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Modelling and Optimization of Biogas Production from Co-Digestion of Cassava Vinasse with other Biodegradation Wastes

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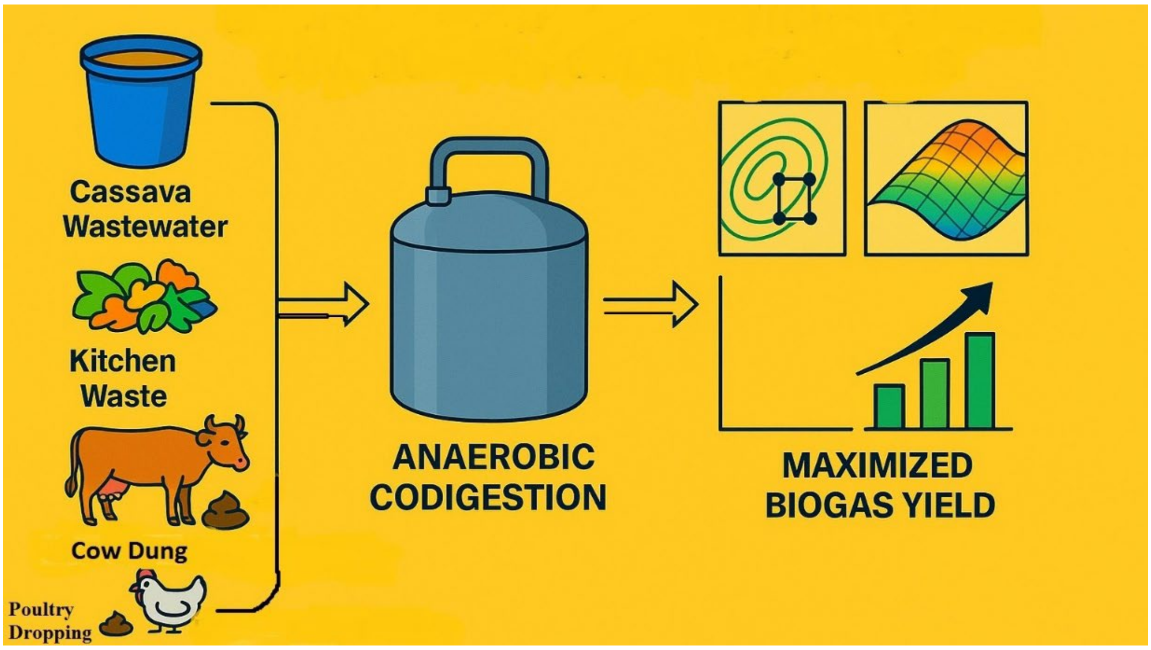
Abstract. Biogas produced via anaerobic digestion where microorganisms break down organic matter in the absence of oxygen, is seen as a promising solution to global energy and environmental challenges. Co-digestion of two or more wastes enhances biogas yield. However, study on optimization of biogas yield using substrate combination is seldom reported. This study was conducted to determine optimum substrate combination to maximize biogas yield. Simple lattice mixture design (SLMD) of Design Expert 13 was employed for experimental design and model development. SLMD was used to systematically vary ratios of different biodegradable wastes. Cassava vinasse (CV), kitchen waste (KW), cow dung (CD) and poultry dropping (PD) were taken as independent variables, and biogas yield as response. Fifteen biodigesters were set-up for the laboratory experiment. Four of the biodigesters were single-waste setups, while the rest digesters were used for co-digestion. A Scheffé quadratic model was developed to predict biogas yield and numerical optimization technique was used for optimization. The model developed gave adequate prediction with coefficient of determination (R^2) of 0.7504 and adequate precision of 7.72. The optimum substrate combination of cassava vinasse (8.6%), kitchen waste (7.1%), cow dung (41.6%) and poultry droppings (42.7%) were obtained for co-digestion process. The findings from this study made invaluable contributions to the field of waste co-digestion to enhance biogas production, offering a sustainable approach to managing organic waste and producing renewable energy.

Graphical Abstract



1. Introduction

Among the main issues facing the globe today are the rising energy consumption and environmental issues [1]. The growing global demand for sustainable and renewable energy has increased interest in biogas production as a promising alternative to fossil fuels. The uncontrolled waste generation worldwide contributes significantly to greenhouse gas (GHG) emissions including carbon dioxide (CO_2) and methane. The conversion of these waste generated to energy can drastically reduce GHG emissions, compared to fossil fuels, by utilization of locally available resources [2]. One of the methods for handling mountainous wastes being generated through our daily activities is anaerobic digestion (AD).

Anaerobic digestion (AD) involves microbial processes that break down organic matter in the absence of oxygen to produce biogas, which has methane (CH_4) as the primary energy component, along with carbon dioxide (CO_2) and trace gases [3]. The percentage composition of biogas includes 55-75% methane, about 25-45% carbon dioxide and other gases in a small proportion [4], [5] and [6]. Biogas produced through the anaerobic digestion of biodegradable waste offers the dual advantage of waste management and energy generation [7]. Various biodegradable wastes, such as food waste, agricultural residues, and animal manure, are commonly used for biogas production [8]. Using any of these wastes as a single substrate for mono-digestion may not always provide an optimal environment for biogas production due to factors such as nutrient imbalances or high concentrations of inhibitory compounds [1]. However, co-digestion has been proposed to overcome these challenges by combining different waste types to achieve a more balanced nutrient profile and enhance microbial activity to improve biogas production [9], [10].

