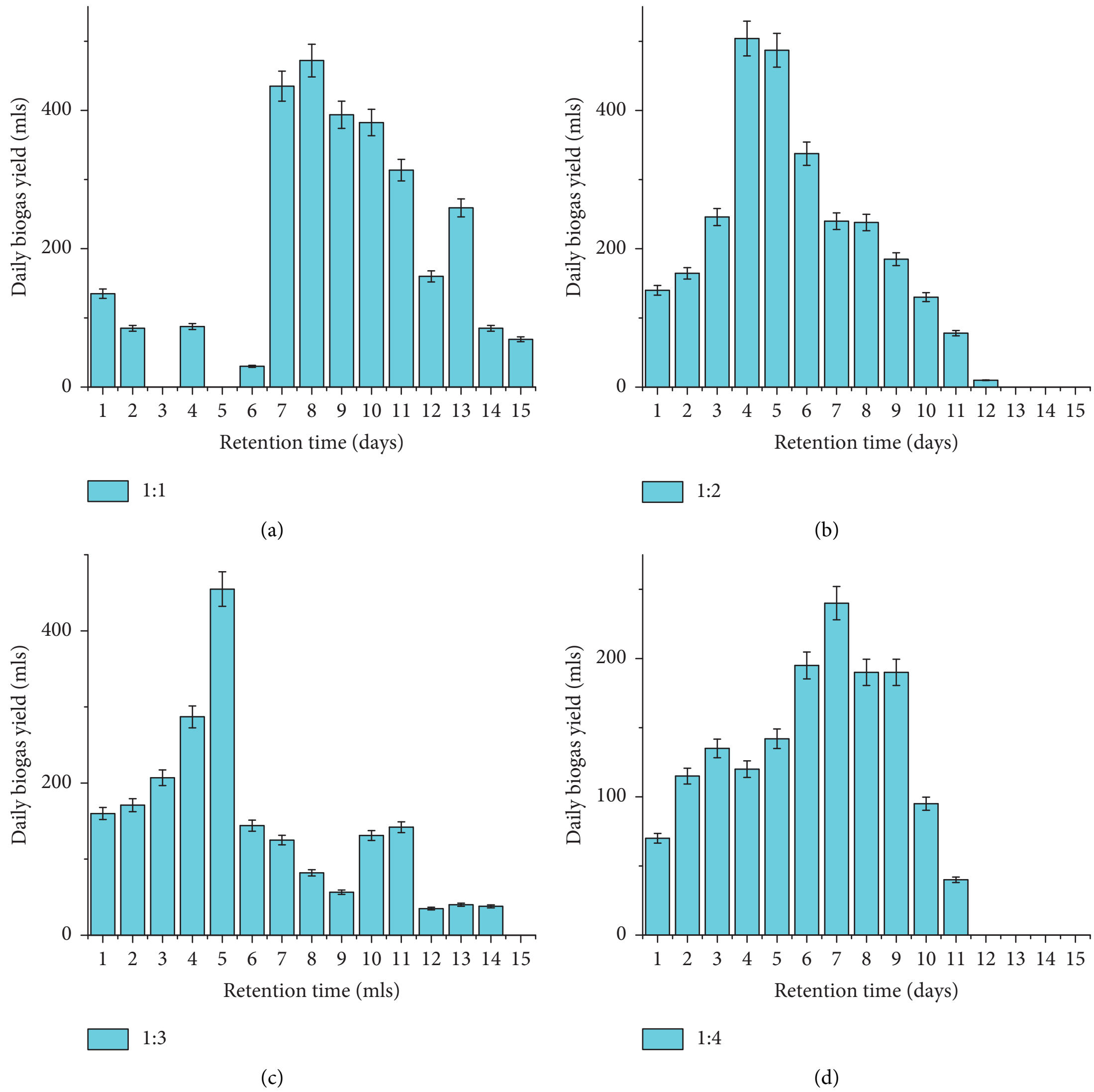

FIGURE 3: Daily biogas yield against retention time in various ratios of TW : FrW.

water hyacinth. Codigestion of banana peels and water hyacinth reported the highest methane yield with methane content 65.65%, carbon dioxide 25%, and hydrogen 8.67% [28]. The composition of biogas produced in this study was methane 58.7%, carbon dioxide 41.0%, oxygen 0.2%, and hydrogen sulfide 903 ppm.

