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Biogas Substrates Performance Ranking Based on Sustainability Potential, Biodegradability, and Yield Characterization: The Case of an Area in Southwest Nigeria

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Abstract
The characteristics of biogas materials (BMs) and the preference for their bio-methane production effectiveness and efficiencies differ by geographical location and are currently an active discussion. This study assessed and ranked BMs based on their biogas production sustainability potential. BMs including Cow dung (CD), food waste (FW), poultry dung (PuD), and fruit and vegetable waste (FVW) were selected from an area in South-West Nigeria. Questionnaire responses on six sustainability criteria (C_i) [Population, availability, non-competing substrate, acceptability, biodegradability, and yield] were collected for the selected BMs. The criteria preference weight (ω_i) was determined using AHP, while a part-subjective, part-objective method was employed to score the BMs based on the C_i. The Sustainability Ranking Model (SRM) was formulated to rank the BMs' sustainability performances. ω_i results showed that acceptability and non-competing substrate were the most and least preferred criteria while most to the least sustainable BMs were FW, CD, FVW, and PuD.

Keywords: Biogas Materials, Biogas Sustainability Criteria, Multi-criteria Decision Making, Sustainability Ranking, AHP

1.0 INTRODUCTION

In recent years, as industrial technology and economies have advanced globally, crude oil has become the predominant fossil energy source for powering industrial equipment as well as for cooking, refrigeration, and related domestic chores [1, 2]. This situation is no different in Nigeria given that it exists as a member of the global community. However, due to the lingering problems of poor electricity availability in the country [3, 4], increasing cost of crude oil-related products [5], and sustainability issues [6, 7, 8], there has been a shift (albeit slowly) towards the use of alternative energy generation sources as a means of augmenting or replacing fossil fuel-based energy sources [9, 10].

Biogas is one of such alternative energy sources, obtained from the degradation of biomass or waste by bacteria present or included in the biomass fermentation by anaerobic biochemical reactions [11]. Methane [CH_4] is the useful constituent of biogas (40-75%), while the impurities include carbon (iv) oxide [CO_2], (25-50%), nitrogen (2-8%), hydrogen sulphide, and other trace materials [12].

At the highest purity, the heating value of biogas can compete with that of natural gas [13, 14]. Biogas is considered one of the energy sources with strong sustainability potential [15, 16] and with a local production base that can contribute significantly to energy availability in Nigeria [17, 18].

Apart from its renewability and greenhouse gas [GHG] reduction characteristics [19], this sustainability potential can be attributed to a plethora of potential bioenergy producing materials that currently exist. Adapting Ozturk and Yuksel [20] definition, Biogas substrate (BS) sustainability are biogas materials that satisfy the present needs, across different regions of the world, without compromising the existence and continuity of the region.

Based on previous research, existing biogas substrates can be classified to include plant waste [21], animal waste [11, 22], food waste [23], fruit waste [24, 25], and agricultural products [26]. Biogas productivity from these substrates is affected by physicochemical conditions [11] such as feedstock type, pH, temperature, carbon-nitrogen content, Chemical Oxygen Demand [COD],

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fermentation nutritional requirements, Volatile Fatty Acid [VFA], Total Solid (TS) and Volatile Solid (VS) content [27, 28].

Research has revealed that biogas yields are significantly affected by the TS and VS contents of substrates and substrate groups [29, 30]. TS refers to the mass of substrate per volume of diluent that is utilised for biogas production while VS is the fraction of the TS that may be digested during the production process. Thus the higher the VS content of a substrate, the likelihood for higher biogas production, the more efficient the degradation process [31], and the more sustainable the substrate.

Previous research in the area of biogas substrate sustainability investigations exists. Some of these works investigated BS sustainability from different perspectives such as environmental effects [32] and economic feasibility and substrate efficiency [33]. Unfortunately, these substrate rankings which were done using different local materials may not apply to Nigeria for the reason that the degree of availability and physicochemical characteristics of biogas substrates differ from one region to another [34, 35]. In that regard, there exists a need to carry out biogas substrate ranking based on locally sourced materials and thus the aim of this work.