The success of anaerobic co-digestion of different wastes depends on nutrient contents of the combined wastes, balancing carbon-nitrogen (C-N) ratio, increasing buffering capacity of the pH as well as right combination of other parameters in the co-substrate mixture. Mata-Alvarez et al. [11] reported that substrate combination enhances biogas production. However, selecting optimal substrate combination for maximum biogas yield remains a challenging task that has not fully explored in literature. This study aims to explore the optimization of biogas production from single and co-digestion of biodegradable wastes, focusing on improving biogas yield, operational efficiency, and environmental sustainability. By investigating various combinations of waste substrates and operational conditions, this research seeks to identify the most effective strategies for maximizing biogas production while minimizing environmental impact. This study designs and constructs biodigesters and biogas storage units, conducts physicochemical analysis of the four substrates used, and develops predictive models for the optimization of biogas yield through different substrate combinations.

2. Materials and Methods

2.1 Substrate Collection, Processing and Characterization

Four different types of substrates were employed for this study. These substrates include cassava vinasse (CV), kitchen waste (KW), cow dung (CD), and poultry droppings (PD). Cow dung and poultry droppings were collected from the Teaching and Research Farm, Obafemi Awolowo University, Ile Ife, Nigeria. Kitchen wastes were obtained from restaurants on and around campus, while cassava vinasse was collected from a cassava food processing facility in Ile Ife, Osun State, Nigeria. The chemicals and reagents used for this research were of analytical grade, and they were obtained from chemical vendor in Ile-Ife. After collection, the substrates, especially KW, were sorted to remove non-biodegradable materials such as stones, nylon and bones. Furthermore, mechanical pretreatment (grinding) was performed on the KW to achieve homogeneity. The pH of the substrates was tested, and only the CV was observed to need extra pretreatment because it is slightly acidic at a pH 4.5. It was reported that vinasse from cassava based ethanol production are moderately acidic [12]. This is expected due to the fact that cassava vinasse consists of different organic compounds such as acetic acid, lactic acid, glycerol and various reducing sugars [13]. Therefore, the pH of CV was normalized to near neutral at a pH 6.93 by buffering with 0.1 M sodium hydroxide (0.1M NaOH).

All the substrates were characterized for their total solids (TS %), volatile solid (VS %), moisture content (MC %), total nitrogen (TN) and total organic carbon (TOC) before and after digestion process using EN12280 and APHA 2540 B standard methods. TS analysis was achieved by drying samples to a constant weight at 103-105°C, while VS was obtained by calcination of solid samples at 550±5°C. (TS %), (VS %) and (MC %) were then calculated using Eqs. (1), (2) and (3), respectively. Furthermore, total carbon (TC) and total nitrogen (TN) of each substrate were determined, after which the C-N ratio of each of the substrate were calculated. The determination of TC and TN was done at the Poultry Meat Research Laboratory, Department of Animal Sciences, Obafemi Awolowo University, Ile-Ife.

$$TS = 100\frac{m_2}{m_1} \quad (1)$$

$$VS = 100\frac{m_2 - m_3}{m_1} \quad (2)$$

$$MC = 100 - TS \quad (3)$$

where m_1 is the weight of substrate before drying, m_2 is the weight of substrate after drying at 106 °C and m_3 is the weight of dried substrate after calcination in the furnace at 550 °C.

2.2 Preparation of Substrate Slurry

The slurry was prepared by mixing the substrate with water. The mixing ratios were determined using the method of Tumusiime et al. [14]. The method was used to achieve a total solids (TS) concentration of 10% which falls within optimum TS range for wet anaerobic digestion [15], [16]. This was accomplished by carefully adjusting the water content of the substrates as shown in Eq. (4).

$$x = \frac{\sigma_2 - \sigma_1}{100 - \sigma_2} \times M \quad (4)$$

where x is mass of water to be added per gram of feedstock [gH_2O/g]; σ_1 is the moisture content of the substrate; σ_2 is the desire moisture content; M is the mass of substrate. The water-substrate mixing ratios for the substrates are presented in Table 1.

2.3 Design of Experiment

Mixture design in Design Expert software 13.0 was used to design experimental runs to achieve optimum substrate combination. Table 2 presents input variables which include CV (A), KW (B), CD (C) and PD (D) and the only output variable is biogas yield. Design Expert software generated randomly twenty (20) combinations including replicates of CV, KW, CD and PD as shown in Table 3.

Table 1. Mixing Ratio for Substrates.

