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Optimization of Biogas Production from Co-Digestion of Pig Dung, Plantain Stem, and Potato Peel Using Response Surface Methodology

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***Abstract-** Biogas production through anaerobic digestion of agricultural residues offers a sustainable pathway for renewable energy generation and waste management, particularly in developing regions. However, mono-digestion of individual substrates often results in process instability and low gas yields due to nutrient imbalance. This study investigates and optimizes biogas production from the co-digestion of pig dung, plantain stem, and potato peel using Response Surface Methodology (RSM). A Box–Behnken experimental design comprising 54 runs was employed to evaluate the effects and interactions of substrate proportions, carbon-to-nitrogen (C/N) ratio, pH, and hydraulic retention time (HRT) on biogas yield in a laboratory-scale batch digester. Statistical analysis indicated that a two-factor interaction (2FI) model adequately described the process, with a high coefficient of determination ($R^2 = 0.996$) and a non-significant lack of fit ($p > 0.05$). Among the studied factors, HRT and substrate interactions exerted the most significant influence on biogas production. Optimal operating conditions were achieved at a near-neutral pH, C/N ratio between 20 and 30, and extended retention time, resulting in a maximum biogas yield of 2.975 L under the experimental conditions. The results demonstrate that RSM is an effective tool for optimizing anaerobic co-digestion systems and highlight the synergistic potential of combining animal manure with lignocellulosic and carbohydrate-rich residues for enhanced biogas production.*

I. INTRODUCTION

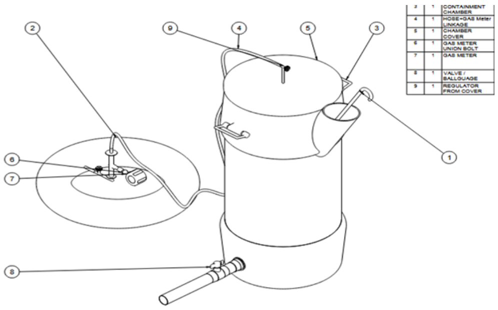
The increasing global demand for energy, coupled with concerns over fossil fuel depletion and environmental degradation, has intensified interest in renewable and sustainable energy technologies. In developing countries such as Nigeria, energy access remains limited and unreliable, particularly in rural and peri-urban communities, where centralized electricity infrastructure is often inadequate (Oyedepo, 2012; Aliyu et al., 2015). Renewable energy systems that enable decentralized power generation are therefore essential for improving energy security and supporting sustainable development. Biogas production through anaerobic digestion of organic waste is a well-established renewable energy technology that simultaneously addresses energy generation and waste management challenges (Bond and Templeton, 2011). Anaerobic digestion converts biodegradable organic matter into biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2), through the metabolic activities of anaerobic microorganisms (Deublein and Steinhauser, 2008). Agricultural residues and animal manures are among the most widely utilized feedstocks for biogas production due to their abundance, low cost, and high biodegradability. However, the anaerobic digestion of single substrates (mono-digestion) often suffers from limitations such as nutrient imbalance, ammonia inhibition, acidification, and poor buffering capacity, which can adversely affect process stability and methane yield (Angelidaki and Ahring, 2003; Li et al., 2011). Co-digestion, which involves the simultaneous digestion of two or more substrates, has been widely reported as an effective strategy for improving biogas yield and digester performance. By combining substrates with complementary characteristics, co-digestion enhances nutrient balance, optimizes the carbon-to-nitrogen (C/N) ratio, and promotes microbial synergy (Alvarez et al., 2000; Adegun et al., 2018). Animal manures, such as pig dung, are nitrogen-rich and provide a robust microbial inoculum and buffering capacity, while lignocellulosic and carbohydrate-rich agricultural residues can supply additional degradable organic matter. Plantain stem, a common agricultural residue in tropical regions, is rich in structural carbon but exhibits slow biodegradation due to its lignocellulosic nature (Kafle and Kim, 2013; Hendriks and Zeeman, 2009). In contrast, potato peel contains readily degradable carbohydrates that support rapid microbial activity during the early stages of digestion (Budiyono et al., 2014). The co-digestion of these substrates therefore presents a promising approach for enhancing biogas production. Despite the demonstrated benefits of co-digestion, biogas yield is highly sensitive to operational parameters such as substrate composition, pH, C/N ratio, and hydraulic retention time (HRT). Traditional one-factor-at-a-time experimental approaches are often inefficient and fail to capture the interactive effects among these variables (Appels et al., 2008; Li et al., 2011). Response Surface Methodology (RSM) is a statistical and mathematical modeling technique that enables the systematic evaluation of multiple process variables and their interactions using a reduced number of experimental runs (Tetteh et al., 2017). RSM has been successfully applied to optimize various anaerobic digestion processes; however, limited studies have investigated the co-digestion of pig dung, plantain stem, and potato peel using RSM, particularly under tropical conditions. The present study aims to optimize biogas production from the co-digestion of pig dung, plantain stem, and potato peel using Response Surface Methodology. Specifically, the study evaluates the individual and interactive effects of substrate proportions, C/N ratio, pH, and hydraulic retention time on biogas yield, and identifies optimal operating conditions for enhanced biogas production. The findings provide statistically validated insights into the synergistic behavior of mixed agricultural residues and contribute to the development of efficient small-scale biogas systems suitable for resource-limited settings.

