

Processing of East African Highland Green Bananas: Waste Generation and Characterization as a Potential Feedstock for Biogas Production in Uganda

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Abstract

Uganda is the second largest global producer of bananas and the industry generates different waste residues both at production and processing levels. This study aimed at assessing the state of banana processing, waste generation and its characterization for evaluation as feedstock for biogas production. The study was undertaken through a reconnaissance visit to western Uganda, one of the most banana producing regions. The information was collected following standard qualitative methods and laboratory analysis. Results revealed that processing of banana fruits mainly involved manual peeling of fruits to generate fresh pulp and large quantities of banana waste. The waste contained more than 80 % moisture content and volatile solids. It also had higher carbon content than total nitrogen that translated into a high C:N ratio of 41:1. The lignocellulose content comprised cellulose 21.16 %, hemicelluloses 10.46 % and lignin 11.31 %. The Biochemical Methane Potential (BMP) test showed a methane yield of 0.436 m³ CH₄/KgVS which was higher than 0.340 m³ CH₄/KgVS for grass. The highest methane production of 79.9 ml CH₄/gVS/day was recorded at a retention time of 24 days. These results showed that banana waste was a favorable feedstock for biogas production through anaerobic digestion. Appropriate pre-treatment of lignocellulose would be required to enhance feedstock digestibility to improve biogas yield. The study concluded that utilization of banana waste via anaerobic digestion to produce biogas was the most economically viable option to alleviate the industry's energy scarcity.

Key words: Banana processing; Banana waste characterization; Anaerobic Digestion; Biogas production.

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1. Introduction

Banana production systems and banana fruit processing accumulate large quantities of waste residues due to high quality demands of the markets [23]. The East African highland cooking banana subgroup (AAA-EA group) locally called *matooke*, is the major grown variety and a leading staple food [49]. Studies on banana production have shown that over 70% of the farmers in major producing districts within the Lake Victoria basin grow bananas as a primary crop and over 50% depend on banana for food and income security [9]. Uganda is the second largest global producer of bananas after India and the leading in Africa, with annual production estimated at 9.77 million tonnes [22, 48]. Generally, crop production and processing produce huge amount of waste termed as agricultural waste [38]. Banana production, post-harvest handling (market value chain) and the ultimate processing to generate edible fruit pulp are all accompanied by release of large volumes of inedible residues that constitute the banana waste. Banana waste (BW) comprises: rotten/damaged fruits, peels, fruit-bunch-stem (stalks), leaves, fibers, pseudo-stem, and rhizome [1]. As a matter of fact, it is estimated that more than three million tonnes of banana waste are generated annually in the country [45, 49]. Studies on banana post harvest losses (PHL) by Asha and his colleagues [6] revealed that poor banana handling methods along the market value chain can lead to a loss of 9.6% of mature banana fruits mainly as a result of short green shelf life and rapid ripening. Such PHL that mainly occur during high production with limited market, can be circumvented by industrial banana processing into dried banana chips that can serve as the raw material for value-added products such as starch and flour, for both export and local food security. Thus, the production and processing that release major waste streams remain the major challenge. However, Uganda's banana industrialization relies mainly on costly imported petroleum products for fuel energy and is grappling with inadequate and expensive energy [24]. Hence, utilization of banana waste as feedstock for energy production to relieve the banana industry from both energy scarcity and reliability can be the best option and first priority for managing banana waste in Uganda. Among the applicable waste-to-energy technologies, anaerobic digestion to generate biogas has been recommended as the most appropriate for banana waste due to it being rich in organic matter with high moisture content [24, 47].

In biogas milieu, the term feedstock is defined as any substrate that can be converted to methane by anaerobic bacteria [46]. Generally, biogas feedstock comprises of all compounds with a substantial amount of organic matter that is finally converted to mainly methane and carbon dioxide through anaerobic digestion. Biogas feedstocks range from readily degradable animal manure, wastewater sludge, and agricultural wastes to complex lignocellulosic biomass that contains high-solid content. Besides, toxic compounds that contain organic matter may also be biomethanised depending on the technology applied [46]. Nevertheless, traditional feedstock for anaerobic digestion has mainly been associated with animal manure (pig, cattle, and poultry) and sewage sludge from wastewater treatment plants. The use of these feedstocks in anaerobic digestion has been mainly to promote good sanitation and local utilization of biogas. However, the increased craving for renewable energy forms for industrial purposes accompanied by the demand for new eco-friendly waste management strategies has broadened the search for alternative biogas feedstocks. This has introduced new field of feedstock sources such as energy crops and the industrial wastes such as residues from agro-processing, slaughterhouses and dairies as well as organic fraction of municipal solid wastes (OFMSW) as shown in Figure 1. Clearly, agriculture accounts for the largest potential sources of

feedstocks for biogas production and includes the harvest remains, animal manure, weeds and energy crops.

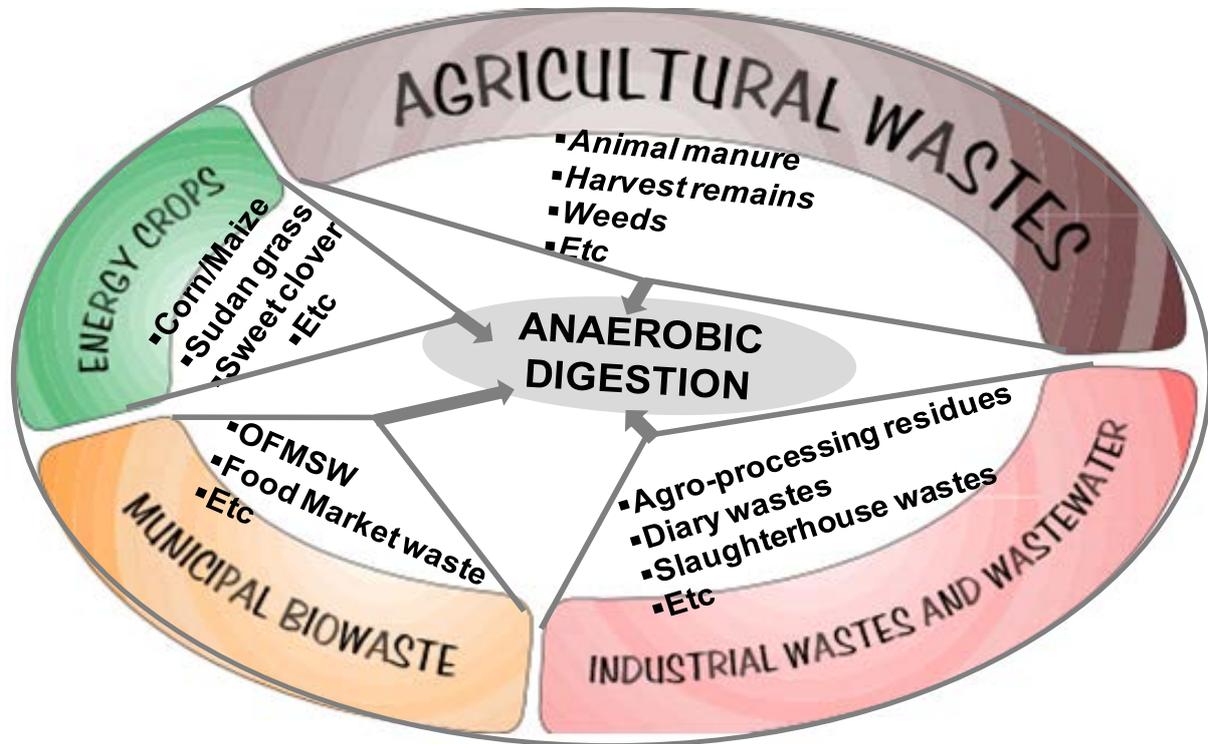


Figure 1: Major sources of feedstocks for anaerobic digestion (adapted from Steffen and his colleagues [46])