Substrate	Mass [kg]	TS [%]	MC [%]	Water to substrate ratio
CV	4	1.20	98.80	Pure substrate
KW	4	16.00	84.00	1:2
PD	4	31.00	69.00	2:1
CD	4	16.00	84.00	1:2
KW + CD	4	37.10	62.90	3:1
CV + PD	4	21.40	78.60	1:1
KW+ CV	4	58.90	40.10	4:1
CV+CD	4	38.05	61.95	3:1
PD+CD	4	42.60	57.40	1:1
KW+PD	4	44.55	55.45	3:1
CV+KW+PD+CD (3.75:0.75:0.75:0.75)	6	24.63	75.37	3:1
CV+KW+PD+CD (1.5:1.5:1.5:1.5)	6	37.50	62.50	3:1
CV+KW+PD+CD (0.75:3.75:0.75:0.75)	6	32.26	67.74	2:1
CV+KW+PD+CD (0.75:0.75:0.75:3.75)	6	31.83	68.17	2:1
CV+KW+PD+CD (0.75:0.75:3.75:0.75)	6	35.70	64.30	2:1

Table 2. Input variables.

			Level		
Notation	Component	Unit	-1	0	+1
A	CV	[%]	0	50	100
B	KW	[%]	0	50	100
C	CD	[%]	0	50	100
D	PD	[%]	0	50	100

Table 3. Mixture design for substrate combination.

Run	A: CV	B: KW	C: CD	D: PD
1	1.000	0.000	0.000	0.000
2	0.500	0.000	0.000	0.500
3	0.000	1.000	0.000	0.000
4	0.000	0.500	0.500	0.000
5	0.250	0.250	0.250	0.250
6	0.000	0.000	0.000	1.000
7	0.000	0.000	1.000	0.000
8	0.125	0.625	0.125	0.125
9	0.000	1.000	0.000	0.000
10	0.625	0.125	0.125	0.125
11	0.000	0.000	0.000	1.000
12	0.500	0.500	0.000	0.000
13	0.500	0.500	0.000	0.000
14	0.500	0.000	0.500	0.000
15	0.125	0.125	0.625	0.125
16	0.000	0.000	0.500	0.500
17	0.125	0.125	0.125	0.625
18	1.000	0.000	0.000	0.000
19	0.000	0.000	1.000	0.000
20	0.000	0.500	0.000	0.500

2.4 Experimental Set-Up and Procedure

The anaerobic digestion process was conducted in dark-coloured plastic batch reactors fabricated within the Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria. The dark-coloured batch biodigester contained a gas outlet connected to gas storage tube, with a gas exit for measuring gas volume and flammability. Additionally, each biodigester included a digestate outlet. Fig. 1 illustrates schematic diagram for anaerobic digestion experimental setup. The mono-digestion and co-digestion processes were set-up under mesophilic temperature and Hydraulic Retention Time (HRT) of 30 days. Each of the set-ups consisted of a 25-liter biodigester, a gas storage tube, and a detachable water displacement mechanism for measuring biogas volume.

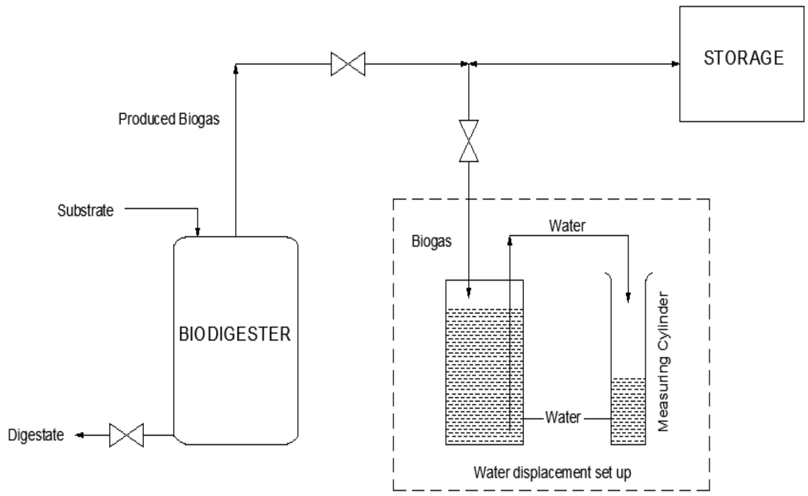


Fig. 1. Schematic diagram for anaerobic digestion process set up for the biogas generation.

2.5 Modelling and Optimization of Biogas Production Process

A quadratic Scheffé model was used to describe the interactive effects of different components and their influence on biogas production. The general form of the quadratic Scheffé model for four components (A, B, C, D) is given in Eq. (5).

$$Y = \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_{12} AB + \beta_{13} AC + \beta_{14} AD + \beta_{23} BC + \beta_{24} BD + \beta_{34} CD \quad (5)$$

$\beta_1, \beta_2, \beta_3, \beta_4$ are the linear coefficients for the respective components; $\beta_{12}, \beta_{13}, \beta_{14}, \beta_{23}, \beta_{24}, \beta_{34}$ are the interaction coefficients between pairs of components. A, B, C and D stand for the proportion of each term, while AB, AC, AD, BC, BD and CD are interactions that affect the response variable Y, which is biogas yield in this case.

Biogas production was optimized using desirability algorithm in the Design Expert software 13.0. Both the input variable (%CV, %KW, %CD and %PD) and the output variable (biogas yield) were constrained to the range of experimental design. The desirability for each solution was examined for the optimum substrate combination.

3. Results and Discussion

The results of this study are discussed in details in this section.