II. MATERIALS AND METHODS

2.1 Substrate Collection and Preparation Pig dung was collected from a local piggery in Owerri, Nigeria, while plantain stems and potato peels were obtained from nearby farms and food processing locations. The plantain stems and potato peels were washed to remove adhering dirt, air-dried, and mechanically size-reduced to improve homogenization and biodegradability. The substrates were mixed with water to form a uniform slurry prior to digestion. Pig dung was used both as a substrate and as a microbial inoculum to facilitate anaerobic digestion due to its high buffering capacity and established suitability for anaerobic digestion (Kafle and Kim, 2013).

2.2 Experimental Setup
Biogas production experiments were conducted in a laboratory-scale batch anaerobic digester with a working volume of 50 L. The digester was operated under ambient mesophilic conditions and equipped with inlet and outlet ports, a gas collection system, and a gas measurement unit. Biogas volume was measured periodically using a calibrated gas meter, and operating parameters such as pH and temperature were monitored throughout the digestion period. Each experimental run was conducted under batch conditions for the specified hydraulic retention time.

A schematic representation of the laboratory scale batch anaerobic digestion system is shown in fig. 1.



Parts lists

Part number	Quantity	Name	Material
1	1	Stirring rod	Stainless steel
2	1	biogas tube	Butyl rubber
3	1	Clamping ring	Metal
4	1	⅛ inch pressure Hose	PU (polyurethane)
5	1	Biogas digester cover	PVC

6	1	Gas meter union bolt	PVC
7	1	Model FT 1 Gas meter	
8	1	1-inch Ball Gauge Valve	PVC
9	1	Valve	Aluminum
10	1	⅛inch Y - Tee Joint	Stainless steel

2.3 Experimental Design and Response Surface Methodology

A Box–Behnken design under Response Surface Methodology was employed due to its efficiency in evaluating quadratic and interaction effects using a reduced number of experimental runs (Tetteh et al., 2017). Six operational factors were considered: proportions of plantain stem, potato peel, and pig dung, carbon-to-nitrogen (C/N) ratio, pH, and hydraulic retention time (HRT). The (C:N) ratio of the substrate mixture was calculated using the weighted average formula as expressed in Equation 1.

$$C{:}N_{final} = \frac{(C{:}N_A \times W_A)+(C{:}N_B \times W_B)+(C{:}N_C \times W_C)}{W_A+W_B+W_C}$$

Where: C:N_A,C:N_B,C:N_C= C:N ratios of plantain stem, potato peel, and pig dung respectively. W_A,W_B,W_C = Weights (kg) of each material as given by Design Expert. After calculating the initial C:N ratio of the mixture, adjustments were made based on the following conditions: If C:N was too high (indicating excess carbon), more pig dung was added to supply additional nitrogen. If the C:N ratio was too low (indicating excess nitrogen), more plantain stem or potato peels were added to increase the carbon content and bring the mixture to an optimal balance. After adjustment, the substrate mixture was thoroughly mixed and left to stand for 6-12 hours to ensure uniform distribution of nutrients before being fed into the biodigester. For example, in run 1,

Target C:N ratio = 20:1

Using the formular

$$20 = \frac{5\times35+5\times25+S_3\times12}{5+5+S_3}$$

$$20 = \frac{175+125+12S_3}{10+S_3}$$

$$20(10+S_3) = 300+12S_3$$

$$200+20S_3 = 300+12S_3$$

$$200-300+20S_3-12S_3 = 0$$

$$-100+8S_3 = 0$$

$$S_3 = \frac{100}{8} = 12.5\ KG$$

Checking

$$\frac{5\times35+5\times25+12.5\times12}{5+5+12.5}$$

$$\frac{175+125+150}{22.5}$$

$$\frac{450}{22.5} = 20$$

S_3 represents pig dung in the equation. Therefore to get the C:N ratio target value of 20, 12.5kg of pig dung will be mixed with 5kg of grounded plantain stem and 5kg of grounded potato peel. In run 9, target C:N ratio 30, dry plantain stem 3kg, potato peel 3kg

