Co-digestion of Fruit and Tuber Waste for Biogas Enhancement: A Synergy Effect

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Abstract: The increase in urbanization and consumerization leads to uncontrolled amounts of food waste and municipal solid waste in the surroundings. This waste contained organic matter that is potential for biogas production that could address the issues of energy insecurity and waste management. Various literature explores methods of generating biogas via co-digestion of feedstock. In this study, different feedstock was co-digested and biogas generation was measured. It was noted that banana peels and Irish potato peels give more yield. Different parameters were studied as mixing ratio, temperature, and pH. The highest amount of biogas production (2907± 32mL) was obtained at 1:1 which is twice the yield obtained in a digester containing 1:4 (1532±17mL). The yield was directly proportional to temperature; the highest yield was obtained at a temperature of 40°C while the lowest yield was at 20°C. Meanwhile, the pH that was considered in this study were 6.5, 6.9, and 7.3 where yield was 2808±31mL, yield (2907± 32mL), and 7810±86mL respectively. It shows that there is an increase in biogas by 178.1%. The pH for fruit waste and tuber waste were 6.9 and 6.7 while their CN ratio were 28 and 18 respectively. A synergy effect of 4.5 was observed which had never been obtained by other researchers before. The study recommends the use of banana peels (fruit waste) and Irish potato peels (tuber waste) as co-digested feedstock for biogas generation.

***Keywords*:** Keywords: Tuber waste, Fruit waste, Co-digestion, Biogas.

I. Introduction

Municipal solid waste and energy insecurity are among the most challenging problem worldwide. Urbanization and consumerization increased MSW generation which has caused a problem regarding waste discarding. Worldwide, MSW generation is more than 2 billion tons, which is dangerous to the environment. The developed nations generate 521.95-759.2kg of MSW per single individual annually [1]. Muniafu et al. (2010) indicated that in Kenya the amount of MSW generated in Nairobi city was 2,680 tons/day during 2002, approximately 0.714 kg/person for 24 hours [2]. In Thika town, the assessment shows that the MSW produced for 6 months in 2014 indicated that the amount of organic waste was 68% [3]. These wastes can be changed into sustainable and renewable energy and therefore a good solution for waste management.

The organic waste can be digested in a bio-digester to generate biogas as well as natural manure as a digestate material. The four steps for biogas generation include hydrolysis, acidogenesis, acetogenesis, and finally methanogenesis [4]. Biogas constituents vary depending on what was used in the bio-digester, but the main composition is methane (55–77%), and carbon dioxide (30–45%). It contains some other impurities at a minimal level as ammonia (NH_3), nitrogen (N_2), hydrogen sulfide (H_2S), and some siloxane [5]. The biodegradability index (BI), CN ratio (CN), and alkalinity are among the most necessary variables that must be observed in the biogas generation process. Nitrogen is an important component for the build-up of the cell's structure while the carbon component is used as an energy provider to the micro-organisms to survive [6]. Literature shows that a Carbon to Nitrogen ratio with a range of 20-30:1 is suitable for microbes to degrade the feedstock, thus the low carbon-to-nitrogen ratio feedstock requires co-digestion with a high carbon-to-nitrogen ratio for high biogas, methane yield, and synergic effect [7]. A study done on fruit waste co-digested with vegetable waste, and cow manure in mesophilic conditions proved that there was an increase of biogas from 230-450 L/kgVS [8] while co-digestion of molasses and manure increased from 60-230 L/kg volatile solid [9]. Biogas generation is normally contributed by various parameters such as carbon-to-nitrogen ratio [10], temperature [11], organic loading rate (OLR), hydraulic retention time, (HRT) [12], digester configuration [13], and particle size of the substrate [14]. The usage of organic waste for biogas production is a good aspect of lowering greenhouse emission that is brought through the decomposition of MSW left to decompose on the land.

Irish potato donates to 1/3 of energy crop consumption in Kenya, and is the second main crop in the country [15]. It grows well in uplifted areas as compared to cereal crops. In Kenya, Irish potato peels generated almost 2.1 million tons around 2021 which is an increase of 40% as compared to 2017 which was 1.5 million tons [16]. The rise in the demand for Irish potatoes has enforced consumption to increase from 35kg/person in 2019 to 63kg in 2021 [15]. This indicated that organic waste from Irish potato peels is extremely produced as

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urbanization and consumption increase. In Kenya, the overall banana production in 2012 contributed to 38% of all the fruit harvesting in the country [17]. Therefore, Irish potatoes and bananas are mostly used in Kenya as food crops; thus their peels are locally available and therefore were applied in the current work.