3.1. Biogas Production from Mono-and Co-Digestion Processes

The biogas production during mono-digestion processes over the period of 30 day is shown in Fig. 2. Biogas production started immediately after loading in all substrates (KW, CD and PD) except in CV which started after 5th day. Cassava vinasse is more acidic when compared with other substrates. This observation shows that KW, CD and PD degrade faster than CV. The delay in the biogas production by CV could be due to the impeding influence of acid on microbial activities as the substrate was being degraded. The process exhibited a lag phase during which the microbial communities adapt to the substrate. Also, except for CV, fluctuations were observed in all the mono-digestion cases, similar to the observation reported by Odejobi et al. [17]. For the case of mono-digestion of CV, biogas production was increasing until after 25th day when the biogas production began to decline till 30th day retention time when no appreciable gas production was observed except for the CD. The CV was sourced from cassava processing facility within Ile-Ife town, Osun State, Nigeria. The CV contained high percentage of water with cassava starch sediments. Hence, the steady biogas production from CV before the steady decline could be due to balanced moisture content. The fluctuation in biogas production from other substrates could be due to effects of temperature, pH imbalance and changes in moisture levels on microbial activities during substrate degradation. It could be observed from

Figure 2 that the biogas production for CD was still increasing after day 30. Cow dung contains fibrous materials which require longer time for the communities of microorganisms to degrade, and in effect, longer time for biogas production to cease. It has been reported that co-digestion improved biogas production, but the results obtained from this study revealed that for co-digestion of substrates to increase biogas production, the composition of participating substrates plays a vital role [17]. During co-digestion of the substrates in this study, biogas production in all cases started within 24 hours. The highest biogas yield of 12,060 mL and the least biogas yield of 3,423 mL were produced from co-digestion of CD+PD and KW+CD, respectively. The positive synergetic effects between CD and PD which provide nutrient balance between the two substrates could be responsible for the observed trend [18]. Kitchen wastes (KW) may have an imbalance of carbon-rich and nitrogen-rich materials due to the presence of oils, fats, or toxic compounds, that can inhibit microbial growth. The low biogas production observed within the specified hydraulic retention time (HRT) in co-digestion of KW+CD may be due to inbalance nutrients and high concentration of ammonia intorduced by KW or poor mixing of the two substrates. Generally, ffluctuations were observed in biogas production in all co-digestion processes as shown in Figure 3. This is in agreement with the study carried out by Odejobi et al. [17]. The reason for the fluctuations in biogas yield in all the co-digestion cases could be due to the same for the mono-digestion cases earlier reported in this study. The observed reduction in biogas yield, after the attainment of maximum biogas yield in each case until the completion of HRT of 30 days, could be due to depletion of degradable part of the participating substrates in the co-digestion process.

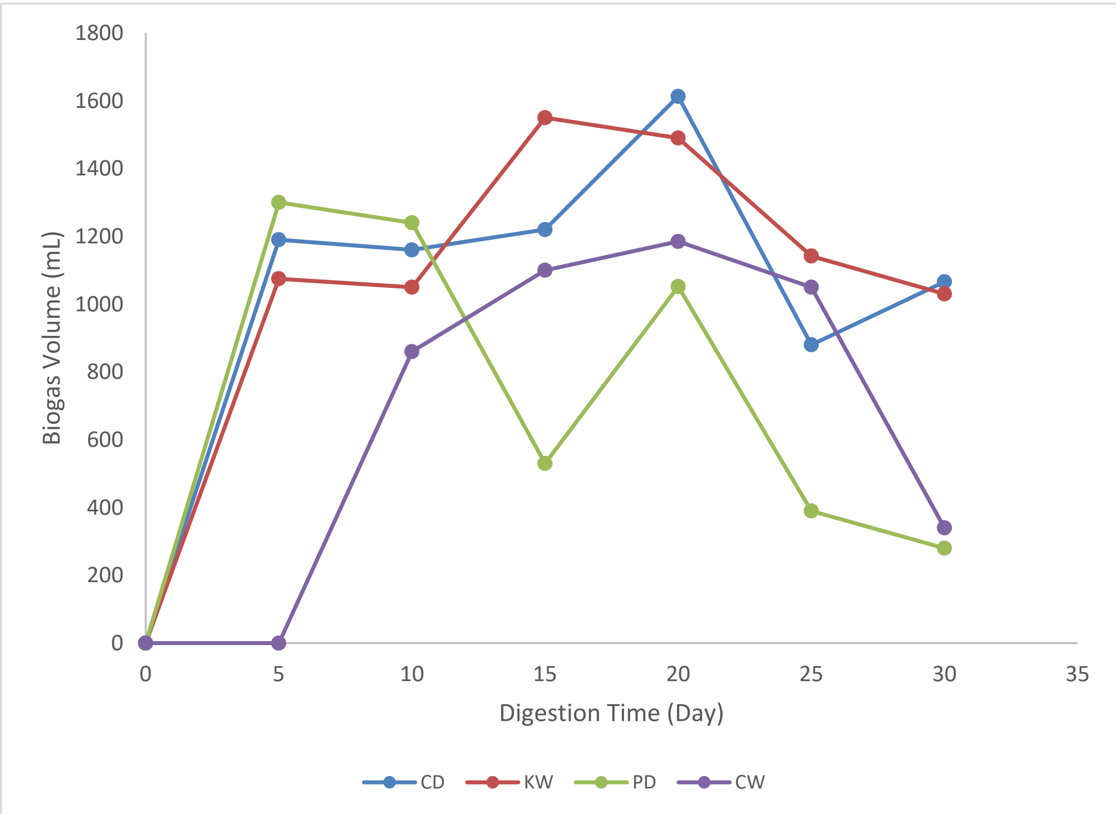


Fig. 2. Biogas production for mono digestion over 30 days.