In achieving this aim, the study which is limited to an area in the South-Western region of the country identifies, characterises, preliminarily ranks, and selects desirable substrates. It further determines the potential biogas biodegradability and yield indices of the selected substrates based on their TS and VS contents. Finally, the ranking of the selected substrates is done. The study provides information to investors in Nigeria on the proper selection of substrates for biogas production processes.

1.0 LITERATURE REVIEW

Biogas production performance is the degree of effective and efficient biogas production BS under certain conditions. Biogas production is impossible without the existence of the materials that produce them. Thus the main target of biogas production is to produce the best biogas yield with the maximum bio-methane content of the substrate [36]. In terms of their yield properties, these biogas substrates behave differently under different physicochemical conditions. As such, some biogas substrates may be preferred over others due to their biogas production performances under certain conditions. BS ranking is the comparison of BS production performances. Various attempts have been made at comparing and ranking biogas substrates. Mursec *et al*. [36] investigated the performances of six different energy crops (including sunflower and sugar beet) and pig slurry under mesophilic temperature conditions and varying pH. They concluded that sunflower and sugar beet performed best and worst respectively. Adamu [37] compared the production performances of waste tomatoes, waste fluted pumpkin leaves, chicken manure, sheep manure, and cow dung under similar biodegradation conditions and concluded that sheep manure performed best.

Although these works provided important information on the substrates considered, the substrates were ranked based only on the physicochemical conditions to which they were subjected. However, the degree of acceptability of biogas as an energy source is strongly hinged on the sustainability of the substrates [38, 39]. With regards to this, Pawlita-Posmyk and Wzorek [40] developed a biogas production performance ranking template. The analysis which considers the economic, social, and environmental impacts of biogas production is based on the adaptation of the Strength, Weaknesses, Opportunities, and Threats (SWOT) analysis concept. Although developed for the Polish community, the template shows great potential for use in biogas substrate ranking and biogas production feasibility evaluation. Also, Bumbiere, *et al.* [33] deployed a multi-criteria Technique for Order Preference by Similarity to the Solution (TOPSIS) to investigate the performances of eight biogas substrates (cattle manure, pig manure, poultry manure, straw, wood, maize silage, waste, and sewage sludge) with considerations given to their yield effectiveness and efficiencies as well as their environmental impacts. They concluded that the best performing substrate was pig manure while the least performing was wood.

Although all of the performance ranking models and applications highlighted provide useful information, their outcomes only find applicability in the localities where they are targeted since the physicochemical and sustainability characteristics of substrates are unique from one location to another. To this end, there is a need to further the biogas performance ranking research to investigate the sustainability of substrates based on their locations.

2.0 METHODOLOGY

A state in the South-Western part of Nigeria was selected for the study. Twelve biogas substrates $M_j(j: 1,2,3, \ldots, 12)$ that are frequently mentioned in the literature as being viable for biogas production in the state were identified and selected. The substrates were namely, cow dung (CD), sheep dung (SD), edible vegetables (EV), pig dung (PD), fruit/Vegetable waste (FVW), goat dung (GD), municipal solid waste (MSW), sewage sludge (SS), poultry droppings (PuD), tomato waste (TW), agricultural residues (AR), and food waste (FW).

Six biogas substrate sustainability criteria [BSSC] (Table 1) were then adopted to enable the ranking procedure. The BSSC were based on the authors' elaboration and adaptations from the Pawlita-Posmyk and Wzorek [40]. The criteria considered were substrate population, availability, non-usability competition, acceptability, biodegradability, and yield capability. The context of the adoption criteria is here defined:

Table 1: List of the biogas substrate sustainability criteria [BSSC] utilized in the study

SN (i)	Biogas substrate sustainability criteria (C_i)	Data collection method for criteria
1	Substrate population	Structured questionnaire
2	Substrate availability	Structured questionnaire
3	Non-usability competition	Structured questionnaire
4	Substrate acceptability	Structured questionnaire
5	Biodegradability	Result from experiments
6	Yield capability	Result from experiments

1. **Substrate population:** This refers to the total amount of the substrate based on the animals and plants that produce them.