Irish potato peels and banana peels have low ash content, high volatile solids (TVS) and are available in abundance for biogas production. The anaerobic co-digestion (ACo-D) of tuber waste and fruit waste speed up the hydrolysis process and dilutes the inhibitory compounds available in the co-digested feedstock as it keeps the bio-digester equilibrium, balance the nutrients, and enhance the amount of biogas generation. Different synergistic index (SI) during co-digestion has also been presented in the literature [18] [19]. It is obtained by dividing the amount of biogas obtained via co-digestion by the amount of biogas obtained from each feedstock during mono-digestion under the same environmental conditions. When there is a (SI) of less than 1 it shows that there is an antagonistic outcome while more than 1 indicates that there is a complementary effect [20]. The present work explored different parameters that affect biogas generation during the co-digestion of Irish potato peels and banana peels. There is no available literature that reported a high synergistic effect as the current study; and therefore a uniqueness of the present study.

II. Materials and Methods

A. Substrate and Inoculum

The utilized kitchen waste in this work includes ugali (UG), cooked Irish potatoes (CIP), cooked rice (CR), cooked banana (CBN), and cooked beans (CB) which were obtained from the cafeteria, at Moi University. The municipal solid waste including banana peels (FrW), spinach leftover (SW), Irish potato peel (TW), cabbage leftover (CBG), and kale (SWW) were obtained from the market near Moi University. The electrical blender was used to reduce the feedstock size thus; increasing the surface area to volume ratio. The sampling techniques used in this study to obtain a sample representative for anaerobic co-digestion were the quartering technique following the method explored by Campos et al. [21]. The inoculum used during biogas production was obtained from a sewer on the University campus. The inoculum had a pH of 7.4 indicating a higher buffering capacity that will assist in maintaining the pH of the digester and avoid volatile fatty acid accumulation.

B. Analytical Technique Methods

The moisture content and total solid were obtained via the air-oven-drying technique by the utilization of an oven (LDO-150) [22]. The pH was recorded using an electronic pH meter (Tecnal, Brazil). On the other hand, gravimetric valorization techniques were used to obtain volatile solids gravimetrically via a muffle furnace (ELF11/14B 220-240V 1PH+N) [22]. The analytical calculation of total dissolved solids (TDS) and electrical conductivity was done via a multipara meter (HQ40d); whereas nitrates were measured by HATCH 8039 using a cadmium reduction procedures via a Spectrophotometer (DR-900) [23]. The biological Oxygen Demand (BOD) was obtained by a BOD incubator (model WTW^{TM} 208432) [24]. COD was conducted using the calorimetric procedure [25] via a spectrophotometer (DR-900). The capability of the feedstock to be degraded by microbes (biodegradability index) was determined via dividing BOD and COD obtained [26] while an electronic balance (HZT –A200) was used to weigh the feedstock.

C. Experimental

Lab work was conducted in a batch order to assess the generation of biogas on a laboratory scale. Plastic bottles with a volume of 1.5 were used as a bio-digester. Some selected municipal solid waste and kitchen waste were co-digested. Tuber waste and fruit waste show a high yield as compared to other feedstock and were assessed for the effect of other variables. The effect of pH, temperature, and mixing ratios was investigated. Mixing ratios were varied as 1:1, 1:2, 1:3, and 1:4, while temperatures were 20-40°C with an incremental of 5. On the other hand, pH varies as 6.5, 6.9, and 7.3. The co-digested feedstock was fed into the digester and biogas was recorded through the displacement of water and biogas yield was noticed to begin during the first 8 hrs. **Figure 1**.