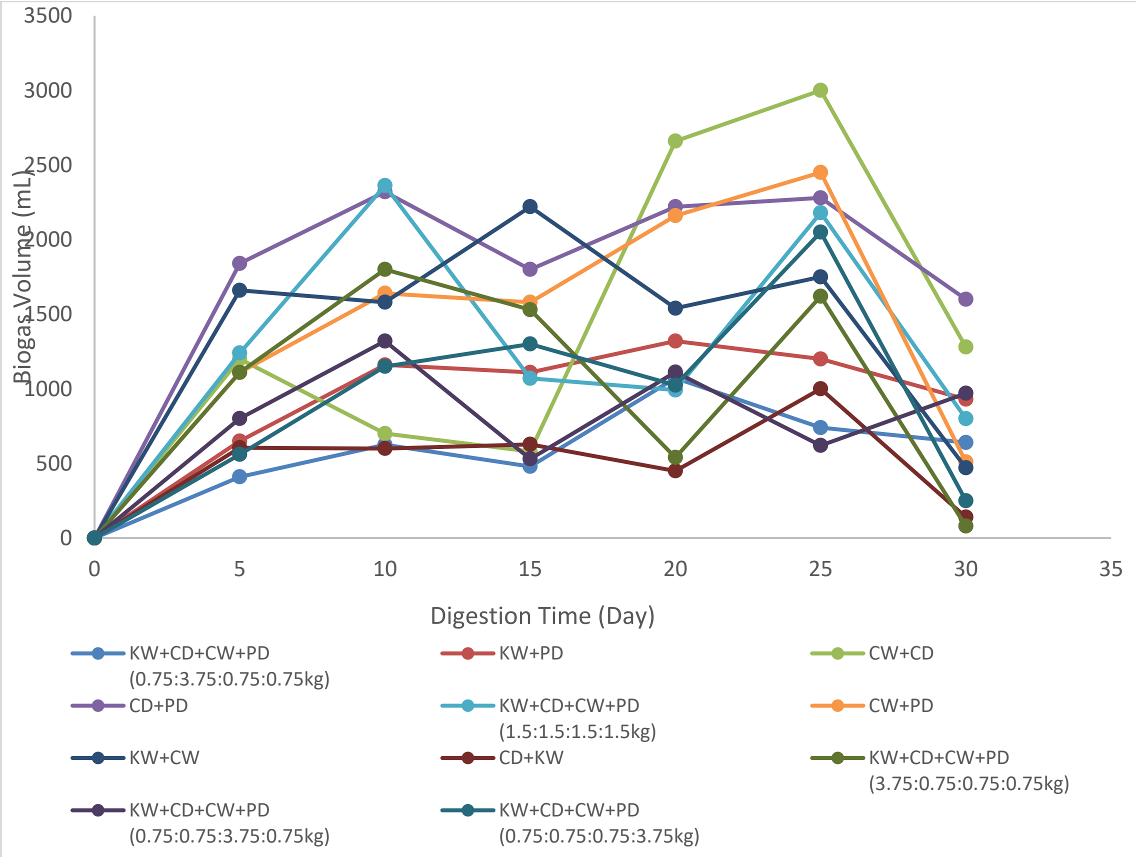


Fig. 3. Biogas production for co-digestion over 30 days.

3.2 Statistical Analysis of the Developed Model

The actual and predicted biogas yield according to the simple lattice mixture design in Design Expert software is presented in Table 4. The quadratic model developed for the prediction and optimization of biogas yield is given in Equation (6). The model comprises both the negative term, which represents antagonistic effect and positive term which indicates synergistic effect on quadratic model. Model adequacy and degree of fitness were determined using coefficient of determination (R^2), predicted R^2 and adjusted $R^{2,}$ Coefficient of variance (C.V), and adequate decision. As presented in Table 5, the R^2 value for the developed model is 0.7504. This value shows that 75.04% of the variance in biogas yield is explained by the model, which is considered acceptable for experimental data. This implies that the model has good fit and ability to predict the biogas yield accurately. Furthermore, C.V was used to test precision of developed model. The C.V value of 22.24 gives good data reliability and high degree of precision. Adequate precision measures the signal to noise ratio. A ratio more than 4 is desirable. Adequate precision 7.7191 for the developed model shows an adequate signal.