Animal manure, as feedstock for biogas production, is popular mainly due to the biotechnological ease of handling during anaerobic digestion. For instance, cow slurry has inherent microbial flora necessary for anaerobic digestion of the feedstock to generate biogas. Typically, cow's rumen is one of the excellent rich sources of methanogenic bacteria required for bioreactor start-up and hence using such animal manure offsets the requirement for feedstock inoculation. However, using animal manure as biogas feedstocks generates less biogas when compared with fresh plant biomass. This low biogas yield may be attributed to the fact that animal manure, probably is not well balanced in other nutrients required for balanced microbial growth, but rather containing complex polysaccharides such as lignocelluloses. These are not only hard to digest, but they also require consortia of microorganisms for complete breakdown. The high ligno-cellulose content of waste substrate such as plant biomass has been reported to slow down the bio-gasification process primarily due to limited microbial hydrolysis of complex polysaccharides abundant in such waste [39]. A research study by Martin-Ryals, [31] however, reported that an eco-friendly and inexpensive way of effective hydrolysis of ligno-cellulosic biopolymers can be achieved by microbial pre-treatment. Effective hydrolysis is only by synergistic interactions and co-metabolism of different microbial strains mainly of fungal origin and a few rare bacterial strains [53].

Moreover, anaerobic digestion has a superior advantage of coupling energy (biogas) generation along with plant organic fertilizer (bioslurry) generation at minimal net operational energy requirement. Other advantages of

anaerobic digestion (AD) process are: reduction in wastes' pathogens, smaller land suitability and decrease in waste's pollution potential to levels that are non toxic to the environment. However, physical-chemical nature of the feedstock influences the bioreactor configuration (bioreactor design and operational parameters) and has a comprehensive effect on liquor microbial biochemistry that ultimately alters the overall AD process.

Thus banana waste must be characterized prior to use as feedstock for biogas production. Banana waste characterization and use as substrate feed for biogas production is limited to biovalorization studies by Salyeem and his colleagues [41] and co-digestion experiments by Kirtane and his colleagues [28,49]. However, thorough characterization of banana waste from mixed streams containing fruit bunch stalks, pseudo-stems and stem fibers was never investigated. Besides, the composition of banana waste varies considerably depending on the variety/cultivar grown, soil, agronomic practices, type of processing, season, geographical origins and also the varying degree of ripeness and post-harvest handling [41]. As such, each waste fraction from banana processing needs to be characterized separately, to provide baseline data for future value addition. Hence, a comprehensive assessment of the quantity and composition (quality) of the feedstock is required prior anaerobic digestion. The objective of this research study was to assess the key steps in processing of green bananas into pulp, and auditing and characterization of the major resulting residual wastes namely peels, peduncle (fruit-bunch stalk) and fruit discard, in order to evaluate their potential as feedstocks for biogas production. Therefore, the physicochemical analysis of composite banana waste and the biochemical quality and feasibility for use of banana waste as a feed stock for biogas production are reported.

2. Methodology

2.1. Assessment of banana processing and banana waste audit

A banana waste audit was done through a reconnaissance visit to western Uganda, one of the most banana producing regions in the country [6]. Information regarding the nature and type of processing, quantity and quality of waste generated, and current waste management methods was collected through guided survey along the processing plant, open-ended interviews, photography and sampling for laboratory analysis [37]. Waste quantification and characterization was done by integration of qualitative and quantitative methods, and ultimately laboratory analysis for evaluation of biochemical composition. Banana waste generated from processing of banana fruit bunch into pulp was quantitatively estimated over a period of six months, based on five commonly cultivated varieties of bananas locally known as *Mporogoma*, *Kishansha*, *Kibuzi*, *Mbwazirime* and *Enyeru*. The fruit bunches were weighed prior to processing and subsequently de-bunched and fruit-fingers peeled to obtain the fresh pulp as the product. The generated waste residue fractions were weighed using a precision balance and their percentage composition determined. Banana waste samples for laboratory analysis were collected from different processing streams and transported to the laboratory for analysis and biogas production experimentation at the Department of Biochemistry, Makerere University, Kampala-Uganda. Sampling was done four times at an interval of three months for one year; between January and December 2015, following standard methods described by [5, 50].

2.2. Physico-chemical Characterization

a) Banana Waste Sample Preparation for Analysis

At the laboratory, raw banana waste samples were shredded into a homogeneous paste (**Figure 2**) using an organic shredder (TR 200: Organic Shredder, BrazAfric Enterprises LTD). The samples were frozen if not used immediately and were thawed for 24 hours at room temperature (26 ± 2 °C) before analysis and use in the subsequent studies.

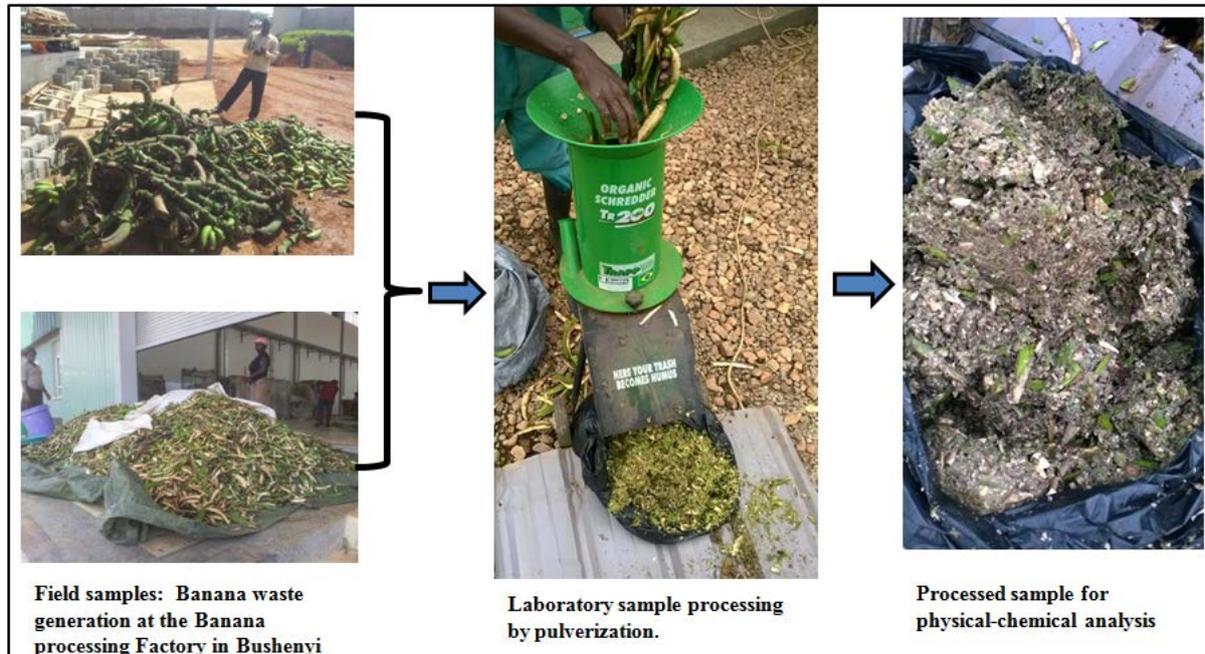


Figure 2: Sample preparation for physico-chemical analysis and feedstock for anaerobic digestion