$$30 = \frac{3\times35+3\times25+S_3\times12}{3+3+S_3}$$

$$30 = \frac{105+75+12S_3}{6+S_3}$$

$$30(6+S_3) = 180+12S_3$$

$$180+30S_3 = 180+12S_3$$

$$30S_3-12S_3 = 180-180$$

$$18S_3 = 0$$

$$S_3 = 0$$

This implies that to get the target C:N ratio of 30:1 using the substrate compositions in run 9, pig dung is not required. This is further confirmed mathematically where by only plantain stem and potato peel was used to calculate for the C:N ratio.

$$\frac{3\times35+3\times25}{3+3}$$

$$\frac{105+75}{6} = 30$$

For this reason, pig dung was not used in run 9 during the experiment because only dry plantain stem and potato peel was required to get the target C:N ratio of 30:1. This calculation was done for all the 54 runs and the results are contained in Table 2.

The experimental design consisted of 54 runs, including replicates at the center point to evaluate experimental error and model adequacy are summarized in Table 1

Table 1: Initial experimental design matrix showing 54 runs generated by the Box-Behnken design prior to C:N ratio adjustment.

	Factor 1	*Factor 2*	*Factor 3*	*Factor 4*	*Factor 5*	*Factor 6*	*Response 1*	*Response 2*	*Response 3*	*Response 4*
Run	A:plantain stem	B:potato peel	C:pig dung	D:C:N ratio	E:pH	F:HRT	biogas volume	rate of biogas production	Temperature	pH
	kg	Kg	Kg			Days	L	L/day	C	
1	5	5	3	20	7	18.5				
2	5	3	3	30	6.8	18.5				
3	1	5	3	30	7	18.5				
4	3	3	5	20	7	7				
5	3	3	3	25	7	18.5				
6	3	3	3	25	7	18.5				
7	5	3	1	25	7	30				
8	3	3	3	25	7	18.5				
9	3	3	1	30	7	30				
10	3	5	1	25	6.8	18.5				
11	1	5	3	20	7	18.5				
12	3	1	3	25	6.8	7				
13	5	3	5	25	7	7				
14	3	5	3	25	6.8	7				
15	3	3	5	20	7	30				
16	5	1	3	30	7	18.5				
17	5	3	1	25	7	7				
18	1	3	3	20	6.8	18.5				
19	5	3	3	30	7.2	18.5				
20	3	1	1	25	7.2	18.5				
21	3	3	3	25	7	18.5				
22	5	3	5	25	7	30				
23	3	1	5	25	6.8	18.5				
24	3	1	5	25	7.2	18.5				
25	3	3	1	20	7	7				
26	5	3	3	20	6.8	18.5				
27	3	3	1	30	7	7				
28	3	5	3	25	7.2	30				
29	5	3	3	20	7.2	18.5				
30	3	5	5	25	6.8	18.5				
31	3	5	5	25	7.2	18.5				
32	1	3	3	30	6.8	18.5				
33	1	3	5	25	7	7				
34	5	1	3	20	7	18.5				

35	3	3	3	25	7	18.5
36	3	3	5	30	7	7
37	1	1	3	30	7	18.5
38	1	1	3	20	7	18.5
39	3	3	3	25	7	18.5
40	3	5	3	25	7.2	7
41	1	3	3	30	7.2	18.5
42	1	3	3	20	7.2	18.5
43	3	3	5	30	7	30
44	3	1	3	25	7.2	30
45	3	3	1	20	7	30
46	3	1	3	25	6.8	30
47	1	3	1	25	7	30
48	3	5	3	25	6.8	30
49	3	1	3	25	7.2	7
50	5	5	3	30	7	18.5
51	3	5	1	25	7.2	18.5
52	1	3	1	25	7	7
53	3	1	1	25	6.8	18.5
54	1	3	5	25	7	30

Table 2: Optimized experimental design matrix showing 54 runs adjusted to meet target carbon-to-nitrogen (C:N) ratios.

