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Enhancing Biogas Yield by Co-Digestion of Cattle Dung and Acha (*Digitaria Exilis*) Hulls

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Abstract:- This study assessed biogas yield enhancement by the co-digestion of Cattle Dung (CD) and acha (*Digitaria exilis*) hulls (AH) due the perceived synergy of these wastes to improve biomethane yield. Ultimate properties of the CD and AH useful for biogas process stability were evaluated. Triplicate experiments were conducted in 1000 mL polyethylene biodigester at the organic loading rates (OLR) of 4, 6 and 8 g VS/L and inoculum to substrate ratio of 2:1 in Biodigesters A, B, C and control at ambient temperature. Response Surface Methodology's was used to assess the effect of process parameters on cumulative biogas yield (CBY). The results show that the average composition (%) of total solids, volatile solids, N and C were 82.43, 64.86, 3.18 and 37.62 respectively for CD and 92.61, 85.22, 1.68, and 49.43 respectively for AH. The C:N ratio was 12:1 for CD, 29.58:1 for AH and averaged 20.79:1. Biodigester B (663.42mL) with 4 g VS/L recorded the highest biogas volume, followed by A (581.95mL) and then the control (489.77). Biodigester C (475.60mL) had the least volume. ANOVA showed that OLR ($F = 62.49$, $p < 0.01$) and time ($F = 89.01$, $p < 0.01$) were significant predictors of CBY but ambient temperature was not. The optimization prediction shows that cumulative biogas volume of 507.63 mL can be attained when the biodigester is operated at 4 g VS/L at 33 °C, over 34 days. This result supports the notion that codigestion increases biogas yields.

Keywords:- *Biogas - Anaerobic Codigestion -Cattle Dung - Acha Hull.*

I. INTRODUCTION

A wide range of waste types can be used as feedstocks for biogas production. For instance, sludge from wastewater, livestock manure, agricultural residues, paper waste, and food waste have been employed as substrates for biogas production (Surra et al., 2019). Currently, most of the commercial biogas plants in the world depend on animal wastes, particularly Cattle Dung (CD), as their primary feedstock in the biogas economy of scale (Ali *et al*., 2020). This is primarily due to the availability of large quantities of the dungs in dairies where they often constitute environmental hazard and the natural presence of viable methanogenic species (*Escherichia coli, Bacillus sp., Pseudomonas sp., Staphylococcus sp*., and *Proteus sp*.) in the dungs that can easily trigger the AD process without extra costs (Itodo *et al*., 2021).

Cattle dung is the undigested remains of fodder excreted by cattle consisting of faeces and urine in the ratio of 3:1 with primarily lignin, cellulose and hemicelluloses matter (Ya'aba and Ramalan, 2020). Although, the exclusive use of CD as the feedstock for biogas production have shown some drawbacks, such as the difficulty in hydrolysing the lignin complex in the dung to caproic acids, by the methanogens, a vital step in the conversion of the organic substrates to CH_4 (Mazurkiewicz, 2022) among others. The combining of crop residues with high Carbon-to-Nitrogen (C:N) ratios in their optimal range of 20-30 with CD has emerged as a novel and easy solution to this drawback (Surra et al., 2019). This mixing of different organic matters, of plant and animal origin, together in the biogas production process, to improve the CH_4 yield, in what is termed as Anaerobic Co-Digestion (AcoD) is well establish, however, several agricultural residues have received little attention.

About 25 thousand tons of acha hulls are processed yearly in Nigeria and constitutes environmental problems (Wilma et al. 2018), however, these hulls contain an average of 44.5 % carbon and 2.5 % nitrogen ideal for AcoD (Balloguo *et al*, 2013). The utilisation of these hulls, co-digested with Cattle dung in the AcoD biogas production process provide opportunity for waste conversion and sustainable energy production in the time of scarce energy as producing cost effective energy and utilizing bioenergy efficiency is the key to improving the living standard of Nigerians. The main objective of this study was to assess biogas yield enhancement by co-digestion of Cattle dung and acha (*Digitaria Exilis*) hulls. Specifically, the study sought to; determine some ultimate properties of CH and AH necessary for biogas production, produce biogas from the co-digestion of CD and AH at ambient conditions and optimize the process parameters of co-digesting CD and AH.

II. METHODS

A. Source of Experimental Material

The experiment was conducted in Makurdi, Benue State, Nigeria. The inoculum was gotten from the digestate of an active 5 m^3 float drum biogas digester at the Livestock Teaching and Research Farm, Joseph Sarwuan Tarka University of Agriculture, Makurdi. Three hundred grams of fresh digestate containing viable microbes was obtained and taken to the laboratory for co-digestion studies. Acha Hulls (AH) were procured from processors in Heipang, Barkin

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Ladi, Plateau State, kept in an airtight container before used for the ACoD studies.