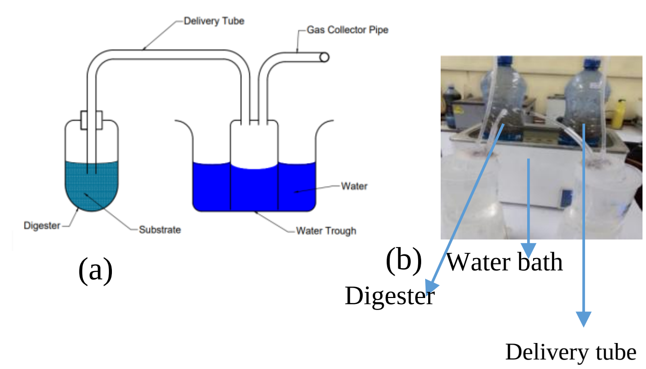

Fig. 1: (a) Illustrative diagram (b) Laboratory-scale setup for co-digestion of banana peels and Irish potato peels.

D. Synergy Index

Synergy Index is attained by dividing the methane generated in the co-digestion digester by the production from independent feedstock under the same environment. Co-digestion of different feedstock enhances the interactive effect that can result in antagonistic or synergistic effects [27]. Eq. 1 was used to find out the value of SI.

$$SI = \frac{Yield\ obtained\ from\ codigestion\ of\ TW\&FrW}{Yield\ obtained\ from\ TW + Yield\ from\ FrW} \quad (1)$$

When the obtained synergy index is $1 < 1$ suggested antagonistic results while > 1 shows that the co-digestion process has positive results [28] [27].

III. RESULTS AND DISCUSSION

A. Characterization of the Feedstock

The obtained results from Irish potato peels, inoculum, and banana peels are tabulated in **Table 1,** and their pH was 6.9, 6.7, and 7.4 respectively. Literature shows that the pH that is suitable for thermophilic AD ranges from 6.5 to 7.6 [29]. The total solid of banana peel feedstock were 21.7±0.2%, volatile solid 94.00±1.9%, and moisture content 78.3±0.2%, these were in matches with the data in literature [30] [31] [32]. Similarly, the mc, vs, and tvs of tuber waste peels were 72.00±0.2%, 92.00±1.7%, and 28.00±0.2%, respectively that were agreed with the data from literature [33], [34] [35]. The TDS for banana peels was 32.5±0.4g/L. The electrical conductivity of the respective feedstock increases due to the increases in total dissolved solid (TDS) which is very crucial for the microbes to survive. The used inoculum had alkalinity pH which buffers the digester and maintains the pH in the bio-digester and therefore avoids VFA accumulation. Literature indicates that the biodegradability index (BI) values vary from zero to unity, for biodegradation to be complete BI should be greater than 0.3 [26].

Parameter	TW	FrW	Inoculum
MC (%))	72.0 ± 0.2	78.3 ± 0.2	86.2 ± 0.2
TS (%)	28.0 ± 0.2	21.7 ± 0.2	13.8 ± 0.5
TVS (%)	92.0 ± 0.2	94.0 ± 1.9	63.4 ± 0.2
AC (%)	08.0 ± 0.2	06.0 ± 1.9	36.6 ± 0.4
pH	6.70 ± 0.2	6.9 ± 0.1	7.4 ± 0.1
COD (mg/L)	694.0 ± 1.0	2120 ± 2.5	7840 ± 1.5
BOD (mg/L)	408.0 ± 1.2	1134 ± 5.3	4013 ± 9.2
BI	0.6	0.5	0.5
NO_3 (mg/L)	47.4 ±0.4	140.7 ± 0.2	20.3 ± 0.3
TDS g/L	39.9 ± 0.2	32.5 ± 0.4	3105 ± 1.5
EC(Ms/cm)	53.5 ± 2.0	51.5 ± 0.4	6243 ± 3.5

B. Co-digestion of various feedstock

Biogas generation through co-digestion of different feedstock is illustrated in **Figure 2**. Fruit waste co-digested with vegetable waste generates the lowest biogas generation (95±1.1mL) which might have been contributed due to the formation of VFA caused by the existence of vegetable and fruit waste that automatically hinders the methanogenic process [36]. The highest biogas generation (2907±32 mL) was noticed in the bio-digester containing fruit waste (FrW) and tuber (TW) and may be contributed to high BI which is in line with [37]. The obtained carbon to nitrogen ratio for Irish potato peels was 18:1 while for banana waste (peels) was 28:1 which agreed with the values obtained in [38] [34] respectively. Recommended CN ratio is 20-30:1 [39] whereas that of tuber waste was lower than the recommended and thus it requires co-digestion with high CN ratio feedstock.