b) Laboratory Analysis

Laboratory analysis of the samples was done in triplicates for physico-chemical parameters namely: moisture content (MC), total solids (TS), volatile solids (VS), ash content (AC), organic carbon (OC), organic matter (OM), total Kjeldahl nitrogen (TKN) and percentage composition of proteins, starch, sugars, crude fat, cellulose, hemicelluloses and lignin content.

MC, TS, VS and AC were determined gravimetrically by the hot air oven-drying and ignition method according to standard methods described in [5]. Analysis for MC and TS was done by drying pre-weighed fresh samples in a hot air oven (model: Gallenkamp & Co. Ltd, and London, UK) for 24 hours at 105°C to get consistent constant weights [18, 29]. VS and AC were determined by ignition of the previously oven-dried samples for 2 hours at 550 °C in a muffle furnace (Model: Carbolite 1100 °C furnace, Chelmsford, England). The ash containing crucibles were cooled in the desiccator to room temperature (25 °C) before re-weighing [25] using a precision balance.

OC was determined by dry combustion method [3], in which one gram of the oven-dried ground sample was heated at 600 °C for 5 hours in a muffle furnace and thereafter cooled in the desiccator to room temperature (25 °C) and the weight of the ash recorded. The OC was calculated as a quotient of percentage weight deficit divided

by a factor of 1.8 to correct for organic matter lost to organic carbon during combustion.

OM content was also determined gravimetrically by the dry combustion method previously described by [30], in which one gram of ground sample previously dried at 80 °C for 24 hours in hot air oven (model: Gallenkamp & Co. Ltd, and London, UK) was heated at 550 °C for 4 hours in the muffle furnace. The total organic matter content was calculated as the difference in weight between dry weight at 80 °C and ash weight at 550 °C.

TKN was determined by the Kjeldahl acid digestion block method as described by [29, 50]. One gram dry ground sample was subjected to Kjeldahl acid digestion (combination of 25 mL H₂SO₄ and Kjeldahl catalysts) using Gerhardt Kjeldatherm digester and allowed to cool for 1 hour and subsequently subjected to distillation (32% NaOH and 2% H₃BO₃ combination) and finally titration using 0.1 N HCl. Crude protein was obtained by multiplying TKN by a factor of 6.25 [4, 18, 41]. Crude fats were determined by ether extraction method as described by [50]. Fats in dry samples were extracted using diethyl ether and dried at 105 °C in an oven for 1 h and finally quantified gravimetrically [18].

Sugars were determined according to Dubois and his colleagues [17] by the phenol-sulphuric acid (Anthrone reagent) method with glucose standard. Diluted solution from homogenized sample was mixed with phenol-sulphuric acid reagent and after colour development; the concentration of sugars was measured colorimetrically at 490 nm [16] using a spectrophotometer.

Starch content was estimated by iodine-starch colorimetric assay according to Hovenkamp-Hermelink and his colleagues [26]. Fresh homogenised samples were extracted to remove free glucose, pigments and dissolution of cell membranes by boiling in 80% ethanol [44]. Ethanol-treated samples were solubilized by boiling with 90% dimethyl sulfoxide. The soluble extracts were mixed with iodine solution for colour development and starch content measured colorimetrically at 620 nm, with standard starch solutions [21, 26].

Lignocellulosic compositional analysis for cellulose, hemicelluloses and lignin was done using gravimetric method according to Ayen and his colleagues [8]. Dried ground sample was weighed and loaded into a cellulose thimble and extractives (sucrose, nitrate/nitrite, protein, chlorophyll and waxes) removed by Soxhlet extractor using boiling acetone (70 °C) for 4 hours. The extractive-free biomass was oven dried at 105 °C for 24 hours prior to re-weighing using a precision balance. The difference in weight between the raw extractive-laden biomass and extractive-free biomass was expressed as the percentage content of extractives.

To determine the percentage of Hemicellulose, one gram of extractive-free sample was digested by boiling with 0.5M NaOH for 3.5 hours [7]; cooled down and washed with distilled water to neutral pH prior to vacuum filtration. The residue was dried to a constant weight at 105 °C in a convection oven and reweighed using a precision balance. The difference in sample weight before and after alkali treatment, expressed as a percentage was the hemicellulose content in the sample.

To determine the percentage of Lignin, the dried extractive-free sample was weighed into glass test tube and digested with 72% H₂SO₄ in an autoclave for 1 h at 121 °C; 15 psi. The slurry was cooled at room temperature, residues filtered through vacuum using a filtering crucible. The lignin content was determined by oven drying

the residues at 105 °C for 24 hours prior to re-weighing. The ash content was determined by ignition of the dried acid hydrolyzate residues at 575 °C in a muffle furnace for 2 hours [43].

The percentage of Cellulose in the sample was estimated as a percentage difference from total summation of % extractives, % hemicellulose and % lignin.

All the samples of were analyzed in three replicates and the recorded results were the average of the three recordings.

c) Determination of Biochemical Methane Potential (BMP) of banana waste

The bioreactor

Anaerobic digestibility of mixed banana waste was tested using a biochemical methane potential (BMP) assay carried out in batch bioreactors as described by Mshandete and his colleagues [35] and Gumisiriza and his colleagues [25]. The reactors were made from 150ml mouth Erlenmeyer conical flasks with a working volume of 100ml at a substrate concentration of 5.0 gVS/L [40]. A solution of 5ml NaHCO₃ was added to the each reactor to buffer the pH changes during anaerobic digestion, since banana waste had a high C:N ratio. The outside of the flasks was covered with black polythene bags to cut off light and thus prevent the growth of anaerobic phototrophs that could release oxygen, which is toxic to methanogens [25, 52].

The inoculum

The inoculum was collected from a highly active fixed-dome anaerobic digester receiving a mixture of cow dung and pulverized hey residues as feedstocks, at a dairy cattle farmer in the vicinity of Makerere University. The inoculum was pre-incubated in anaerobic jars for two weeks to deplete the residual biodegradable organic matter prior to use in this experiment. The total solids of the inoculum at the time of loading were 22g/L.