3.4. Effect of Temperature on Biogas Yield. Five different working temperatures were considered. It was noted that the yield increases with the temperature rise. A temperature of 20°C produced the lowest yield of 2907 ± 32 mL, while 40°C produced the highest yield of 4963 ± 55 mL, nearly twice that of 20°C (Figure 4). The cumulative biogas yield was higher at 40°C, and it was observed that it increases with an increase in temperature. The cumulative biogas yield from the digester at a temperature of 40°C is a 70.7% increase as compared to the yield in the digester at 20°C. A related trend was noticed by Deepanraj et al. [54, 55] who studied the effect of temperature on the biogas yield from the AD of food wastes. The results revealed that the microbe's activity in this work depends on the operating temperature.

3.5. Effect of pH on Biogas Yield. The experiment was conducted for 7 days at a pH of 6.5, while for a pH of 6.9 and 7.3, it took 10 days for the production to cease. The highest production (7810 ± 86 mL) was achieved at a pH of 7.3 at 40°C, which is a 178.1% increase, while 2808 ± 31 mL was attained at a pH of 6.5. The daily and cumulative biogas production versus the retention time for all the digesters is shown in Figure 5. Cumulative biogas production was higher at a pH of 7.3, and it was observed that production increases as we increased the pH to optimal. The optimal pH for biogas production ranges from 6.5–7.5 [56]. A study by Abdui et al. [57] on the effects of an alkali pretreatment of mango leaves for biogas production by variation of pH from 6.5–8.0 shows that high production was obtained at an optimal range of pH 7.5. The addition of lemon juice causes the pH to drop from 6.9–6.5 because lemon, being highly acidic, is the

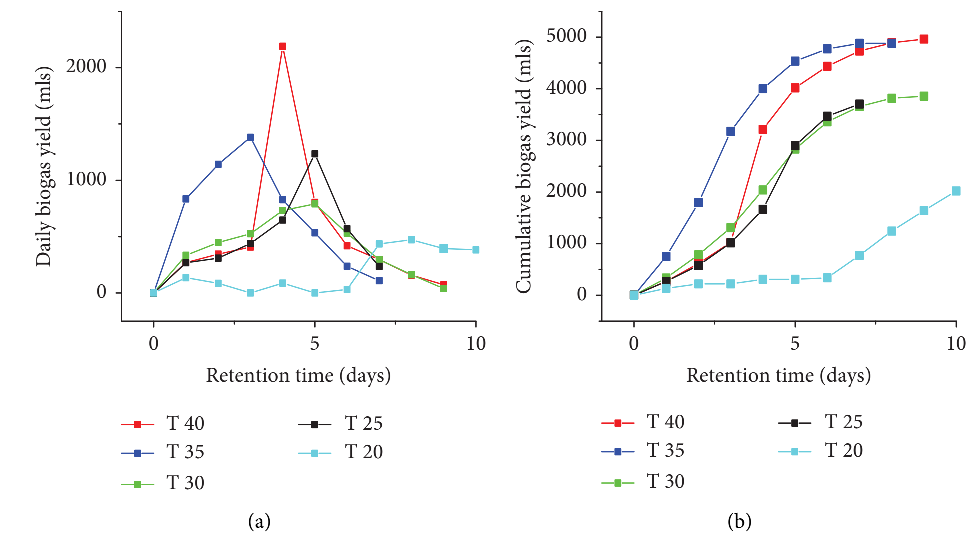

Figure 4: Biogas yield per retention time on the effect of temperature: (a) daily; (b) cumulative.