B. Determination of the Total Solids (TS) and Volatile Solids (VS) of CD and AH

The determination of TS and of VS was modelled after DIN 12880 / 12879 (2001) German standard for the determination of TS, ash and VS.

C. Ultimate analysis of feed stock

To determine the elemental composition of carbon (C) hydrogen (H) nitrogen (N) and sulphur (S), triplicated samples were analysed using a CHNS analyser Model Thermo Flash EA12 series.

D. Biodigester System

The biogas production system comprised three parts (Plate 1). The first is the reactor, second is the gas quantification unit- consists of a gas bag that was weighed on the digital balance, and the third was the biomethane quantification unit. The reactor was a 1000 mL transparent polyethylene cylindrical bottle of 60 mm diameter and a height of 120 mm. One end of reactor was completely sealed and the other has a screwcap. Two 2 mm holes were drilled on the screwcap for inserting PVC tubing and pH meter into the digester. The outer top of the screw cap where the holes were made was sealed with silicon epoxy to prevent air from entering the digester.

Biogas quantification was based on the density method. A biogas collection bag was attached to the outlet of the bioreactor and the gas flowing into the bag was weighed with a Eosphorus digital mass scale (0.01 g.)

Plate 1: Biogas Production Setup

Accuracy, China) daily. The volume of the biogas was estimated from mass- density relation and corrected according to the methods of Raposo et al. (2011). Biomethane quantification was based on the liquid displacement method using a guard solution (NaCl –180 g and $C_6H_8O_7$-5g dissolved in 1 L of distilled water) of 75 % salinity (Boe et al., 2010). An inverted burette held with a retort stand was filled with the guard solution and immerse inside a trough also containing the solution. The PVC tubing from the biogas quantification gasbag was passed under the solution in the trough into the inverted calibrated burette filled with the guard solution. The valve of weighed gasbag was opened during CH_4 measurement and biogas was liberated into the guard solution which removed most of the impurities. The CH_4 gas exerted pressure in the burette and displace the guard solution by equal volume. The liberated CH_4 was collected in second gas bag attached at the topmost end of the inverted burette and weighed. The CH_4 volume was estimated by measuring the difference in the height of the guard solution daily at 4 pm during the experimental period and compared to weighed bags. The guard solution was replaced daily after taking the reading when biogas yield in the systems had commenced.

E. Anaerobic Co-Digestion Experiments

Triplicate experiments were carried out using nine 1000 mL polyethylene biodigester (Plates 1). The biodigesters were cleaned with distilled water before the loading of feedstocks. Nine biodigesters, three for each treatment sample, labelled A,A_2,A_3; B,B_2, B_3, C-C_2 C_3 and one for the Control were used in the experiment. The characteristics of the substrates are in Table 1. The combinations of substrates and inoculum was based on the recommendation of Holliger *et al*. (2016) for an inoculum to substrate ratio of 2- 4:1 and organic load rate (OLR) of 6-10 g VS/L. In this study, the inoculum to substrate ratio (ISR) of 2:1 was used throughout to prevent souring (Surra *et al*.,2019). The OLR was computed at 4 g VS/L, 6 g VS/L and 8 g VS/L using Equation 1;

$$OLR = \frac{\dot{m} \times S}{V_R} \tag{1}$$

$\dot{m}$ – substrate flow rate (g),
S- substrate concentration in inflow (VS) = % VS
V_r – Effective volume of biodigester, 0.75 L
$\dot{m}_{AH}$ = 0.8518 % VS
$\dot{m}_{CD}$ = 0.6487 % VS

For example, using the ISR of 2:1 and 750 mL of water, the mass of influents was calculated;

OLR	CD 2-parts	AH 1-part	Total
4 g VS/L:	(0.75 ×2.6)/0.65 =3.01	(0.75 ×1.4)/0.85 =1.23	4.24 g
6 g VS/L:	(0.75 ×4.0)/0.65 = 4.63	(0.75 ×2)/0.85 =3.13	7.74 g
8 g VS/L	(0.75×5.2)/0.65 = 6.01	(0.75 ×2.8)/0.85 =2.47	8.48 g

In the first pair of biodigesters; A-A_3, 3.01 g of the CD inoculum was homogenously mixed with 1.23 g of AH in a 750 mL distilled water and brought to a volume of 4 g VS/L, leaving a 250 mL headspace for biogas to occupy. The procedure was repeated using 4.63 g and 6.01 g of CD mixed homogenously with 3.13 g and 2.47 g of the AH in 0.75 L distilled water to make OLR of 6 g VS/L and 8 g VS/L for digesters B-B_3 and C-C_3 respectively (Table 1). A control was provided by mixing 7 g of CD in 750 mL of distilled water (6 g VS/L). The experiment was conducted at ambient temperature in the range of 25.56 – 32.22 (mean =28) °C for 34 days.