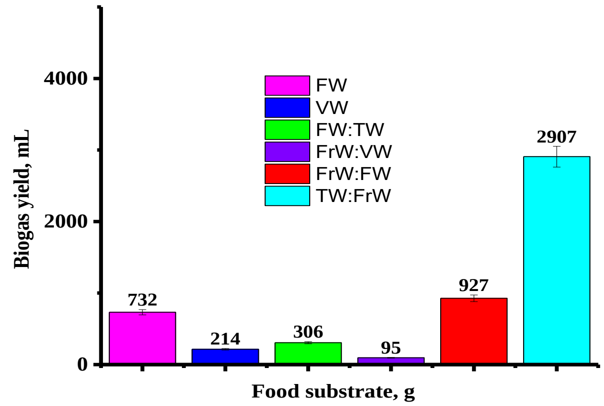

Fig. 2: Biodegradation against co-digestion of various feedstock

C. Effect of mixing ratios of the feedstock

Banana peels and Irish potato peel waste were mixed in a ratio of 1:1 TW: FrW, 1:2 TW: FrW, 1:3 TW: FrW, and 1:4 TW: FrW. The mixing ratio balances the nutrients and behaves as a synergism to increase the availability of microbial communities. The pH for both reactors in a duplicated form ceased as the production proceed. The Anaerobic co-digestion (ACo-D) of tuber waste and fruit waste is important as it keeps the bio-reactor equilibrium, balances the nutrients in the digester, and accelerates the biodegradation process, thus enhancing the yield. Thermal pretreatment was done and biogas yield commences within the first 8hrs. As the days numbered, the pH of both digesters decreased because of the accumulation of volatile fatty acid, thus no production was recorded on day 16. The accumulation of VFA resulted because of banana peels as indicated by other researchers [40] in comparison to TW. **Figure 3** indicates biogas generation from various mixing ratios, the cumulative biogas generation was increased progressively over the process.

As the mixing ratio increased the production of biogas ceased. This can be explained as 1:1 (2907mL), 1:2 (2760mL), 1:3 (2073 mL), and 1:4 (1532 mL). The yield recorded in the digester with 1:1 produce biogas that is nearly twice the biogas generated in the digester contained 1:4. This is due to the balancing of nutrients in the digester having 1:1 and thus accelerates the hydrolysis process. Syaichhurozi et al. [41] communicated that the maximal biogas yield of 114 mL was noticed on day 18 from co-digestion of banana peels and rice straw in a ratio of 2:3 whereas [40] observed the maximal amount of biogas during the 16th day of 170mL. Tasnim et al.

studied the co-digestion of water hyacinth, sewage sludge, and cow dung where the researchers recorded that carbon dioxide was 14%, and methane was 65%, meanwhile, other gases contributed 21% [42]. During the co-digestion of banana peels and water, hyacinth was reported to have carbon dioxide 25%, methane 65.65%, and hydrogen gas 8.67% [40]. Biogas yield from the current study composed of carbon dioxide 41.0%, methane 58.7%, hydrogen sulfide 903 ppm, and oxygen 0.2%.

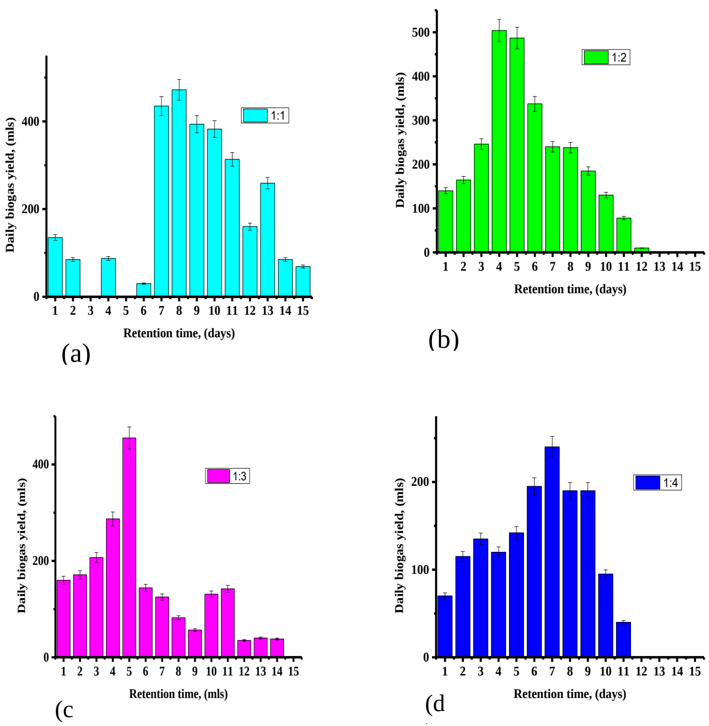

Fig. 2: Biogas production versus time in four various ratios for Tuber waste and Fruit waste