2. **Substrate Availability**: This refers to the ability to freely access the substrate as they are produced by farms and related businesses

3. **Non-usability competition:** This criterion considers different sources that compete for the use of the substrate. For example, edible vegetables will be competed for by human beings. Also, municipal waste can be competed for by government waste clean-up policies making it difficult to access. Lesser competition for the use of the substrate implies a higher biogas sustainability potential of the substrate and vice-versa.

4. **Substrate acceptability:** This concerns the extent to which the biogas substrate is accepted for use in biogas production. The adoption of this factor was necessary as the use of some of the identified substrates could be constrained by cultural and religious issues.

5. **Biodegradability:** This is the characteristic of the substrate to be decomposed during the biogas production process. Since the by-product of the biogas production process has the potential for use as plant manure, a higher biodegradability value of the substrate is both economically and environmentally beneficial. In this study, biodegradability was measured using the VS reduction property of the substrate.

6. **Yield Capability:** This criterion measures the amount of biogas that can be produced by the substrate concerned within the substrate's retention period under regular temperature (mesophilic range) and pressure conditions, optimal diluent and pH conditions ($pH = 7$).

For each M_j identified, data on its BSSC was collected and analysed. For some parts of the criteria, the mode of collection was subjective (through the use of a structured questionnaire) and for other parts experimental (Table 1).

2.1 Data collection on Criteria using a Questionnaire

Regarding the subjective data collection approach adopted, two questionnaire types (Type1 and Type2) were developed to aid this study. The content of questionnaire Type 1 included information on the relative importance of all the BSSC ($C_i: i = 1, 2, 3, \dots, 6$) as it relates to biogas production sustainability. The questions were structured in such a form to capture the respondent's perception based on a pair-wise comparison of the BSSC. The Oguztimur [41] Analytical hierarchical process (AHP) technique was adopted for analysis to ascertain the relative importance of the criteria based on the subjects' responses. Questionnaire Type 2 content was related to the subjective BSSC (Table 1).

The respondents were required to state their perceptions regarding the importance of each BSSC item to biogas production sustainability using a numeric scoring scale of 1 – 10. The two questionnaires were subsequently administered to fifteen research experts in the field of biogas production who possessed reasonable knowledge regarding the substrates that existed within the study area.

2.2 Formulation of the Biogas Substrate Sustainability Ranking Model

A ranking model (Equation 1) otherwise referred to as the Sustainability Ranking Model (SRM) for the BSSC was developed to utilise the questionnaire responses to obtain the sustainability index for the substrates (j) based on the subjectively determined criteria. In formulating the SRM, firstly, the sustainability score for the non-experiment based criteria responses $C_i\{i = 1,2,3,4\}$ were computed for (Equation 1).

$$I_j = \sum_{i=1}^{4} \omega_i S_{ij} \quad \{j = 1,2,3, \dots, J\} \tag{1}$$

Next, the initial sustainability score for the experiment based criteria $C_i(: i = 5,6)$ using questionnaire responses as initial input (Equation 2)

$$Q_j = \sum_{i=5}^{6} \omega_i S_{ij} \quad (2)$$

Where: I_j: sustainability index of substrate j; ω_i:

Weight of importance attached to criteria i concerning biogas sustainability and S_{ij}: Score of perceived importance of criteria i property that exists in substrate j as supplied by the respondents. ω_i was obtained using the Oguztimur [41] Analytical Hierarchy Process (AHP) technique and was considered satisfactory if the consistency ratio (CR) of the AHP is less than 10%.

2.3 Preliminary Selection of High Ranking Substrates

The next procedure was the determination of the experiment-based rank score for the biodegradability and yield criteria ($S_{5j}$and S_{6j}) via experiment. However, in many cases, multiple forms of this experiment are costly to achieve and are even more so if numerous substrates have been identified for ranking. As such, a procedure that strove to eliminate less significant substrates and select the more viable ones before the experiments is proposed. The procedure is described using the following steps.

i. For resource management purposes, the choice of deploying K out of the J identified substrates for comparison may be made (in the case of this study K=4 was decided). The choice of the substrates ($k = 1,2 \ldots, K$) can be made by conducting a preliminary ranking and comparison M_j.