	Factor 1	*Factor 2*	*Factor 3*	*Factor 4*	*Factor 5*	*Factor 6*	*Response 1*	*Response 2*	*Response 3*	*Response 4*
Run	A:plantain stem	B:potatoe peel	C:pig dung	D:C:N ratio	E:pH	F:HRT	biogas volume	rate of biogas production	Temperature	pH
	Kg	Kg	Kg			Days	L	L/day	^{O}C	
1	5	5	12.5	20	7	18.5				
2	5	3	0.556	30	6.8	18.5				
3	1	5	1.89	23	7	18.5				
4	3	3	7.5	20	7	7				
5	3	3	2.3076	25	7	18.5				
6	3	3	2.3076	25	7	18.5				
7	5	3	3.846	25	7	30				
8	3	3	2.3076	25	7	18.5				
9	3	3	0	30	7	30				
10	3	5	2.3076	25	6.8	18.5				
11	1	5	2.7	20	7	18.5				
12	3	1	2.3076	25	6.8	7				
13	5	3	3.846	25	7	7				
14	3	5	2.3076	25	6.8	7				
15	3	3	7.5	20	7	30				
16	5	1	1.11	30	7	18.5				

17	5	3	3.846	25	7	7
18	1	3	3.75	20	6.8	18.5
19	5	3	0.56	30	7.2	18.5
20	3	1	2.3076	25	7.2	18.5
21	3	3	2.3076	25	7	18.5
22	5	3	3.846	25	7	30
23	3	1	2.3076	25	6.8	18.5
24	3	1	2.3076	25	7.2	18.5
25	3	3	7.5	20	7	7
26	5	3	3.846	20	6.8	18.5
27	3	3	0	30	7	7
28	3	5	2.3076	25	7.2	30
29	5	3	11.25	20	7.2	18.5
30	3	5	2.3076	25	6.8	18.5
31	3	5	2.3076	25	7.2	18.5
32	1	3	2.4	22	6.8	18.5
33	1	3	0.769	25	7	7
34	5	1	10	20	7	18.5
35	3	3	2.3076	25	7	18.5
36	3	3	0	30	7	7
37	1	1	0	30	7	18.5
38	1	1	2.5	20	7	18.5
39	3	3	2.3076	25	7	18.5
40	3	5	2.3076	25	7.2	7
41	1	3	2.4	22	7.2	18.5
42	1	3	3.75	20	7.2	18.5
43	3	3	0	30	7	30
44	3	1	2.31	25	7.2	30
45	3	3	7.5	20	7	30
46	3	1	2.31	25	6.8	30
47	1	3	0.769	25	7	30
48	3	5	2.3076	25	6.8	30
49	3	1	2.31	25	7.2	7
50	5	5	0	30	7	18.5
51	3	5	2.3076	25	7.2	18.5
52	1	3	0.769	25	7	7
53	3	1	2.3076	25	6.8	18.5
54	1	3	0.769	25	7	30

This table shows the optimized 54 experimental runs after adjusting the substrate mixtures to meet the target C:N ratio for effective biogas production. The adjustment was performed using the weighted average formula for C:N ratio, ensuring each run met the desired nutrient balance. All other coded variable levels remain consistent with the initial Box-Behnken design. These optimized mixtures were used in the actual experimental procedure. Design-Expert software (version 13) was used to generate the first experimental matrix in Table 1. The matrix was optimized using the average weighted formula to calculate for the mixture that will amount to the target C/N ratio. The software was further used to carry out regression analysis, and evaluate model significance. A two-factor interaction (2FI) polynomial model was selected to describe the relationship between the response variable (biogas yield) and the independent factors. Model adequacy was assessed using analysis of variance (ANOVA), coefficient of determination

(R^2), adjusted R^2, predicted R^2, adequate precision, and lack-of-fit tests. Numerical optimization was conducted to identify the combination of process variables that maximized biogas production within the experimental range.

Results and Statistical Analysis

3.1 Experimental Biogas Production

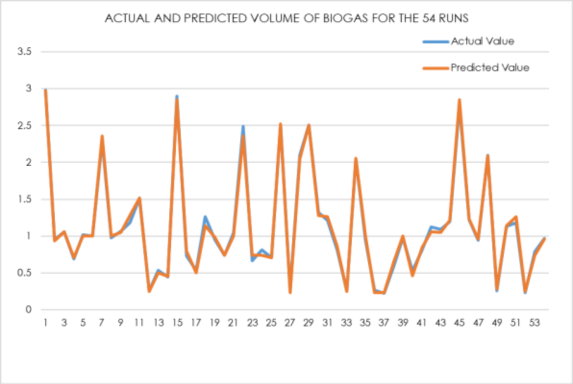
Biogas production varied considerably across the experimental runs, indicating strong dependence on substrate composition and operating conditions. The total biogas yield ranged from 0.225 L to 2.975 L under batch digestion conditions. Higher biogas yields were generally observed at near-neutral pH values, moderate-to-high proportions of pig dung and plantain stem, and extended hydraulic retention times, which are favorable for methanogenic activity. Runs characterized by low substrate loading or short retention times produced comparatively lower biogas volumes, reflecting insufficient time for complete degradation of the lignocellulosic fraction of the feedstock. The observed variation in biogas yield across the design space highlights the importance of optimizing both substrate combinations and operational parameters rather than relying on mono-digestion or fixed operating conditions.