F. Statistical Analysis

Design Expert (DX) Response Surface Methodology's (RSM) central composite design (DX-13, Stat Ease Inc., Minneapolis, USA) was used to assess the effect of process parameters; OLR, ambient temperature and hydraulic retention time (HRT) on cumulative biogas yield and for optimizing the process parameter. The Online Biogas APP (Sasha *et al*. 2020) was used for biogas and biomethane volumes.

Table 1: Characteristics of Influents used for Biogas Production

	Biodigester			
Parameter	**A**	**B**	**C**	**Control**
Cattle Dung (g)	3.01	4.63	6.01	7
Acha Hull (g)	1.23	1.76	2.47	-
Total influent mass (g)	4.24	6.39	8.48	7
I/S ratio	2:1	2:1	2:1	-
Water (mL)	750	750	750	750
OLR (g VS/L)	4	6	8	6
C/N ratio	20.79	20.79	20.79	12.00

III. RESULTS AND DISCUSSION

The ultimate compositions of the substrates used in this study show that the averages of TS (%), ash (%), VS (%), N (%), C (%) and C:N ratio was 82.43,17.57, 64.86, 3.18, 37.62 and 12.00 respectively for CD. The mean values for AH were 92.61, 7.39, 85.22, 1.68, 49.43 and 29.58 for TS (%), ash (%), VS (%), N (%), C (%) and C:N ratio. The average C:N ratio of the two substrates was 20.79, which is within the best range for optimal biogas yield (Surra et al., 2018). The range of the degradability of the substrate and inoculum was at 85 and 65 % based on the concentration of VS of the AH and CD. The average composition of TS of *82*.43 % in the CD is within the range of 89 %, 81 %, and 78 %. reported by Okewale et al. (2018); Saha et al. (2024) and Owamah and Izinyon (2015). However, it was disparate from the values of 14.17 % and 18.38 % reported by Iweka and Owuama (2020); Baitha and Kaushal (2019). The variation in the TS can be as a result of whether the dung is fresh or its level of dryness. The VS in the CD was at 64.86 % which is similar to the values of 60.92 % reported by Ukpai and Nnabuchi (2012). Okewale *et al*. (2018); Makhura *et al*. (2020); Saha *et al.* (2024) reported values of VS in CD in the range 78 - 92 %. The range of the degradability of the inoculum (CD) was at 65 % based on the VS. The CH_4 potential from biogas is typically expressed specifically per mass of volatile solids (VS) added. The is because VS is the degraded portion of organic matter that is converted to biogas but not all of it is converted to biogas (Angeldaki *et al.*, 2018).

The N and C contents of CD were 3.18 and 37.62 which is the equivalent of 11.83 C:N ratio. The N and C values are similar to values reported by Ukpai and Nnabuchi (2012); Degunloye and Abe (2020); Okewale *et al*. (2018). This low C:N is known to have adverse effects on biogas yield. According Surra *et al*. (2019), C and N are the two macro-nutrients necessary for cell growth and therefore the C: N ratio in the substrate is an important parameter for AD process. A high C:N ratio means the lack of nitrogen, which can be due eventually to the lack of proteins and/or of their failure to solubilize. Thus, low C:N reflects low concentrations of total available nitrogen (TAN) and can be related to volatile acid acids (VFAs) accumulation, which results in acidification of the medium and failure of the process (Surra *et al*., 2019). This necessitates the need for co-digestion with crop residues with high C:N ratios.

The mean ultimate composition for AH was 92.61, 85.22, 1.68 and 29.58 for *TS* (%), VS (%), N (%), C (%) and C:N respectively. The report of the ultimate analysis for AH is sparse, especially for biogas production. Elinge *et al.* (2021) reported TS of 83.5 % which is similar to the result of this study. However, their value of 33% VS for acha hulls from Kebbi State, Nigeria reported by Egga et al. (20216) was lower than in this study. The C:N ratio for AH was 29.58 and within the ideal range of 20-30 for biogas production (Surra *et al*., 2018).