D. Effect of working temperature on biogas production

Various working temperature was studied in this study and was noted that as the temperature rises yield increase. The bio-digester with a working temp of 20°C generate 2907±32 mL while a bio-digester at 40°C produced 4963±55 mL, which is almost twice the yield obtained at 20°C **Figure 4**. The cumulative biogas yield from the digester with a temperature of 40 °C is a 70.7% increase as compared to the yield in the digester at 20°C. The same trend was observed and studied by Deepanraj et al.[43] [44] where the consequences of temperature variation on biogas production from the anaerobic digestion of food wastes were studied. The results prove that the microbe’s activity in the current study relies on the working temperature of the digester.

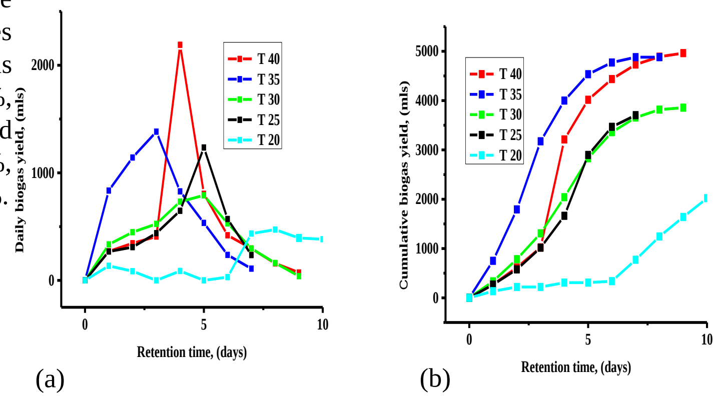

Fig. 3: Effect of temperature on biogas generation versus time (a) day-to-day (b) accumulating

E. Outcome of pH on biogas generation

For the pH of 6.5, the experiments were conducted for 7 days, whereas for 6.9 & 7.3 the production took a longer number of days (10 days) to end. At a pH of 7.3, the temperature of 40°C biogas production was (7810±86mL) which is a 178.1% increase as compared to a pH of 6.5 2808±31mL. **Fig 5** indicates the day-to-day and accumulative biogas generation against time for the three digesters having different pH but the same feedstock. The cumulative biogas generation at a pH of 7.3 was higher in comparison to other digesters with other pH, it was noticed that there was an improvement in the yield as the pH increases to the optimum. The maximum pH for biogas generation varies from 6.5-7.5 [45]. Research done on biogas production using mango leaves pretreated with an alkaline solution proved that the pH of 7.5 produced the highest amount of biogas [46] which is in line with the present study. A drop of lemon juice was used to pretreat the co-digested feedstock (Irish potato peels and banana peels) from 6.9 to 6.5 and therefore methanogenic activities within the digester-contained feedstock with pH of 6.5 were inhibited in comparison to other digesters. Thus, the results proved that the methanogenic activities depend on the pH of the digester **Fig 5.**

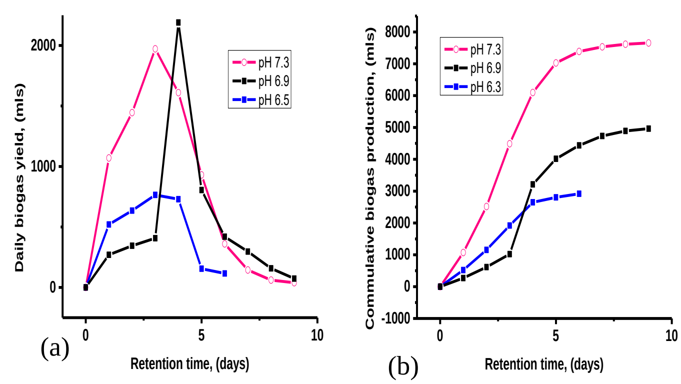

Fig. 5: Effect of pH on biogas production versus time (a) day-to-day (b) cumulative