3.2 Model Fitting and Analysis of Variance

The experimental data were fitted to a two-factor interaction (2FI) polynomial model using Response Surface Methodology. The results of the analysis of variance (ANOVA) indicated that the developed model was highly significant ($p < 0.0001$). The coefficient of determination ($R^2 = 0.996$) demonstrated an excellent agreement between the predicted and experimental biogas yields, suggesting that the model adequately captured the underlying process behavior. The results of the Analysis of Variance (ANOVA) for the developed two-factoe interaction model are presented in Table 3.

Source	*Sum of Squares*	*df*	*Mean Square*	*F-value*	*p-value*	
Model	27.94	21	1.33	383.11	< 0.0001	Significant
PS-plantain stem	0.0283	1	0.0283	8.16	0.0075	Significant
PP-potato peel	0.0555	1	0.0555	15.97	0.0004	Significant
PD-pig dung	0.0004	1	0.0004	0.1181	0.7334	Not significant
CNR-C:N ratio	0.0099	1	0.0099	2.85	0.1010	Not significant
pH	0.0009	1	0.0009	0.2627	0.6118	Not significant
HRT	0.6673	1	0.6673	192.15	< 0.0001	Significant
PS × PP	0.0046	1	0.0046	1.31	0.2607	Not significant
PS × PD	0.0047	1	0.0047	1.34	0.2557	Not significant
PS × CNR	0.0026	1	0.0026	0.7442	0.3947	Not significant
PS × pH	0.0009	1	0.0009	0.2614	0.6127	Not significant
PS × HRT	0.1006	1	0.1006	28.98	< 0.0001	Significant
PP × PD	0.0035	1	0.0035	1.02	0.3203	Not significant
PP × CNR	0.0134	1	0.0134	3.86	0.0580	Not significant
PP × pH	0.0007	1	0.0007	0.1889	0.6667	Not significant
PP × HRT	0.2176	1	0.2176	62.66	< 0.0001	Significant
PD × CNR	0.0092	1	0.0092	2.64	0.1142	Not significant
PD × pH	0.0009	1	0.0009	0.2729	0.6050	Not significant
PD × HRT	0.0494	1	0.0494	14.23	0.0007	Significant
CNR × pH	0.0012	1	0.0012	0.3499	0.5583	Not significant
CNR × HRT	0.0049	1	0.0049	1.41	0.2444	Not significant
pH×HRT	0.0012	1	0.0012	0.3500	0.5583	Not significant
Residual	0.1111	32	0.0035			
Lack of Fit	0.0770	16	0.0048	2.26	0.0567	Not significant
Pure Error	0.0341	16	0.0021			
Cor Total	28.05	53				

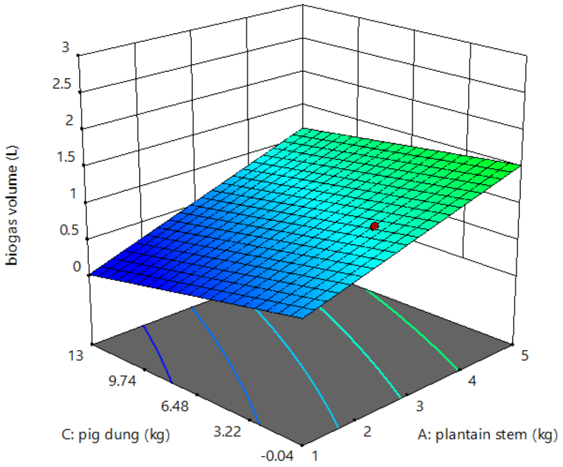
The lack-of-fit test was non-significant ($p > 0.05$), confirming that the model error was primarily due to random experimental variation rather than systematic inadequacy. Additionally, the adjusted R^2 and predicted R^2 values were in close agreement, indicating strong predictive reliability. Adequate precision values exceeded the recommended threshold of 4, further confirming a satisfactory signal-to-noise ratio for navigating the design space. The agreement between predicted and actual biogas yield is illustrated in Fig 2, further confirming the adequacy of the developed model.