ii. Substrates M_k can then be chosen by selecting M_j for which the corresponding cumulative sustainability score [δ_j] value ranked higher than those of the other substrates (Equation 3). This selection procedure is continued for $k = 1, \ldots$ until $k = K$. Let the set of the selected substrates be W. That is $W = \{M_k : k = 1,2,3, \ldots, K\}$.

$$\delta_j = I_j + Q_j \quad (3)$$

iii. On the completion of step 2, $I_k\{M_k\}$ is retained while Q_k can be determined from the substrates' yield and biodegradability properties based on outcomes from experiments

It is worth noting that in situations where preliminary substrate selections are not required, the procedure in section 3.3 will not be required i.e K=J. In this study, the preliminary substrate selection procedure was utilised to select K = 4 substrates.

2.4 Data Collection on Criteria using Experiment

The Information on the biodegradability and yield capability of the substrates ($C_i : i = 5,6$) was obtained from the biogas experiment.

2.4.1 Materials and Equipment used for carrying out the experiment

The following materials and equipment were used for the experiment; 100g of each biogas substrates M_k, weighing balance, a furnace as a source of heat, a thermocouple for temperature measurement, a tong, twelve 1500ml sized bio-digesters, laboratory tubes, measuring cylinders, a pH meter, a weighing balance, 0.5 Molar Hydrochloric acid (HCl), and 0.1 Molar sodium hydroxide ($NaOH$) solution.

2.5 Experiment Procedure

The experiment was carried out in two phases. The first phase involved the determination of the volatile solid contents (VS) of M_k. Thus VS_{kt} $\{t = 0\}$ was obtained by adopting the prescribed standard experimental conditions [42] at a University foundry located in a state in South-West Nigeria. The initial TS and VS concentration (in g/L) [VS^*_{k0}] was subsequently determined. The second phase which was a laboratory-based experiment involved the determination of the methane yield ($\bar{Y}_k$) of M_k. One experiment run of three replications (r) was undertaken for each substrate material at mesophilic temperature ranges and neutral starting pH conditions.

For each experiment, one end of a laboratory tube was fitted into the digester. The other end was fitted into one end of a two-ended airtight bag for the collection of the biogas produced by the digester. Before proceeding, the volume of biogas in the airtight bag was measured and recorded as V_{Bkr} by releasing the collected gas through the other end of the airtight bag into an inverted graduated cylinder immersed in a container of 0.5M HCl solution. Methane was then measured by adding 0.1M $NaOH$ solution progressively until the pH of the resulting solution was at least 9. A diagram of the experiment setup is shown in Figure 1. The volume of methane cumulatively (Y_{krt}) within a 20-day retention period (T) was measured via the downward displacement of water by the gas and recorded.

At the end of each replication, the final TS and VS concentration [VS^*_{krT}] of each substrate were determined. At the end of the experiment run for each substrate, the mean cumulative methane yield ($\bar{Y}_{kt}$), and mean final VS concentration ($\overline{VS}^*_{kT}$) were computed from Y_{krt} and VS^*_{krT} of the replicated experiments.

2.6 Determination of Substrate Biodegradability and Yield and Capability Scores

The biodegradability score $\left(D_k^S\right)$ and yield capability score $\left(Y_k^S\right)$ for substrate k were determined by reassigning the total score of the substrate provided by the questionnaire responses for the respective criteria based on the measured property of each substrate as determined from the outcome of the experiment (Equations 4-6).