The cumulative biogas volume (mL±SD) produced in Biodigesters A, B, C and the control were 581.95 (±213.18), 663.42 (±262.19), 475.60 (±177.32), and 489.77 (±183.20) respectively. The high standard deviations (SD) are a manifestation of the of high fluctuations in biogas volumes during different stages of the AD process. Digester B recorded the highest cumulative biogas volumes and Digester C had the least volume. Figure 1 is the plot of the cumulative biogas volume and it reveals the cumulative volume in the highest order of Biodigester B > A > Control > D.

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Table 2: Result of Cumulative Biogas Yield

	Digester			
Statistics	**A**	**B**	**C**	**Control**
Cumulative Biogas Volume	581.95	663.42	475.60	489.77
Mean	180.07	228.11	147.26	151.78
Standard Error	35.05	43.10	29.15	30.12
Standard Deviation	213.18	262.19	177.32	183.20
Kurtosis	-0.99	-1.38	-1.17	-1.14
Skewness	0.76	0.57	0.72	0.73

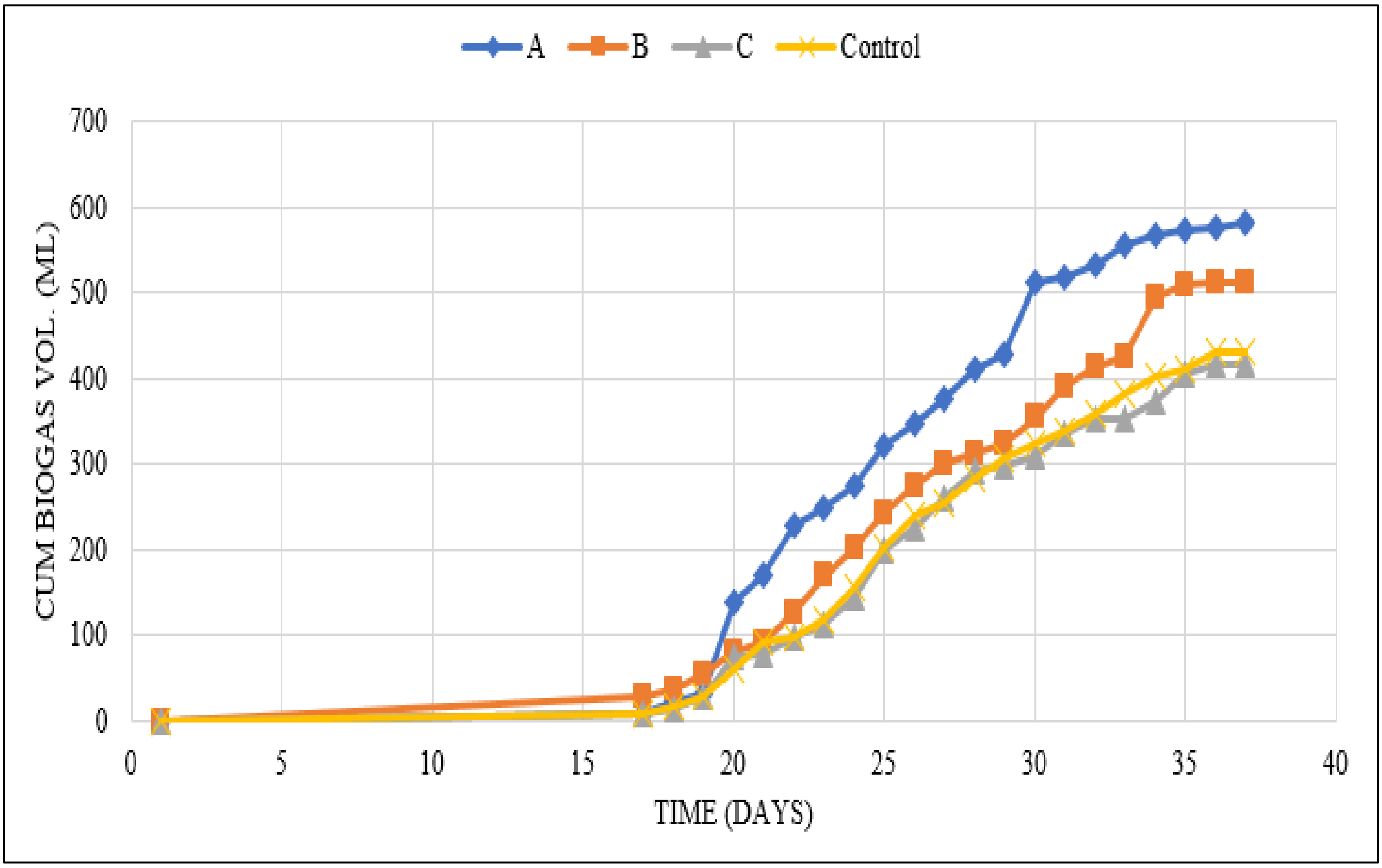

Fig 1: Cumulative Biogas Yield of Digesters A, B, C and Control

The cumulative CH_4 volume (mL) produced Biodigesters A, B, C and the control wee 390.02 (±148.30), 468.29 (±187.50), 286.31 (±17.79) and 308.55 (±19.16) respectively (Table 3). The cumulative CH_4 volumes for digesters A, B, C and the control. Consistent with the cumulative biogas volume, the high standard deviations (SD) of the CH_4 volumes of the different digesters are a manifestation of