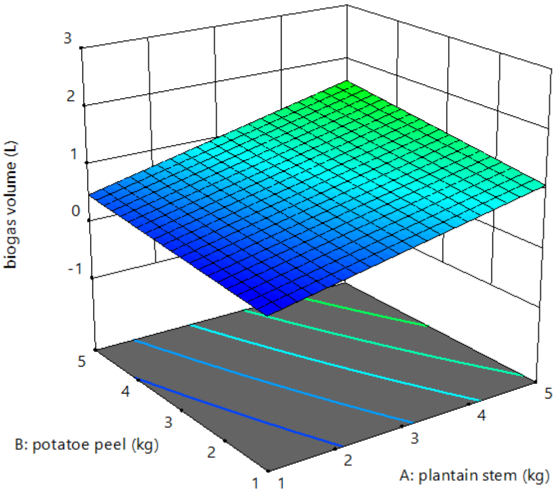
Among the investigated factors, hydraulic retention time (HRT), pig dung proportion, and plantain stem proportion exerted statistically significant effects on biogas production. Several interaction terms were also significant, highlighting the synergistic nature of co-digestion and the importance of considering factor interactions during optimization.

3.3 Interaction Effects of Process Variables

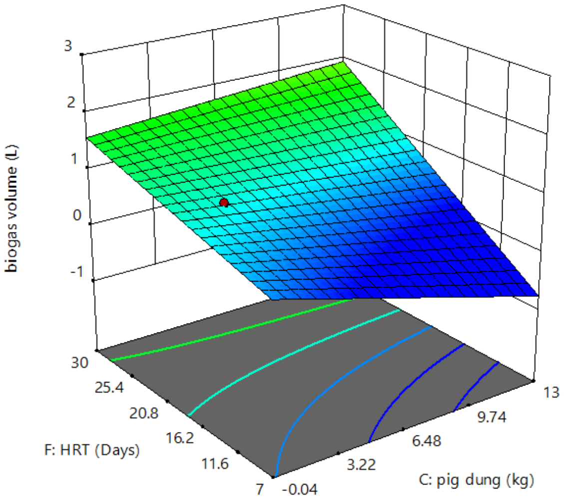
The interaction between pig dung and plantain stem proportions had a pronounced influence on biogas yield. Increasing pig dung content enhanced microbial inoculation and buffering capacity, while moderate additions of plantain stem supplied structural carbon necessary for maintaining an optimal C/N balance. However, excessive plantain stem loading resulted in reduced gas yield, likely due to the recalcitrant nature of lignocellulosic components. The interaction effect between pig dung and plantain stem proportions on biogas yield is shown in Fig. 3



Similarly, the interaction between plantain stem and potato peel demonstrated that the inclusion of readily degradable carbohydrates from potato peel enhanced early-stage biogas production, while plantain stem sustained methane generation over extended digestion periods. These complementary effects underscore the advantages of co-digesting substrates with different biodegradation rates. The interaction effect between plantain stem and potato peel proportions on biogas yield is shown in Fig. 4



The interaction between pig dung proportion and hydraulic retention time further revealed that extended retention periods significantly improved biogas yield when higher proportions of lignocellulosic material were present. This observation confirms that sufficient digestion time is critical for the hydrolysis and methanogenesis stages of anaerobic digestion, particularly for fibrous substrates. The interaction effect between pig dung and hydraulic retention time on biogas yield is shown in Fig. 5



3.4 Optimization of Biogas Production

Numerical optimization using the desirability function approach identified optimal operating conditions for maximum biogas production within the experimental range. The optimal conditions included pig dung content of at least 3.8 kg, plantain stem content of approximately 5 kg, potato peel content between 3 and 5 kg, a C/N ratio of 20–30, pH close to neutral (≈ 7.0), and a hydraulic retention time between 18.5 and 30 days.. the optimal operating conditions and corresponding predicted and actual biogas yields are summarized in Table 3