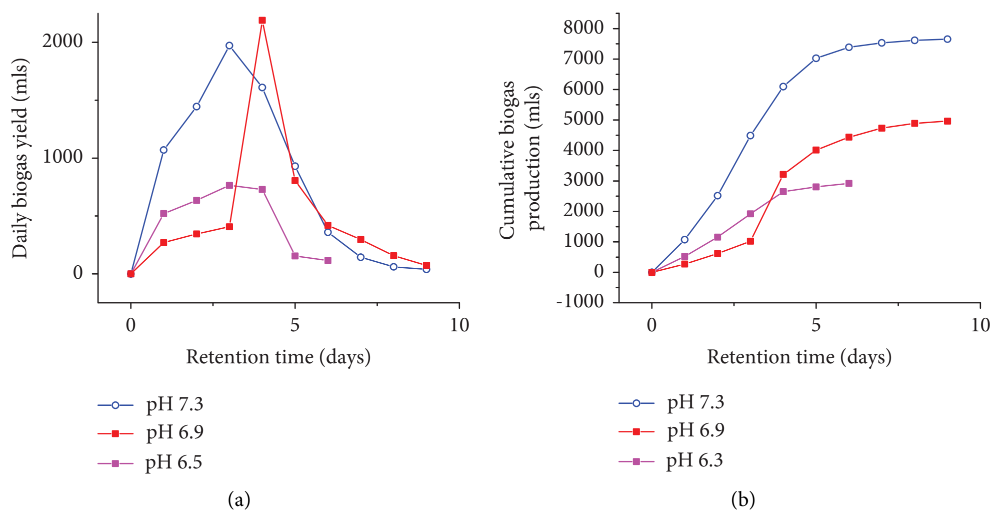

Figure 5: Biogas yield per retention time on the effect of pH: (a) daily; (b) cumulative.

reason for this decrease in pH, hence inhibiting the methanogenic activities as in the digester with a pH of 7.3. The results revealed that the activity of methanogenic microbes used in this study depends on the operating pH. The biogas produced contained methane 58.7%, carbon dioxide 41.0%, oxygen 0.1%, and hydrogen sulfide 903 ppm.

3.6. Synergy Effect of Anaerobic Codigestion. Methane produced from monodigestion of tuber waste and fruit waste was 294 and 357 mL, respectively. The synergy index (SI) value was obtained under the same conditions (temperature 20°C). Table 3 indicates the synergy index values for the codigestion of tuber and fruit waste. It was observed that codigestion has visibly positive synergistic effects (SI greater than 1) on AD for the methane yield from the two substrates (tuber waste and fruit waste). Kim et al [30] observed that codigestion of toilet paper, human excrete, and FW has no significant synergistic effects as the synergy index values vary from 0.939–1.05.

Table 3: SI for codigestion of tuber waste (Irish potato peels) and fruit waste (banana peels).

Feedstock	Biogas yield (mL)	SI
Monodigestion (TW)	294	—
Monodigestion (FrW)	357	—
Codigestion (TW : FrW)	2907	4.5

Ebner et al. [29] obtained a synergy index of 0.68 for the codigestion of dairy manure and FW, which shows a significant antagonistic effect. In contrast to this study, the two feedstock used had significant synergistic results. The current study found that codigestion of tuber waste and fruit waste can give a successful approach to generate energy by using available biomass wastes. The SI results may be related to the mixture proportions and characteristics of the feedstock, which could increase the corresponding buffer capacity, stimulate microbial synergism, balance nutrients, and dilute

Table 4: A correlation between the present work and previous studies.