the of high fluctuations in volumes during different stages of the AD process. Digester B also yielded the highest average and maximum CH_4 volumes and Digester C had the least average and maximum CH_4 volumes. The plot of the cumulative CH_4 volume over time in days is depicted in Figure 2.

Table 3: Result of Cumulative Methane Volume (mL)

	Digester			
Statistics	**A**	**B**	**C**	**Control**
Cumulative Methane Volume	390.02	468.29	286.31	308.55
Mean	126.87	165.76	90.21	96.87
Standard Error	24.38	30.83	17.79	19.16
Standard Deviation	148.30	187.50	108.20	116.55
Kurtosis	-1.21	-1.51	-1.22	-1.18
Skewness	0.68	0.50	0.70	0.71

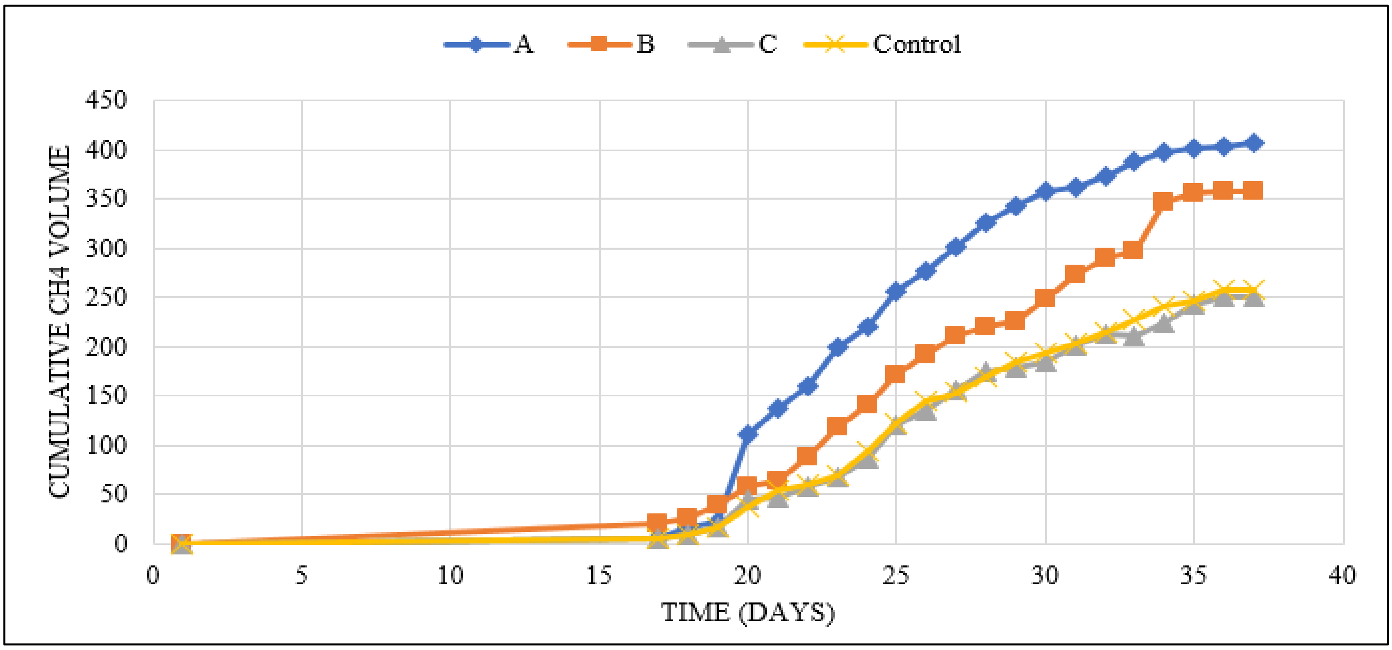

Fig 2: Cumulative CH_4 of Digesters A, B, C and Control

The Analysis of Variance (ANOVA) (Table 4) was used for the assessment of the regression coefficient and the prediction of the linear equation model (Table 5). The **model Fisher's statistic (F-value)** of 57.06 is significant ($p < 0.01$) and implies the model is a good fit for prediction CBY. The **F-value** of **the first independent factor TVS is** 62.49 ($p < 0.01$), indicating that the term is a significant predictor of CBY. The HRT ($F = 89.01$, $p < 0.01$) is also a significant predictor of CBY. The lack of fit ($F = 0.57$, $p > 0.05$) indicates that the model is a good fit and the coefficient of determination as represented by the Predicted R^2 show that the model accounts for 88 % of the variation in CBY.