Analysis of variance (ANOVA) for quadratic model is presented Table 6. The model developed represents how the proportion of each biodegradable waste (A: CV, B: KW, C: CD and D: PD), and their interactions affect biogas yield. ANOVA showed that the model has an F-value of 3.34 and a p-value of 0.0370, indicating that the model is significant and can accurately predict biogas yield. Significant interactions were observed between cassava vinasse and kitchen wastes (AB), cassava vinasse and poultry droppings (AD), kitchen waste and cow dung (BC), and cow dung and poultry droppings (CD), with p-values less than 0.05. These interactions highlight the importance of combining specific substrates to maximize biogas production. The interaction between cassava vinasse and cow dung (AC), and kitchen waste and poultry droppings (BD), and other terms that have p-values greater than 0.05, indicating they are not significant in this model. Furthermore, the positive coefficients associated with cassava vinasse (A), kitchen waste (B), cow dung (C), poultry droppings (D), co-digestions of cassava vinasse and kitchen waste (AB), cassava vinasse and cow dung (AC), cassava vinasse and poultry droppings (AD) and cow dung and poultry droppings (CD) as given in Eq. (6) indicate that all contributed positively to biogas yield. The particularly high positive coefficient for the interaction between cow dung and poultry droppings (CD) suggests a strong synergistic effect, likely resulting from complementary microbial communities or nutrient profiles. Conversely, the negative interactions between kitchen waste and cow dung (BC) and kitchen waste and poultry droppings hint at a potential antagonistic effect, where these components may impede each other's effectiveness, and consequently produce low biogas.

Table 4. Mixture design for biogas prediction.

Run	A: CV	B: KW	C: CD	D: PD	Actual biogas yield	Predicted biogas yield
1	1.000	0.000	0.000	0.000	4535	4524.70
2	0.500	0.000	0.000	0.500	9450	8408.54
3	0.000	1.000	0.000	0.000	7337	7585.70
4	0.000	0.500	0.500	0.000	3423	2530.46
5	0.250	0.250	0.250	0.250	8644	7622.40
6	0.000	0.000	0.000	1.000	4792	4841.11
7	0.000	0.000	1.000	0.000	7129	6993.57
8	0.125	0.625	0.125	0.125	6680	6624.42
9	0.000	1.000	0.000	0.000	7337	7585.70
10	0.625	0.125	0.125	0.125	5353	7369.42
11	0.000	0.000	0.000	1.000	4792	4841.11
12	0.500	0.500	0.000	0.000	9220	8898.86
13	0.500	0.500	0.000	0.000	9220	8898.86
14	0.500	0.000	0.500	0.000	7420	6009.46
15	0.125	0.125	0.625	0.125	3967	6984.47
16	0.000	0.000	0.500	0.500	12060	10768.28
17	0.125	0.125	0.125	0.625	6334	7875.15
18	1.000	0.000	0.000	0.000	4535	4524.70
19	0.000	0.000	1.000	0.000	7129	6993.57
20	0.000	0.500	0.000	0.500	6370	5846.54

$$Biogasyield = +4524.69729A + 7585.69729B + 6993.56591C + 4841.10646D + 11374.65421AB + 1001.30933AC + 14902.55257AD - 19036.69067BC - 1467.44743BD + 19403.76432CD \quad (6)$$

Table 5. Fit statistics for biogas yield model.

Std. Dev.	Mean	C.V. %	R^2	Adjusted R^2	Adeq Precision
1509.24	6786.35	22.24	0.7504	0.5257	7.7191

Table 6. ANOVA for quadratic model for biogas prediction.

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	6.846E+07	9	7.607E+06	3.34	0.0370	significant
(1)Linear Mixture	1.548E+06	3	5.159E+05	0.2265	0.8759	
AB	1.145E+07	1	1.145E+07	5.02	0.0489	
AC	57139.11	1	57139.11	0.0251	0.8773	
AD	1.266E+07	1	1.266E+07	5.56	0.0401	
BC	2.065E+07	1	2.065E+07	9.07	0.0131	
BD	1.227E+05	1	1.227E+05	0.0539	0.8211	
CD	2.139E+07	1	2.139E+07	9.39	0.0120	
Residual	2.278E+07	10	2.278E+06			
Lack of Fit	2.278E+07	5	4.556E+06			
Pure Error	0.0000	5	0.0000			
Cor Total	9.124E+07	19				

df = Degree of Freedom

3.3 Interaction Effect of Substrate Combination

Fig. 4 shows the 3D plot which offer a more comprehensive view of how the three components interact simultaneously, allowing for a deeper understanding of the combined effects on biogas yield. This plot describes how varying the fraction of one component can affect the biogas yield. In this plot, A, B, C and D represent cassava vinasse (CV), kitchen waste (KW), cow dung (CD), and poultry droppings (PD), respectively. Biogas yield is the dependent variable, represented on the vertical axis, showing the amount of biogas produced as a result of the mixture combinations. The plot shows that binary combination A-C produced the highest biogas, but as it tends towards C, more biogas is being produced. In the binary combination A-B, while A decreases, B increases towards mid-point. The binary B-C was negative where the curve from vertex C decreasing towards mid-point indicating reduction in biogas. Furthermore, the plot shows that when component C increased, and components A and B reduced, the biogas yield is higher, approaching value 9,390.45mL of biogas. The lowest yield occurs when component B is present in significant amount while A, and C are minimized. This suggests that increasing the proportions of A or B significantly reduces biogas yield. The results as presented in 3D plot and Eq. (5) imply that AB and AC have positive effect on biogas, while BC has negative effect on biogas yield.