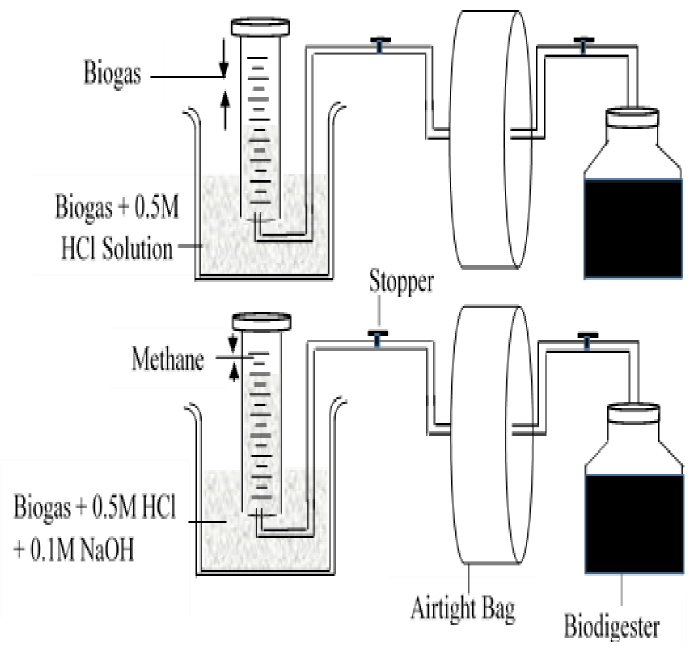

Figure 1: Experiment set up to determine biodegradability and yield of substrates

$$D_k^S = S_{5k}^* = \left({VS_{kR}}\Big/{\sum_{k=1}^{K} VS_{kR}}\right)\sum_{k=1}^{K} S_{5k} \quad (4)$$

$$Y_k^S = S_{6k}^* = \left({\bar{Y}_{kT}}\Big/{\sum_{k=1}^{K} \bar{Y}_{kT}}\right)\sum_{k=1}^{K} S_{6k} \quad (5)$$

$$VS_{Rk} = VS_{k0}^* - \overline{VS}_{kT}^* \quad (6)$$

Where, VS_{Rk} is the reduced volatile solid concentration (g/L) of substrate k; S_{5k}^* and S_{6k}^* are the recomputed substrates' sustainability scores for C_5 and C_6 based on the reassigned S_{5k} and S_{6k}.

The reasons for carrying out the objective scoring based on the reassigned subjective score are:

1. To avoid imposing an exaggerated (positive or negative) penalty on the criteria being scored
2. Although the objective score will improve the correctness of the overall substrate sustainability score, no fixed maximum or minimum score exists for C_5 and C_6, thus the need to utilise the pre-existent subjective score.

Finally, the sustainability index for substrate k (I_k) was recomputed using equation 8. Thus, if the sustainability index of a substrate is higher than that of another, the former substrate was ranked as more sustainable than the latter.

$$\delta_k = I_k + Q_k \quad (8)$$

$$Q_k = \sum_{i=5}^{6} \omega_i S_{ik}^* \quad (9)$$

$(k = 1,2,3,\dots,K)$

3.0 RESULTS AND DISCUSSION

The AHP response table, corresponding relative weight of importance, and rank of the BSSC obtained from the AHP process are shown in Table 2. Table 3 displays the score $\left(S_{ij}\right)$ and ranks $\left(R_{ij}\right)$ for all 12 substrates required for the preliminary selection process while the decomposition characterisation of the substrates is shown in Table 4. Table 5 shows the selected substrates' sustainability ranking.

3.1 Subjective Scoring of sustainability criteria

AHP analysis based on the responses from the questionnaire survey indicated that concerning the BSSC, substrate acceptability (0.4086), yield capability (0.2866) and biodegradability (0.1541) ranked 1st, 2nd, and 3rd respectively while Non-competing substrate ranked least (0.0274) [Table 2]. This implies that community acceptance of biogas materials is the most key factor in the sustainable use of BS while non-usability competition was least prioritised. The ability to produce biogas as well as non-environmental pollution potential were also considered as being important.

This seems to be the general perception of the participants in the study given that the percentage consistency ratio determined from the AHP analysis is 7.34%.