Equations 2 and 3 are the actual and coded equations for CBY. The actual equation can be used for recreating the result of this experiment while coded equation enables the identification of the impact of individual factors using their coefficients.

$$CBY_A = -46.64 - 76.69A + 7.10B + 22.37C \quad (2)$$

$$CBY_C = 282.45 - 153.39A + 26.63B + 178.94C \quad (3)$$

Where; A- TVS, B- ambient temperature, C -HRT.

Figure 3 show that the residuals plot of the actual and predicted residuals of CBY are in close agreement and linear due to their clustering around the centre line and the model is a good fit. The contour plot is in Figure 4, it shows that 663, 500, 400 and 300 mL of biogas can be produced at OLRs of 4, 5.2, 6.4 and 7.8 g VS/L respectively. The 3D surface plot is in Figure 5 is in agreement with the contour plot as the red portion show OLR at which maximum gas can be produced and green portion is the area of lower yield. The optimization points prediction (Table 6) shows that 663 mL of biogas can be obtained if the bioreactor is operated at 4 g VS/L at ambient temperature of 33 °C for 34 days.

Table 4: ANOVA Summary of Cumulative Biogas Yield

Source		Sum of Squares	df	Mean Square	F-value	p-value
Model		5.926E+05	3	1.975E+05	57.06	< 0.0001
A-TVS		2.163E+05	1	2.163E+05	62.49	< 0.0001
B-Ambient Temp		8750.96	1	8750.96	2.53	0.1359
C-HRT		3.081E+05	1	3.081E+05	89.01	< 0.0001
Residual		45002.18	13	3461.71		
Lack of Fit		21368.85	8	2671.11	0.5651	0.7747
Pure Error		23633.33	5	4726.67		
Cor Total		6.376E+05	16			
Std. Dev.	58.84					
Mean	249.53					
C.V. %	23.58					
R^2	0.93					
Adjusted R^2	0.91					
Predicted R^2	0.88					
Adeq Precision	25.16					

Table 5: Summary of Fit Statistics

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.7747	0.9131	0.8832	Suggested
2FI	0.2319	0.9150	0.9250	0.8599	
Quadratic	0.7802	0.8014	0.9074		
Cubic	0.8014		0.8814		Aliased