Number	*plantain stem (KG)*	*Potato peel (KG)*	*pig dung (KG)*	*C:N ratio*	*pH*	*HRT (DAYS)*	*biogas volume (L)*	*Desirability*
1	2.9	4.9	4.5	25	6.8	29	1.516	1.000
2	3.0	1.0	2.3	25	7.2	7	0.278	1.000
3	1.0	5.0	5.0	20	7.0	18.5	1.524	1.000
4	3.0	1.0	2.3	25	7.2	30	1.208	1.000
5	5.0	3.0	0.6	30	6.8	18.5	0.936	1.000
6	5.0	3.0	3.8	25	7.0	30	2.360	1.000
7	1.0	3.0	0.8	25	7.0	30	0.959	1.000
8	3.0	5.0	2.3	25	6.8	7	0.456	1.000
9	3.0	3.0	0.0	30	7.0	7	0.234	1.000
10	3.0	5.0	2.3	25	7.2	18.5	1.256	1.000
11	3.0	5.0	2.3	25	6.8	30	2.095	1.000
12	1.0	3.0	2.4	22	6.8	18.5	0.858	1.000
13	1.0	3.0	3.8	20	6.8	18.5	1.144	1.000
14	3.0	3.0	0.0	30	7.0	30	1.045	1.000
15	1.0	3.0	3.8	20	7.2	18.5	1.059	1.000
16	3.0	3.0	7.5	20	7.0	30	2.853	1.000
17	3.0	1.0	2.3	25	6.8	18.5	0.737	1.000
18	5.0	1.0	10.0	20	7.0	18.5	2.057	1.000
19	3.0	5.0	2.3	25	7.2	7	0.461	1.000
20	3.0	5.0	2.3	25	7.2	30	2.050	1.000
21	5.0	1.0	1.1	30	7.0	18.5	0.795	1.000
22	1.0	3.0	2.4	22	7.2	18.5	0.848	1.000
23	5.0	3.0	3.8	25	7.0	7	0.502	1.000
24	3.0	3.0	7.5	20	7.0	7	0.711	1.000
25	1.0	1.0	0.0	30	7.0	18.5	0.233	1.000
26	5.0	3.0	3.8	20	6.8	18.5	2.516	1.000
27	1.0	5.0	1.9	23	7.0	18.5	1.060	1.000
28	1.0	3.0	0.8	25	7.0	7	0.249	1.000

29	5.0	5.0	12.5	20	7.0	18.5	2.975	1.000
30	3.0	5.0	2.3	25	6.8	18.5	1.275	1.000
31	3.0	1.0	2.3	25	6.8	30	1.227	1.000
32	3.0	1.0	2.3	25	7.2	18.5	0.743	1.000
33	3.0	1.0	2.3	25	6.8	7	0.248	1.000
34	5.0	3.0	11.3	20	7.2	18.5	2.514	1.000
35	1.0	1.0	2.5	20	7.0	18.5	0.646	1.000
36	5.0	3.0	0.6	30	7.2	18.5	0.985	1.000
37	5.0	5.0	0.0	30	7.0	18.5	1.142	1.000
38	4.3	2.0	4.6	29	7.0	21	0.670	1.000
39	3.6	1.4	7.5	25	7.2	21	1.111	1.000
40	3.2	4.4	9.6	24	7.2	14	0.836	1.000
41	2.2	2.3	2.6	26	7.0	17	0.542	1.000
42	3.3	1.2	4.5	29	7.2	17	0.470	1.000
43	2.7	2.5	1.0	24	7.0	27	1.417	1.000
44	2.5	3.3	4.2	25	7.0	18.5	0.822	1.000
45	3.2	3.8	4.9	23	7.0	7	0.509	1.000
46	4.7	1.0	2.4	23	7.2	11	0.695	1.000
47	1.7	1.2	2.4	20	7.1	14	0.608	1.000
48	3.3	1.1	4.2	26	7.1	29	1.257	1.000
49	1.1	1.2	0.8	26	7.0	24	0.427	1.000
50	1.8	4.7	3.7	21	7.1	10	0.852	1.000
51	2.0	1.0	11.9	22	7.0	18	0.859	1.000
52	2.7	4.7	3.5	26	7.2	17	0.942	1.000
53	3.6	1.3	8.9	24	7.0	15	0.583	1.000
54	2.8	2.0	0.0	21	7.0	18.5	1.339	1.000

Under these conditions, the maximum predicted biogas yield was 2.975 L, which closely matched the experimentally observed value, thereby validating the optimization results. The optimization outcomes demonstrate the effectiveness of Response Surface Methodology in identifying favorable operational windows for anaerobic co-digestion systems.

IV. DISCUSSION

The results of this study confirm that co-digestion of pig dung, plantain stem, and potato peel significantly enhances biogas production compared to digestion of individual substrates. The improved performance can be attributed to synergistic interactions among the substrates, leading to improved nutrient balance, enhanced microbial activity, and improved process stability. Pig dung played a crucial role by supplying active microbial consortia and providing buffering capacity, which mitigated pH fluctuations during digestion. The lignocellulosic nature of plantain stem contributed structural carbon but required extended hydraulic retention time to achieve effective degradation. The inclusion of potato peel, rich in easily degradable carbohydrates, supported rapid microbial metabolism during the initial digestion phase, thereby complementing the slower degradation of plantain stem. The strong influence of hydraulic retention time observed in this study is consistent with previous reports emphasizing the need for extended digestion periods for lignocellulosic substrates (Hendriks and Zeeman, 2009; Appels et al., 2008). Compared to similar studies on agricultural residue co-digestion, the biogas yields obtained in this work are within the reported range for laboratory-scale batch digesters operating without chemical or thermal pretreatment (Budiyono et al., 2014; Angelidaki et al., 2011). Differences in absolute biogas volume can be attributed to variations in substrate characteristics, digester configuration, and operating conditions. The high predictive accuracy of the developed RSM model demonstrates the suitability of statistical optimization techniques for analyzing complex anaerobic digestion systems. By capturing interaction effects among process variables, RSM provides valuable insights that are not attainable through conventional experimental approaches. These findings reinforce the applicability of RSM as a decision-support tool for designing and optimizing small-scale biogas systems, particularly in resource-constrained environments.