Table 2: Geometric mean response, normalised weights, and rank for criteria

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	Weight (ω_i)	Rank
C_1	1.0000	1.0000	3.0000	0.2000	0.3333	0.2000	0.0649	4
C_2	1.0000	1.0000	3.0000	0.1429	0.3333	0.1429	0.0584	5
C_3	0.3333	0.3333	1.0000	0.1111	0.1429	0.1111	0.0274	6
C_4	5.0000	7.0000	9.0000	1.0000	3.0000	3.0000	0.4086	1
C_5	3.0000	3.00	7.0000	0.3333	1.0000	0.3333	0.1541	3
C_6	5.0000	7.0000	9.0000	0.3333	3.0000	1.0000	0.2866	2
Consistency Ratio=7.34%								

Table 3: Mean Sustainability score and rank for substrates preliminary selection process

j	M_j		$C_i(\omega_i)$ 1 (0.0649)	2 (0.0584)	3 (0.0274)	4 (0.4086)	5 (0.1541)	6 (0.2866)	I_j	Q_j	δ_j	Rank
1	CD	Mean Substrate score (S_{ij})	5.461	7.714	8.428	9.630	6.300	4.605	4.971	2.291	7.262	4
2	SD		6.119	2.171	7.912	8.549	5.901	4.420	4.234	2.176	6.41	9
3	EV		5.314	3.571	1.033	8.131	7.341	6.873	3.904	3.101	7.005	6
4	PD		4.793	3.722	8.931	3.174	6.823	6.604	2.070	2.944	5.014	12
5	FVW		7.337	6.143	5.245	8.907	6.869	7.256	4.618	3.138	7.756	3
6	GD		5.344	3.714	8.857	8.419	6.457	4.285	4.246	2.223	6.469	8
7	MSW		9.737	6.070	4.714	6.713	4.428	6.293	3.859	2.486	6.345	10
8	SS		9.531	8.857	5.428	2.481	7.740	6.500	2.298	3.056	5.354	11
9	PuD		7.482	7.571	8.285	9.350	5.056	7.018	4.975	2.79	7.765	2
10	TW		3.410	4.571	1.714	9.472	5.187	5.362	4.405	2.336	6.741	7
11	AR		5.753	6.286	2.143	8.612	6.445	6.384	4.318	2.823	7.141	5
12	FW		7.784	8.428	6.285	9.577	8.427	8.571	5.083	3.755	8.838	1

Table 4: Result of total solids content, volatile solids content, and methane yield of the selected substrates measured before the start and at the end of the experiment

Substrate (k)	VS^*_{k0} (g/L)	VS_{kT} (%)	$\overline{VS}^*_{kT}$ (g/L)	VS_R (g/L)	$\bar{Y}_{kT}$ (cm^3)	$\bar{Y}_{kT}$ per VS added (L/g)	Expected yield per VS added (L/g) $\bar{Y}_{kT}$ per VS added (L/g)	Source
FW	6.22	9.57	2.91	3.31	1153.50	0.185	0.101-0.707	[43, 44]
PuD	21.65	50.50	18.59	3.06	723.50	0.043	0.020-0.390	[45]
FVW	5.70	8.62	1.98	3.72	934.50	0.156	0.060-0.732	[46, 47]
CD	9.50	15.67	5.52	3.98	887.50	0.093	0.130-0.240	[45]

Table 5: Substrate sustainability ranking determined from on non-experiment and experiment-based criteria

Substrates (k)	I_k	S^*_{5k}/D^S_k, ω_5 =0.1541	S^*_{6k}/Y^S_k, ω_6 =0.2866	Q_k	$\delta_k=(I_k+Q_k)$	Rank
FW	5.083	6.270	8.560	3.420	8.503	1
PuD	4.975	5.796	5.369	2.432	7.407	4
FVW	4.618	7.047	6.935	3.074	7.692	3
CD	4.971	7.539	6.586	3.049	8.020	2

3.2 Substrate Sustainability Criteria Score and Preliminary Substrate Selection

The sustainability criteria score for each of the substrates as obtained from questionnaire responses showed that for substrate population (C_1), Substrate Availability(C_2), Non-competing substrate (C_3), Substrate acceptability(C_4), Biodegradability (C_5), Yield Capability (C_6), the highest-ranked substrates were MSW, SS, PD, CD, FW, and FW respectively while the least ranked were TW, SD, EV, SS, MSW, and GD respectively (Table 3).