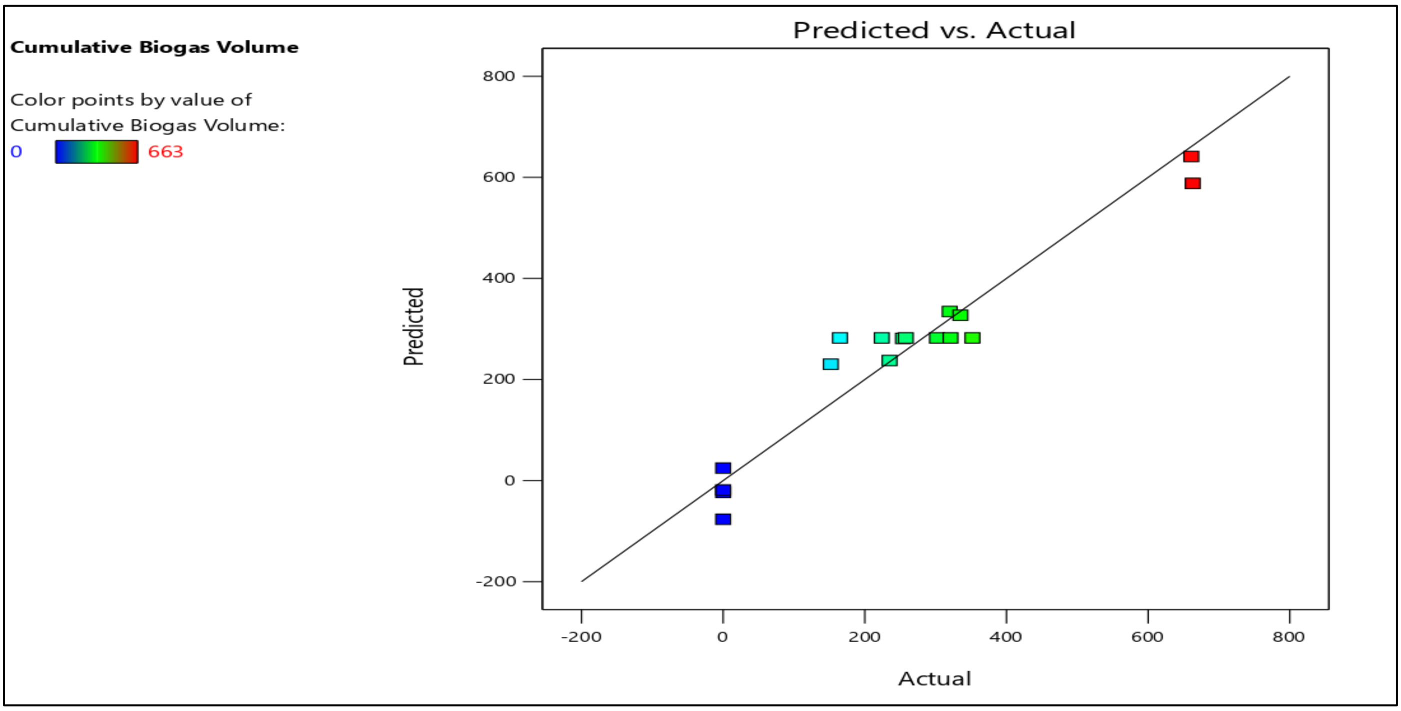

Fig 3: Actual VS Predicted Values of Cumulative Biogas Yield

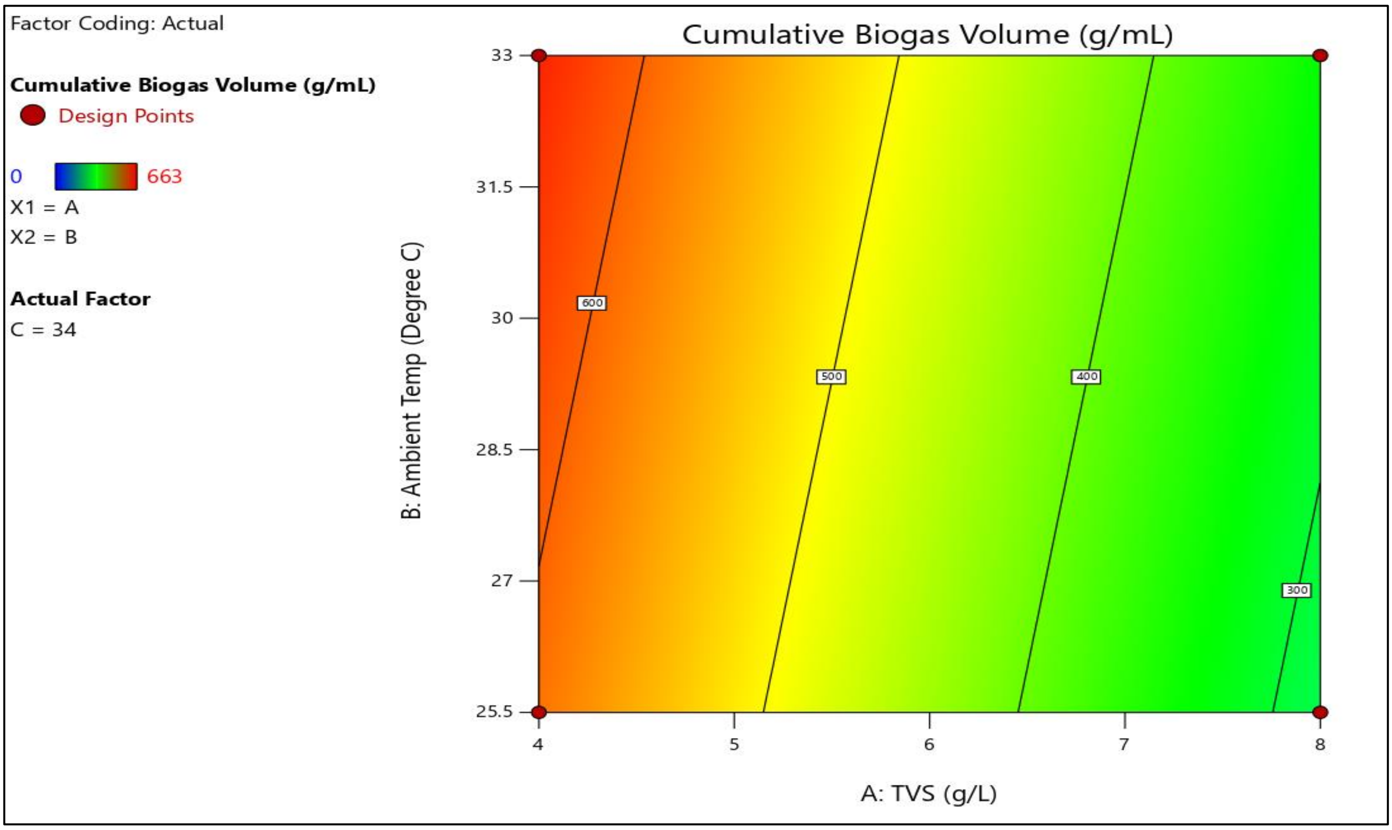

Fig 4: Optimization Contour