The inoculum-to-Substrate loading (ISL) ratio

The substrate was seeded at an ISL ratio of 1:1, gVS basis according to Gumisiriza and his colleagues [25] and moody, [34] following the calculations below:

If;	Total Solids (TS) of Substrate (g/L)	= A
	Total Solids (TS) of Inoculum (g/L)	= B F
	Volatile Solids (VS) of Substrate (% of A)	= C
	Volatile of S of Inoculum (% of B)	= D

$$\begin{aligned} \text{Then;} \quad & \text{gVS/L of inoculum} && = D \times B \\ & \text{gVS/L of Substrate} && = C \times A \end{aligned}$$

And if the volume (in Litres) of Inoculum used = V_i

$$\text{Thus;} \quad \text{gVS in } V_i \text{ of inoculum} = [D \times B] \times V_i.$$

Hence, for bioreactor ISLR of 1:1 (gVS basis);

$$\text{The gVS of the substrate} = \text{gVS of the Inoculum.}$$

$$\text{Implying that;} \quad \text{gVS of the substrate} = [D \times B] \times V_i$$

$$\text{Therefore;} \quad \text{Volume of substrate (in Litres) loaded} = \frac{[D \times B] \times V_i}{C \times A}$$

All the experiments were carried out in triplicates including a control without substrate to account for any endogenous biogas residual produced from the inoculum. The calculated biogas production was corrected for blank biogas production before data recording. Each bioreactor was manually shaken once a day and further swirled for 1 minute prior to biogas volume measurement.

Measuring biogas production and methane content

The biogas production was measured by water displacement method [28, 42]. A tube connected to the reactor delivered the produced biogas to an inverted 250 mL graduated measuring cylinder immersed in a 1000 mL beaker filled with water. Biogas produced was collected in the graduated cylinder connected with a water reservoir which allowed volumetric biogas measurements at atmospheric pressure [40]. The methane content was estimated according to Erguder and his colleagues [19] and Mshandete and his colleagues [35], by the concentrated alkaline absorption method. Each bioreactor was manually shaken by swirling for 1 minute prior to biogas volume measurement.

Comparison BMP of banana waste with other potential substrates

In addition, the digestibility of banana waste was compared with grass and fish waste (animal waste) by carrying out a BMP of hey grass and fish waste following similar method as for banana waste. The fish waste comprised

of trimmings, skin and viscera was collected from the fish market waste bins. Hey grass mainly comprised of *Chloris gayana* residues was obtained from the dairy cattle barn yard at the time of inoculum collection. Samples were pulverized prior to loading into the bioreactor.

3. Results

3.1. Banana processing and waste generation

A survey of the major banana producing regions revealed that processing of banana fruit bunches is carried out manually by peeling of fruits to generate fresh pulp for domestic consumption, and is usually done by women (**Figure 3**). The banana waste streams generated at production level mainly include pseudo-stem, leaves, fibers and corm (rhizome) that remain in the garden after cutting off fruit-bunches. The survey also revealed that processing of fruit bunches into fruit-pulp generates residue fractions mainly comprising peels, fruit-bunch-stem (peduncle or stalk) and rotten/damaged fruits.

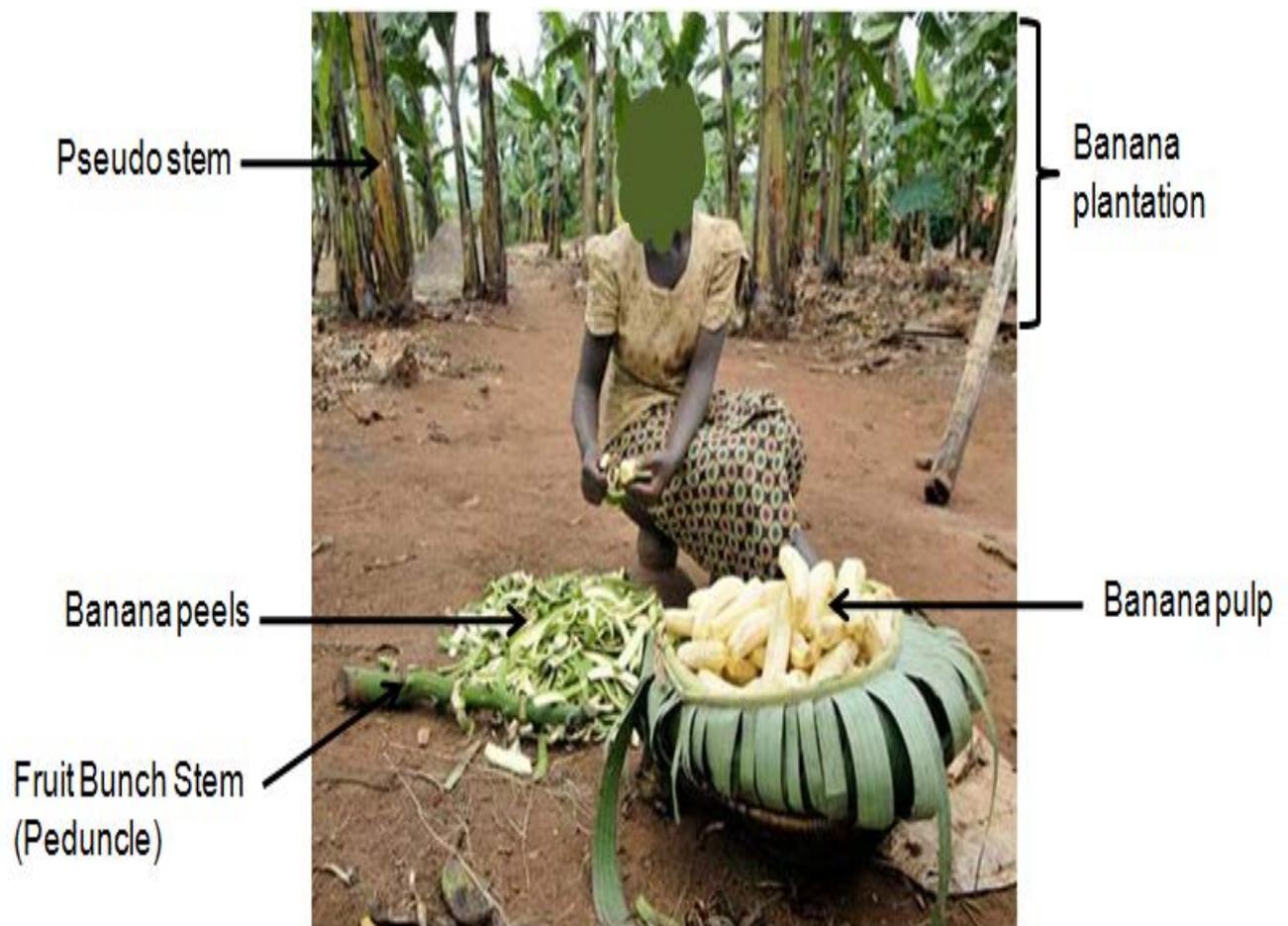


Figure 3: Banana peeling; a traditional method for banana processing in Uganda

It was further noted that the Government of Uganda had initiated industrial banana processing, through a organization called Presidential Initiative on Banana Industrial Development (PIBID), into banana chips that could serve as the raw material for value-added products such as starch and flour, for both export and local food

security.

At this industry, banana processing start with receiving of mature banana fruit bunches that were subsequently de-bunched to separate fruit-fingers from the peduncle (**Figure 4**).