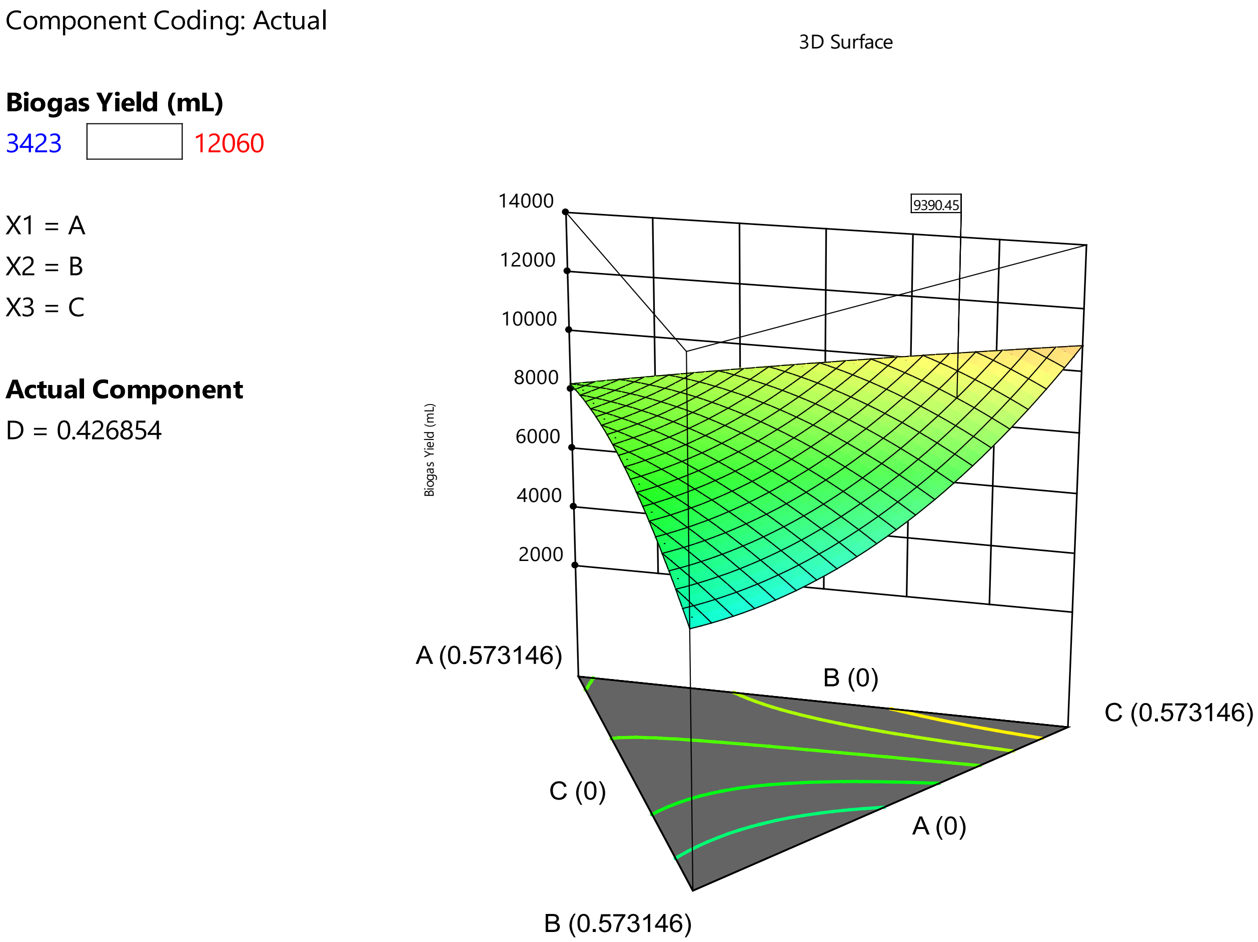


Fig. 4. 3D surface plot for combination of substrates.

3.4. Optimization of Biogas Production Process

After careful investigation of the combination of biodegradable wastes that would give optimum biogas yield from the experimental run and analyses, the solutions presented in Table 7 were obtained using desirability algorithm in Design Expert software. All solutions provided by the software were feasible due to their desirability values of 1, but Solution 1 was recommended by the software as the optimum substrate combination. Additionally, as shown in Fig. 5, the optimum substrate combination that gave maximum biogas yield of 9,390.45 mL/kg VS are of 8.6% CV, 7.1% KW, 41.6% CD, and

42.7% PD. This result is in agreement with the observation reported by Jaro et al. [19] with optimum biogas yield of 7,430 mL/kg VS.

Table 7. Optimization solutions for biogas production process.