For example, it is clear from the result that although sewage sludge (SS) is the most available and easily accessed substrate, it is the least acceptable in the community for biogas production. Similarly, municipal solid waste is considered to exist in large amounts, however, its biodegradability is ranked lowest relative to the other substrates considered. Overall the four highest-ranked substrates were FW $\left(\delta_{j=12} = \delta_{k=1} = 8.838\right)$, PuD $\left(\delta_{j=9} = \delta_{k=2} = 7.766\right)$, FVW $\left(\delta_{j=5} = \delta_{k=3} = 7.756\right)$ and CD $\left(\delta_{j=1} = \delta_{k=4} = 7.261\right)$. This result is expected as all four substrates were generally ranked highly in terms of C_4, C_5, and C_6 which had the highest BSSC values. It was also observed that the four least ranked substrates were SD $\left(\delta_{j=2} = 6.410\right)$, MSW $\left(\delta_{j=7} = 6.344\right)$, SS $\left(\delta_{j=8} = 5.354\right)$, and PD $\left(\delta_{j=4} = 5.014\right)$. SD rank score was affected by its relatively low availability and yield potential, while PD was particularly affected by its low population, availability, and acceptability characteristics.

3.3 Yield and Biodegradability Characteristics of Substrates from Experiment

The cumulative methane yield obtained from the experiment for the four substrates selected at the end of the preliminary substrate selection phase was 1153.5, 723.5, 934.5, and 887.5 for FW, PuD, FVW, and CD amounting to yield sustainability ranks of 1, 4, 2, 3 respectively (Table 4). These amount to 0.185, 0.043, 0.156 and 0.093L/gVS_{added} for the respective substrates. These values all fall within the lower expected methane production ranges reported in the literature (Table 5). The yield values of the substrates underscore the need to avoid assessing the yield sustainability properties of biogas substrates based on established theoretical and practical results determined from random geographical areas but rather to do so based on the yield characteristics of area-specific substrates.

Regarding the biodegradability of M_k, $\overline{VS}^*_{kT}$ for the four substrates; FW, PuD, FVW, and CD, was 2.91,18,59, 1.98, and 5.52 respectively (Table 4). This meant a reduced VS concentration (VS_{Rk}) of 3.31, 3.06, 3.32, and 3.98g/L corresponding to a VS_{Rk} rank of 3,4,2,1 respectively.

3.4 Substrate Sustainability Ranking

From the analysis, VS_{kR} and $\bar{Y}_{kT}$ of M_k obtained from the experiments, the biodegradability score and yield sustainability (D_k^S, Y_k^S) were determined as (6.270, 8.560), (5.296, 5.369), (7.047, 6.935) and (7.539, 6.586) for FW, PuD, FVW, and CD respectively (Table 5).

The recomputed substrates' sustainability rank index based on experiments to determine VS_R and $\bar{Y}_{kT}$ (Table 5) shows that FW (8.503), CD (8.020), FVW (7.692), and PuD (7.407) rank from the most sustainable to the least sustainable substrates. Although the sustainability rank index differs for each of the four substrates the high score range (7-9) to which they all belong indicates that all the substrates considered are very sustainable for use as biogas production substrates.

4.0 CONCLUSION

An attempt has been made to rank materials identified in a community in South-West Nigeria based on their biogas production sustainability potential using a combination of four questionnaire-based subjective, and two experiment-based objective criteria. The AHP was adopted for the criteria weight ranking procedure, while a scoring technique was used to rank the sustainability of selected substrates. From the results obtained it can be concluded that,

1. In order of increasing rank, biodegradability, yield capability, and substrate acceptability are the most rated sustainability criteria, while Non-competing substrate, availability, and substrate population are the least rated criteria.
2. The ranking procedure showed that the sustainability of the substrates decreased in the order of food waste; Cow dung; fruit and vegetable waste and poultry dung. However, all four substrates display good sustainability potential.

It is important to note that firstly, the study was limited to the use of six selected biogas production sustainability criteria. One area of further study could be that of adopting the sustainability ranking approach using an all-encompassing sustainability criteria framework. In addition, the outcomes of this study on selected criteria are based partly on subjective inputs. Regarding this, methods that aid improved subjective responses or appropriate objective techniques may be adapted in the improvement of the approach. Further, as the biogas substrates properties considered in the study are assumed to be location-influenced, the method can be adopted to assess the sustainability of biogas materials in other communities, regions, and locations where bio-energy adoption is desired.

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