Fingers were peeled to get the pulp that was sliced, and finally dried into banana chips. The major waste fractions generated at the banana processing industry mainly comprised peels, peduncle and fruit rejects (**Figure 5**). Banana peels constituted the major percentage of the industrial waste stream followed by the peduncle and lastly, the fruit rejects.

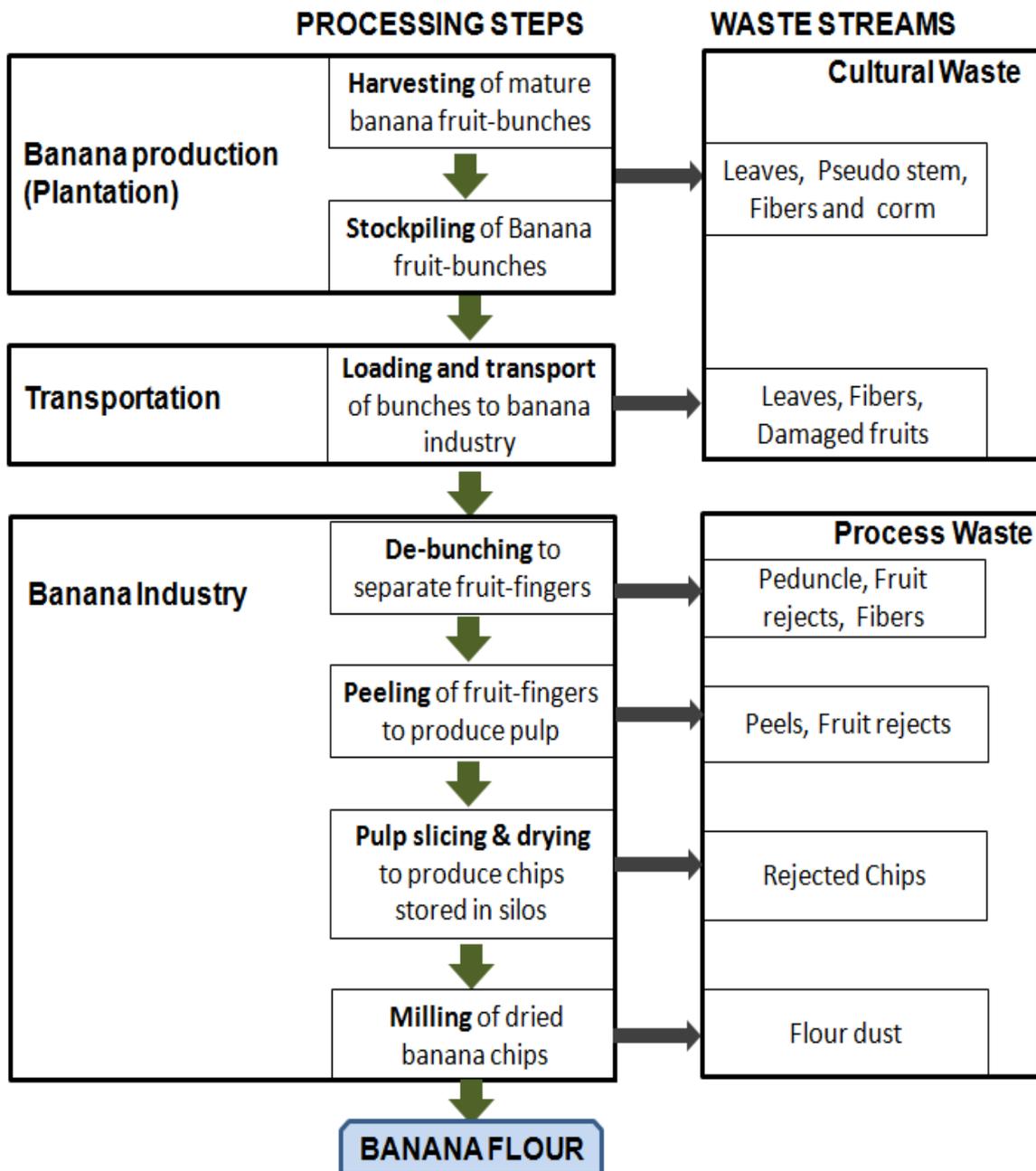


Figure 4: Steps for banana industrial processing and major waste streams

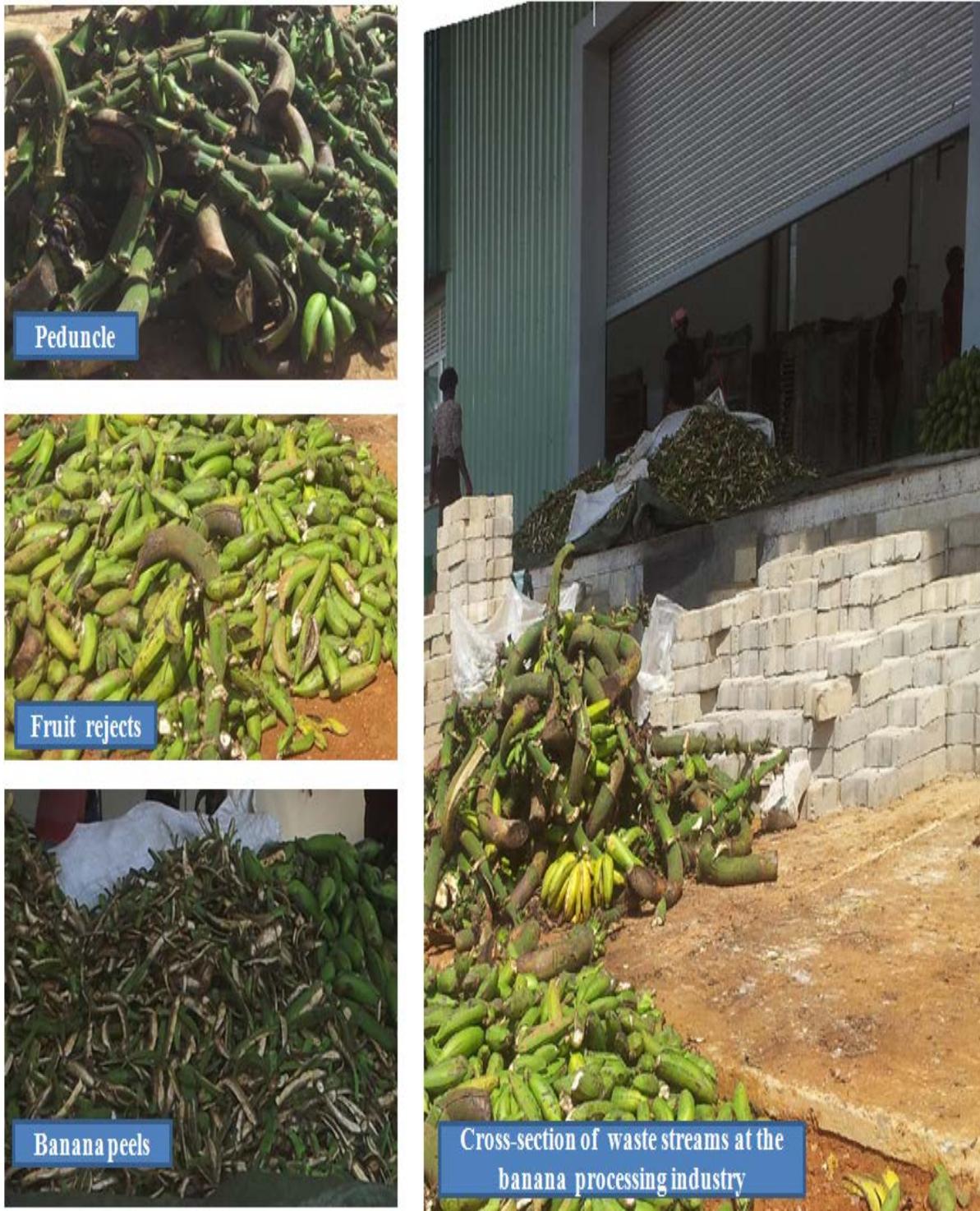


Figure 5: Major waste fractions generated from industrial banana processing

3.2. Current in-situ methods for management of banana waste

The field survey also noted that banana waste was not utilized properly, both ecologically and economically. The major methods employed in utilization of banana waste (**Table 1**) were, direct application as mulches, dumping on the ground and feeding to animals especially dairy cows.

Table 1: Current methods for management of banana waste

Waste stream	Current Management	Major Challenge
Process wastes		
Peels	▪ Animal feed supplement	▪ Only small fraction used ▪ Spread of plant disease such as Banana Bacterial Wilt
	▪ Dumping	▪ Emission of GHGs ▪ Water-body eutrophication by leachate ▪ Spread of plant Disease such as Banana Bacterial Wilt
Peduncle	▪ Dumping	▪ Water-body eutrophication by leachate ▪ Emission of GHGs ▪ Spread of plant Disease such as Banana Bacterial Wilt
	▪ Mulching	▪ Spread of plant Disease such as Banana Bacterial Wilt
	▪ Direct use of dried materials for Fuel	▪ Air-pollution by smoke emissions
Fruit rejects	▪ Animal feed supplement	▪ Spread of plant Disease such as Banana Bacterial Wilt
Cultural (Production)Wastes		
Leaves, Pseudo-stem, Fibre and Corm	▪ Mulching	▪ Spread of plant Disease such as Banana Bacterial Wilt
	▪ Dumping	▪ Water-body eutrophication by leachate ▪ Emission of GHGs ▪ Spread of plant Disease such as Banana Bacterial Wilt
	▪ Direct use of dried materials for Fuel	▪ Air-pollution by smoke emissions

3.3. Estimation of banana waste generation per unit fruit-bunch

All the banana waste fractions generated from processing of banana fruit bunches into pulp were quantitatively estimated by weighing all the residue fractions and pulp, repeated over a period of six months.

The results as shown in table 2, were expressed as a percentage per unit bunch and indicated that processing of a bunch of green bananas generates 40% as pulp and 60% as total waste residues with peel / pulp ratio of 1.3.

Table 2: Percentage residual fractions generated from industrial processing of green bananas

Residues per unit fruit bunch	% wet weight
Pulp	40.1 ± 3.5
Peels	50.2 ± 3.4
Peduncle	7.1 ± 1.7
Reject Fruits	2.6 ± 1.4
Total waste	59.9 ± 1.5
Total Waste: Pulp Ratio	1.5 ± 0.4
Peel: Pulp Ratio	1.3 ± 0.2
Peduncle: Pulp ratio	0.2 ± 0.1