Solution	CV	KW	CD	PD	Biogas Yield	Desirability	
1	**0.086**	**0.071**	**0.416**	**0.427**	**9390.450**	**1.000**	**Selected**
2	1.000	0.000	0.000	0.000	4524.697	1.000	
3	0.500	0.000	0.000	0.500	8408.540	1.000	
4	0.125	0.125	0.125	0.625	7875.149	1.000	
5	0.000	0.500	0.000	0.500	5846.540	1.000	
6	0.250	0.250	0.250	0.250	7622.401	1.000	
7	0.000	1.000	0.000	0.000	7585.697	1.000	
8	0.625	0.125	0.125	0.125	7369.423	1.000	
9	0.000	0.000	0.000	1.000	4841.106	1.000	
10	0.500	0.500	0.000	0.000	8898.861	1.000	

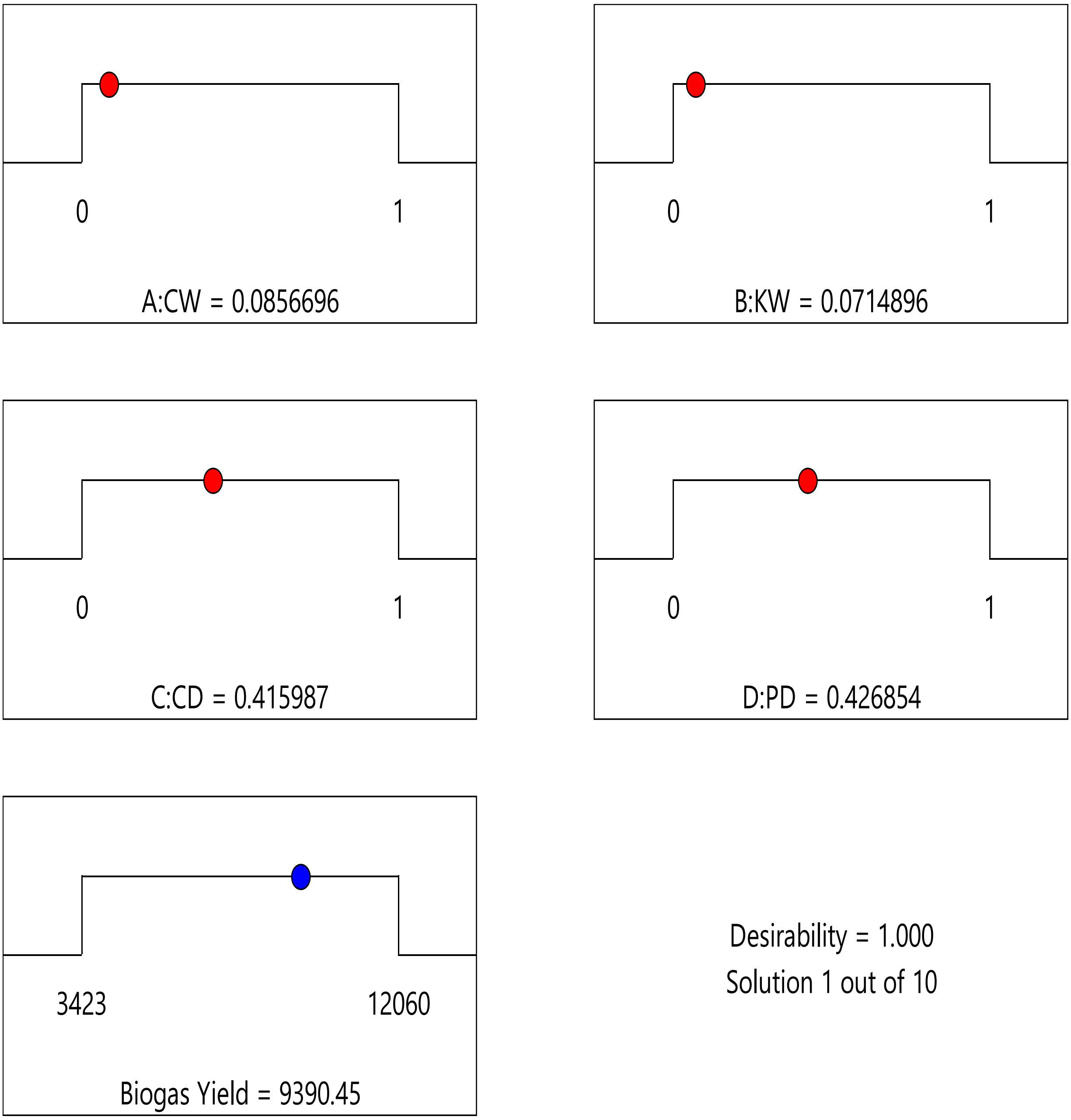


Fig. 5. Ramp plot for optimization.

4. Conclusion

The study investigated optimization of biogas production from mono- and co-digestion of biodegradable wastes. Simple lattice mixture design in Design Expert software was used to design the experiment and develop the model, while numerical optimization technique was employed to obtain optimum substrate combination. The model was found to be significant with an F-value of 3.34 and a p-value of 0.0370. Significant interactions were observed between cassava vinasse and kitchen waste, cassava vinasse and poultry droppings, kitchen wastes and cow dung, and cow dung and poultry droppings, with p-values less than 0.05. These interactions highlight the importance of combining specific substrates to maximize biogas production. The R^2 value suggests that 75.04% of the variance in biogas yield is explained by the model. This study showed that, optimum substrate combination gave maximum biogas yield of 9390.45 mL/kg VS are 8.6% CV, 7.1% KW, 41.6% CD and 42.7% PD. This investigation could guide future experiments or industrial applications where adjusting the proportions of different biodegradable wastes can maximize production from biogas.

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