V. CONCLUSION

This study successfully applied Response Surface Methodology to optimize biogas production from the co-digestion of pig dung, plantain stem, and potato peel in a laboratory-scale batch anaerobic digester. The developed two-factor interaction model exhibited high predictive accuracy and effectively captured the synergistic effects among substrate proportions and operating conditions. Hydraulic retention time, pig dung proportion, and plantain stem proportion were identified as the most influential factors affecting biogas yield. Optimal biogas production was achieved at near-neutral pH, a C/N ratio between 20 and 30, and extended retention time, resulting in a maximum biogas yield of 2.975 L under the experimental conditions. The findings highlight the potential of combining animal manure with lignocellulosic and carbohydrate-rich residues to enhance anaerobic digestion performance. Although the study was conducted at laboratory scale, the results provide practical insights for the design and operation of small-scale biogas systems utilizing locally available agricultural wastes. Future studies should focus on substrate pretreatment, methane composition analysis, and scale-up investigations to further improve biogas yield and process efficiency.

REFERENCES

[1] Oyedepo, S. O. (2012). Energy and sustainable development in Nigeria: The way forward. Energy, Sustainability and Society, 2, 15.

[2] Aliyu, A. S., Saleh, M., & Garba, Z. (2015). Renewable energy potentials and electricity access in Nigeria. Int. J. Renewable Energy Res., 5(2), 555–566.

[3] Bond, T., & Templeton, M. R. (2011). History and future of domestic biogas plants. Energy Sustain. Dev., 15(4), 347–354.

[4] Deublein, D., & Steinhauser, A. (2008). Biogas from waste and renewable resources. Wiley-VCH.

[5] Angelidaki, I., & Ahring, B. K. (2003). Methods for increasing biogas potential. Water Sci. Technol., 47(10), 1–8.

[6] Mata-Alvarez, J., Macé, S., & Llabres, P. (2000). Anaerobic digestion of solid organic wastes. Bioresour. Technol., 74(1), 3–16.

[7] Adegun, O. B., Olaniran, A. O., & Babalola, O. O. (2018). Optimization of biogas production from co-digestion. Renew. Energy, 121, 173–182.

[8] Kafle, G. K., & Kim, S. H. (2013). Co-digestion of pig slurry and agricultural residues. Bioresour. Technol., 129, 170–175.

[9] Hendriks, A., & Zeeman, G. (2009). Pretreatment to enhance lignocellulosic digestibility. Bioresour. Technol., 100(1), 10–18.

[10] Budiyono, Widiasa, I. N., Sunarso, S., & Johari, S. (2014). Biogas from co-digestion of cow dung and potato peel. Energy Procedia, 47, 101–107.

[11] Appels, L., Lauwers, J., Degrève, J., et al. (2008). Anaerobic digestion in global bio-energy production. Renew. Sustain. Energy Rev., 12(2), 345–356.

[12] Li, Y., Yang, G., & Zhang, R. (2011). Factors affecting biogas production. Renew. Sustain. Energy Rev., 15(1), 70–77.

[13] Tetteh, E., Anning, A. K., & Amoah, R. S. (2017). Optimization of biogas production using RSM. Renewable Energy, 109, 331–339.

[14] Igoni, A. H., Ayotamuno, M. J., Ogaji, S. O. T., & Probert, S. D. (2020). Performance evaluation of batch biogas digester. Renewable Energy, 146, 2422–2431.

[15] Angelidaki, I., Alves, M., Bolzonella, D., et al. (2011). Defining biomethane potential. Water Sci. Technol., 63(8), 1571–1577.

[16] Angelidaki, I., & Sanders, W. (2004). Assessment of anaerobic biodegradability. Rev. Environ. Sci. Biotechnol., 3(2), 117–129.

[17] Mshandete, A. M., & Parawira, W. (2009). Biogas technology in sub-Saharan Africa. Renew. Sustain. Energy Rev., 13(9), 2430–2440.