Results of percentage residual fractions generated from common banana varieties locally grown in the region (*Mporogoma*, *Kishansha*, *Kibuzi*, *Mbwazirime* and *Enyeru*) are shown in table 3. The results indicated that *Mporogoma* had most of the fruit rejects at 8 %, followed by *Kishansha* at 4.4 % while *Kibuzi*, *Enyeru* and *Mbwazirime* had the least at 0.9 %, 0.7 % and 0.5 %, respectively.

Table 3: Common banana varieties and percentage waste fraction per unit fruit bunch

Banana Variety	Residues per unit fruit bunch						
	Pulp	Peels	Peduncle	Fruit Reject	Total Waste	Peel/pulp ratio	Total Waste/Pulp ratio
<i>Mporogoma</i>	36.8 ± 3.1	48.0 ± 1.5	7.2 ± 1.1	8.0 ± 1.8	63.2 ± 2.8	1.3 ± 0.2	1.7 ± 0.2
<i>Kishansha</i>	40.0 ± 0.9	50.0 ± 1.6	5.6 ± 0.9	4.4 ± 2.8	60.0 ± 2.2	1.3 ± 0.2	1.5 ± 0.2
<i>Kibuzi</i>	36.5 ± 3.7	56.5 ± 0.9	6.1 ± 0.9	0.9 ± 0.2	63.5 ± 0.8	1.5 ± 0.1	1.7 ± 0.1
<i>Mbwazirime</i>	38.9 ± 2.9	50.6 ± 1.5	10.0 ± 1.0	0.5 ± 0.2	61.1 ± 1.0	1.3 ± 0.2	1.6 ± 0.1
<i>Enyeru</i>	38.5 ± 1.8	54.1 ± 1.1	6.7 ± 0.6	0.7 ± 0.2	61.5 ± 1.0	1.4 ± 0.1	1.6 ± 0.1

3.4. Physico-chemical analysis

Pulverized samples comprising peels, peduncle, fruit rejects, a mixture and pulp were analyzed at the Department of Biochemistry, Makerere University for physico-chemical content analysis. The results (**Table 4**) revealed that banana waste has high moisture content of over 80 % making it unsuitable for direct thermochemical conversion without considerable drying, but rather a high potential substrate for biochemical conversions such as anaerobic digestion for biogas production.

Table 4: Physico-chemical composition of residues from industrial processing of green bananas

Parameters	Process streams				
	Peels	Peduncle	Fruit reject	Mixed waste	Pulp
MC ^{wb}	83.30 ± 3.04	90.50 ± 2.70	78.61 ± 2.21	85.47 ± 0.35	70.31 ± 4.62
TS ^{wb}	16.71 ± 2.33	9.51 ± 3.10	21.40 ± 2.02	14.55 ± 0.35	29.68 ± 3.11
VS ^{db}	86.78 ± 2.33	80.91 ± 3.02	88.71 ± 2.11	91.79 ± 0.16	96.11 ± 1.12
Ash ^{db}	13.22 ± 2.00	19.11 ± 3.53	11.32 ± 1.91	8.21 ± 0.16	3.90 ± 0.40
OC ^{db}	41.03 ± 4.31	40.02 ± 0.81	53.09 ± 4.71	51.99 ± 0.26	56.13 ± 2.10
OM ^{db}	89.04 ± 1.44	81.12 ± 1.01	87.11 ± 4.32	87.00 ± 0.50	89.83 ± 3.33
TKN ^{db}	1.20 ± 0.09	1.93 ± 0.21	0.89 ± 0.32	1.26 ± 0.50	0.74 ± 0.11
C:N ratio	34.19 ± 1.31	20.74 ± 2.11	59.65 ± 1.38	41.26 ± 0.02	75.68 ± 1.10
Protein ^{db}	7.53 ± 1.21	12.06 ± 2.00	5.56 ± 1.81	7.88 ± 0.01	4.63 ± 0.62
Starch ^{db}	40.11 ± 2.22	1.73 ± 0.97	51.21 ± 2.13	50.30 ± 2.01	80.70 ± 2.30
Sugars ^{db}	1.42 ± 0.11	0.01 ± 0.01	3.61 ± 0.51	0.29 ± 0.03	4.11 ± 2.11
Cellulose ^{db}	13.09 ± 0.09	31.21 ± 1.50	4.11 ± 0.13	21.16 ± 2.00	Nil
Hemicellulose ^{db}	14.66 ± 0.31	8.83 ± 0.13	4.88 ± 0.46	10.46 ± 0.51	1.21 ± 0.01
Lignin ^{db}	13.97 ± 0.02	18.77 ± 1.9	4.20 ± 0.20	11.31 ± 1.33	Nil
Crude Fat ^{db}	1.52 ± 0.22	0.33 ± 0.10	1.16 ± 0.19	1.43 ± 0.11	0.71 ± 0.16