Studies	Biogas produced (mL/g VS)	References
Ultrasonic processing of dairy manure and maize straw accompanied by its codigestion	240.32	[59]
Effect of pretreatment and anaerobic codigestion of waste-activated sludge and food waste	197 ± 16.7	[60]
Anaerobic codigestion of alkali-pretreated submerged acidified food waste and macrophytes	274.8	[61]
Codigestion of poultry droppings and briquetted wheat straw alkali pretreatment	227.87 ± 2.81	[62]
Anaerobic codigestion of microalgal biomass and coffee husks after thermal hydrolysis	196	[63]
Codigestion of water hyacinth and banana peels	296 ± 9	[28]
Codigestion of banana peels and Irish potato peels	7810 ± 86	This study

toxic compounds during digestion. According to Wang et al. [58], the synergistic effect is due to some additional beneficial nutrients which can enhance biodegradability and increase the microbes' metabolism rate in the digester.

3.7. A Correlation between the Present Work and Previous Studies. A correlation between the present work and previous studies was made, and it was observed that the codigestion of Irish potato peels and banana peels yield more biogas than that in other studies in Table 4. Irish potato peels and banana peels are highly recommended for codigestion instead of monodigestion.

3.8. Limitations of the Study. The biogas yield through codigestion of MSW and kitchen waste can be applied in the scope of household and industrial applications. This study focused on the codigestion of Irish potato peels and banana peels as a representative of MSW and KW. More studies can be performed using other components of MSW and KW under various processing conditions. The effect of temperature shows that productivity increases as the temperature rises, and therefore, it is more applicable in the industry as it is difficult for households to maintain the digester under 40°C.

3.9. Challenges and Future Directions. The potential challenges posed by the availability of MSW and KW due to rapid urbanization in the environment include pollution and emission of greenhouse gases which is now an agenda worldwide. Different technologies on how to treat municipal solid waste and kitchen waste have been discussed including sanitary landfill, incineration, anaerobic digestion, and bioreactor landfill. AD is the technology that has more advantages than the other three [64] as it is a more environmentally friendly technology, the best in electricity generation, and a cheap option. The authors recommend the use of anaerobic digestion at household and community levels to produce biogas for cooking and other energy requirements. Biogas production through codigestion of banana peels and Irish potato peels will also address the problems associated with waste management and disposal.

4. Conclusions

The results obtained from the codigestion of different food wastes and some selected municipal solid waste show that the codigestion of TW and FrW produces more yield than the rest of the reactors. On the effect of the mixing ratio, it was observed that a high yield (2907 ± 32 mL) was observed when the mixing ratio was 1 : 1, which is nearly twice the yield observed at 1 : 4 (1532 ± 17 mL). On other hand, the effect of temperature was observed on a high yield at a temperature of 40°C (4963 ± 55 mL), nearly twice of 20°C, while a low yield was observed at 20°C (2907 ± 32 mL); furthermore, the effect of pH was observed at a pH of 6.5 and 7.3, and yields were 2808 ± 31 and 7810 ± 86 mL, respectively, which is a 178.1% increase. The synergy effect of codigestion of tuber waste and fruit waste shows a positive result of about 4.5, which was not obtained in any codigestion before. Therefore, production increases with an increase in temperature and pH to optimal, while it decreases with an increase in the mixing ratio. Irish potato peels and banana peels produced the highest biogas yield and are recommended for use as codigested feedstock.

Abbreviations

MSWM: Municipal solid waste management
CIP: Cooked Irish potato
MSW: Municipal solid waste
CB: Cooked beans
AfDB: African Development Bank
CBN: Cooked banana
kg: Kilogram
TW: Tuber waste
AD: Anaerobic digestion
FrW: Fruit waste
CH_4: Methane
SWW: Kale
NH_3: Ammonia
CBG: Cabbage
N_2: Nitrogen
COD: Chemical oxygen demand
H_2S: Hydrogen sulfide
FW: Food waste
CN: Carbon-nitrogen ratio

BOD: Biological oxygen demand
BI: Biodegradability index
TDS: Total dissolved solid
L: Litre
VFA: Volatile fatty acid
SI: Synergy index
VW: Vegetable waste
OLR: Organic loading rate
mL: Milliliter
HRT: Hydraulic retention time
CR: Cooked rice
KW: Kitchen waste
UG: Ugali.

Data Availability

Data used to support the findings of this study are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest concerning the publication of this article.

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