F. Synergic effect for ACo-D

Biogas yield from mono-digestion of fruit waste was 357mL while tuber waste was 294mL. The synergic index (SI) value was calculated from mono-digestion with a temperature of 20°C. A synergy index for anaerobic co-digestion (ACo-D) of fruit waste and tuber waste is indicated in **Table 2**. It was noted that the (ACo-D) of tuber waste and banana peels (fruit waste) has a beneficial synergistic effect on the anaerobic digestion of the two feedstock. Literature shows that co-digestion of human excretion, toilet paper, and food waste did not show a notable synergistic effect as the SI number ranged from 0.939 to 1.05 [19]. On the other hand, a synergy index of 0.68 was obtained when co-digest food waste and dairy manure which shows an antagonistic effect [18]. The SI is related to feedstock properties and the proportionality of mixing the substrate, which increases the buffering capacity of the co-digested feedstock. Literature shows that a synergetic effect is because of the addition of some important nutrient that can enhance the biodegradability and therefore rise the microbe's rate in the digester. Based on the current study, the co-digested feedstock had a significant synergetic effect, as its SI value was 4.5. The present work proves that the use of Irish potato peels (tuber waste) and banana peels (fruit waste) can solve the twin challenges of energy insecurity and waste management.

TABLE II: SI FOR IRISH POTATO PEELS (TUBER WASTE) CO-DIGESTED WITH BANANA PEELS (FRUIT WASTE) FOR BIOGAS YIELD

Food substrate	Biogas yield, mL	SI
Mono-digestion (TW)	294	-
Mon-digestion (FrW)	357	-
Co- digestion (TW: FrW)	2907	4.5

G. A Comparison Between The Current Work And The Previous One.

A comparison between the current study and the literature was conducted and observed that co-digestion of the feedstock used in this study produce a high amount of biogas in comparison to the literature **Table 3**.

TABLE III: A RELATIONSHIP BETWEEN THE CURRENT WORK AND PREVIOUS WORK FROM LITERATURE.

A study	**Biogas generation (mL/g VS)**	**Reference**
Anaerobic co-digestion of dairy maize straw and manure	240.3	[47]
ACo-D of food waste and waste-activated sludge pretreated with an alkali solution	197 ± 16.7	[48]
ACo-D of acidified food waste and macrophytes pretreated with alkaline	274.8	[49]
ACo-D of briquetted wheat straw and poultry droppings pretreated with alkali	227.87 ± 3	[50]
Banana peels waste co-digestion with water hyacinth	296 ± 9	[40]
Coffee husks co-digested with microalgal biomass under thermal treatment	196	[51]
Co-digestion of banana peels (fruit waste) and Irish potato peels (tuber waste)	7810±89	This study

H. Limitations of the present study

The generation of biogas via food waste co-digested with MSW can be used in different sectors such as industrial and household purposes. The study is based on kitchen food waste co-digested with some selected MSW; more studies can be conducted using other components of kitchen food waste and MSW while varying the parameters. On the effect of temperature, it was noticed that biogas production rises as how the temperature increases and thus it is more applicable in industrial rather than household as it is hard to maintain the bio-digester at the recommended temperature (40°C).

IV. Conclusions

The obtained results from ACo-D of some selected MSW and kitchen food waste indicated that co-digestion of tuber and fruit waste gives the highest yield. Four different parameters were considered and proved that 1:1 (TW: FrW) gives the highest yield (2907±32mL) while 1:4 (1532±17mL). The yield obtained in the digester of 1:1 is almost twice, what has been recorded in the digester having 1:4. On the effect of temperature it was noticed that the highest amount of biogas was recorded when the temperature was 40°C (4963±55mL) and was twice of what was recorded in the digester having 20°C (2907±32mL). On the effect due to pH, it was noticed that at pH of 7.3 yield was 7810±86mLwhich was a 178.1% increase of what was recorded in the digester with a pH of 6.5 (2808±31mL). The synergetic index of 4.5 was obtained using fruit waste and tuber waste and no data from literature work showed high SI as the current work. Production of biogas using fruit waste and tuber waste is recommended to be used as co-digested feedstock.

V. Conflicts of Interest

The authors declared that no conflicts of interest concerning the publication of this manuscript.

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