MC = Moisture Content; TS = Total Solids; VS= Volatile solids; OC= Organic Carbon; OM= Organic Matter; TKN= Total Kjeldahl Nitrogen; *wb* = wet basis (% wet weight); *db* = dry basis (% TS)

3.5. The BMP of banana waste

The digestibility of banana waste was carried out in batch bioreactor and the results compared with animal waste and grass. Generally daily methane yield showed variable peaks as a function of retention time (**Figure 6**). Fish waste had one optimal peak at day 10 corresponding to 106 ml CH₄/gVS/day and then the gas production dropped drastically to 23 ml ml CH₄/gVS/day at day 35. The BMP of banana waste and grass showed double peaks with related trend. The first peak of daily methane production appeared at day 8 corresponding to 51.2 and 37.4 ml CH₄/gVS/day, respectively for banana waste and grass. In the second peak, both banana waste and grass produced higher methane than first peak. Banana waste produced highest volume of methane at day 24 (79.9 ml CH₄/gVS/day) while hey grass produced 69.7 ml CH₄/gVS/day at day 20. This was in agreement with other reported related research on anaerobic digestion of banana waste and grass [10, 40]. Moreover, banana waste showed highest methane yields at 436.6 ml CH₄/gVS, followed by fish waste at 427 ml CH₄/gVS and least by grass at 340 ml CH₄/gVS as shown in figure 7.

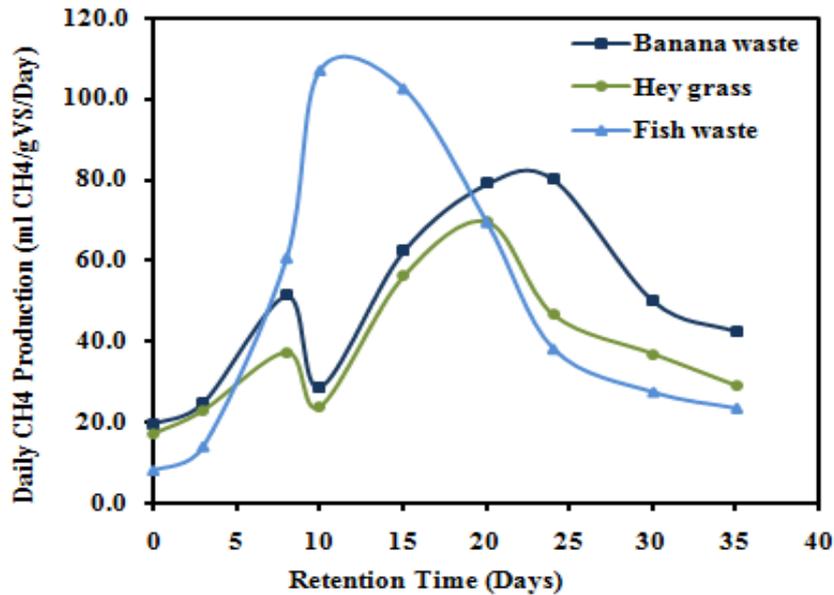


Figure 6: Effect of retention time on methane production from banana waste, grass and fish waste

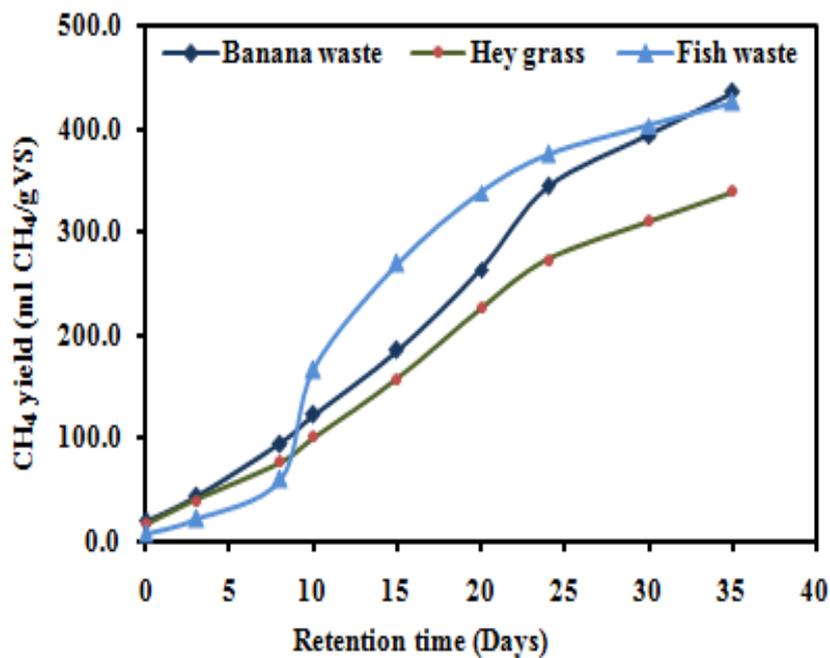


Figure 7: Comparison of methane yield from banana waste with grass and fish waste

4. Discussion

4.1. The waste survey

Results from the survey indicated that banana processing in Uganda is done manually and there is less value addition to the fruits to enhance their shelf life by farmers. A recently installed banana processing factory under

Presidential Initiative on Banana Industrial Development (PIBID) is the only industrial enterprise adding value-addition to green bananas through pulp drying and conversion into banana flour. However, a challenge of lack of a 24-hour supply of cheap and reliable sufficient energy for complete drying of banana pulp into dried products with consistent standard quality was prominently noted for both industry and local farmers. Local farmers need such energy for drying of banana pulp to sell to the banana industry as a raw material in form of dried chips. Indeed, this survey found out that most of the rural areas with high banana production were not connected to the electricity grid power. For the ones connected, the cost of the grid energy was considered costly and cannot be afforded for use in produce drying. Alternatively, the use of wood and petroleum fuels was undesirable due to high costs and adverse environmental impact. As a result, solar drying of banana pulp by directly spreading the fresh pulp on a mat and exposing it to sunshine was practiced by some rural farmers. This method cannot be easily controlled and its output is not reliable. The practice is considered unhygienic leading to inconsistent and substandard product quality, characterized by rotting and infestation with moulds that produce aflatoxins [24]. On the other hand, large quantities of banana waste were generated both at farm production level and during the processing of fruit-bunch into pulp. This was in agreement with findings from previous researchers [23] and is attributed to the high quality standards desired for the market demands of green bananas. Moreover, the short shelf life of mature bananas leads to quick quality deterioration resulting into huge piles of damaged/spoiled fruit waste fraction. The methods for management of banana waste residues were mainly by dumping, reuse as mulching materials and animal feeds, as well as use of dried fibrous fraction for fuel. While these methods are cheap and convenient, they are being discouraged owing to their association with the spread of plant diseases, especially the Banana Bacterial Wilt, as well as their lack of economic value to farmers. The use of dried banana waste as fuel by direct burning was an indication that there was scarcity of energy for both domestic usage and drying of pulp. However, since banana waste has high moisture content it cannot be appropriately utilized via such a waste-to-energy process especially during the rainy season [24].

4.2. Physico-chemical analysis

Quantitative analysis based on percent weight by residual fraction revealed that processing of a unit bunch of green bananas generates 40% as pulp and 60% as total waste residues with total waste to pulp ratio of 1.5:1 and peel to pulp ratio of 1.3:1. The high waste to pulp ratio is attributed to high moisture content of peduncle (MC of 90 %) and peels (MC of 83 %) in freshly harvested fruit bunches [15, 41, 49]. The high waste to pulp ratio implied that the waste contained more water than the pulp. Indeed, when bunches were left at room temperature for a day before processing, the fruits lost more moisture from peels than pulp consequently lowering peel to pulp ratio to 1:1. The high moisture content of banana waste suggests that the waste is more amenable to biochemical conversion than thermal technologies and would require minimal additional water thus reducing biogas production costs. On the other hand, the high moisture content of pulp suggests that it requires a lot of energy to achieve complete dryness.

Qualitatively, wastes generated at production level (on farm) are more fibrous and hence highly lignocellulosic. This must be pre-treated for effective energy harnessing through anaerobic digestion. Physical-chemical analysis of banana waste fractions from the industrial processing indicated that the residues had organic matter of over 80 %, suggesting that they were highly organic and thus amenable to value addition through bioconversion

technologies such as anaerobic digestion. The high moisture content is favorable for biochemical conversion technologies that proceed without any additional water requirement thus reducing on water use and costs. Furthermore, analysis results showed that more than 80 % of the total solids in banana wastes were volatile. This confirms reports by previous researchers [10, 28, 49, 51]. Such waste characteristic indicates that these solids were of organic origin and have high potential energy production, if efficiently biodegraded through anaerobic digestion. However, the mixed waste had high organic carbon with low nitrogen content resulting into a C:N ratio of 41. This ratio is above the range of 20-32 recommended for optimal anaerobic digestion [12, 14, 24, 54]. The high C:N ratio implies that optimal anaerobic digestion of banana waste requires co-digestion with nitrogen-rich feed substrate such as fish waste, slaughterhouse waste and chicken manure [24]. The high ratio was attributed to high starch content from fruit reject and the high lignocellulosic content of peduncle. The high carbon content and low TKN was translated into higher carbohydrate content than protein of 50.3 % and 7.8 %, respectively for mixed waste. The sugar content varied depending mainly on the maturity of the fruit bunches and time lag from harvesting to processing. The lipid content was higher in peels than other fractions but generally lower than sugars and protein contents. These findings compare well to the ones reported by Essien and his colleagues [20] and Salayem and his colleagues [41]. Besides, the process of anaerobic digestion of substrates with high C:N ratio is susceptible to failure mainly due to acidification [36, 11, 24]. The lignocelluloses content of mixed waste comprised 21.16 %, 10.46 % and 11.31 % for cellulose, hemicelluloses and lignin, respectively. The results of lignocellulose content of banana waste agree with similar analysis reported by previous researchers [2, 27, 33, 51], and imply that banana waste can generate more biogas through anaerobic digestion, if appropriately pre-treated to optimally solubilize the lignocellulose content.

4.3. The BMP of banana waste

Results from BMP assays showed that banana waste has high anaerobic digestibility. The peaks in daily methane production represent retention times that gave optimal gas production of digested substrates. The first peak in both banana waste and grass was likely due to quick microbial assimilation of soluble sugars released from the substrates during pulverization process while the second peak was related to the lag microbial solubilization of starch and other complex biomolecules in waste substrate [49]. The banana waste gave a methane yield of $0.436 \text{ m}^3 \text{ CH}_4/\text{KgVS}$ which was higher than $0.340 \text{ m}^3 \text{ CH}_4/\text{KgVS}$ for grass. Moreover, the daily methane production curve appears superimposed over the one for grass. This was due to the different nature of VS in the two phytomass substrates. That is, the VS in banana waste contained higher starch and sugar content than in grass, in addition to more lignocellulosic content in the latter [40]. The values of methane yield from all the wastes assayed were below the theoretical maximum methane production of $0.490 \text{ m}^3 \text{ CH}_4/\text{KgVS}$ but slightly higher than $0.332 \text{ m}^3 \text{ CH}_4/\text{KgVS}$ previously reported for grass [40]. This could have been due to the inoculum that was already pre-adapted to digest here at the fixed dome digester. Besides, the single peak for daily methane production exhibited by the BMP assay of fish waste indicated that the nature of VS in such waste has a nearly similar complexity. Implying that, it could be digested continuously once the reactor microorganisms have acclimatized to the substrate. The peak for digestion of fish waste coincided with the retention time at lower methane production from banana waste. This suggested that the fish waste could be a good substrate for co-digestion with banana waste to yield more methane at lower retention time of less than 15 days.

5. Conclusion

This study aimed at assessing banana processing, auditing of banana waste generated from banana processing activities in Uganda and evaluation of the waste management options as well as potential for value-addition through biogas production. Findings revealed that the banana industry in Uganda is faced with a challenge of lack of cheap, reliable and sufficient energy for complete drying of banana pulp into chips with consistent standard quality. The huge banana wastes generated and currently underutilized were rich in organic matter with high moisture content and thus a good substrate for biogas production through anaerobic digestion. The high moisture content makes banana waste a better feedstock for biogas production since it would require minimal additional water thus reducing the cost of bioenergy production. The biochemical methane potential assay showed that banana waste has a higher methane yield than grass and fish waste due to high starch and sugar content. The high lignocellulosic content in banana waste however suggested that application of appropriate pre-treatment is necessary to increase nutrient bioavailability that enhance anaerobic digestion and ultimately improves biogas yield from the substrate.

Never the less, this study faced the following general limitations:1);The peeling of banana fruits was done manually by different persons giving varying sizes of peels and resulting into large variation of waste to pulp ratio and 2); Other banana varieties were not studied, mainly due to lack of fruits during the study period.

6. Recommendations

- The peeling process needs to be standardized by either using standard tools or using an automated peeling machine
- The fraction of banana fruit-rejects can be reduced by harvesting the banana bunches at early maturity stage as compared to late maturity stage where ripening is at on-set.
- Anaerobic digester should be installed to utilize the banana waste for energy (biogas) generation as well as reduction of the risk of spreading plant diseases especially banana bacterial wilt.

7. Competing Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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