Plot of Cumulative Biogas Yield

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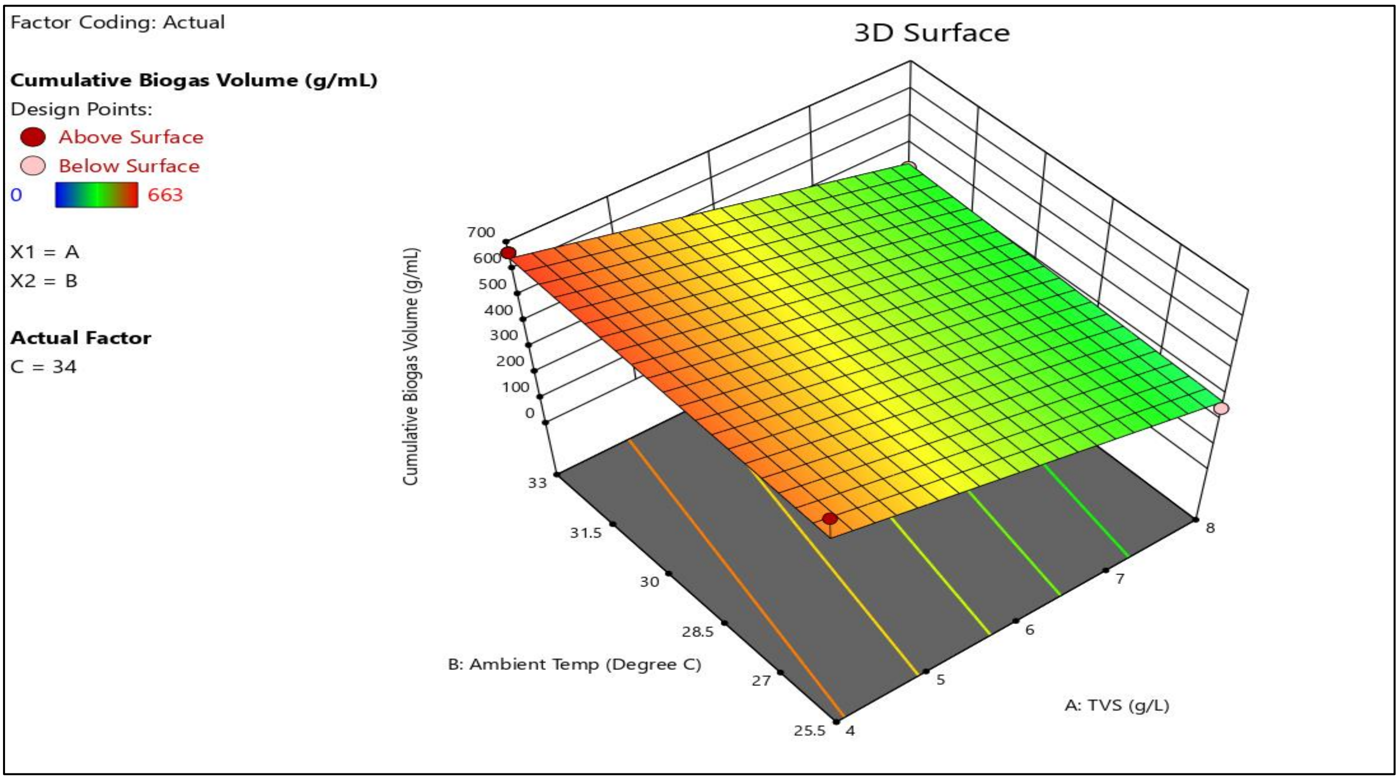

Fig 5: 3D Optimization Plot of Cumulative Biogas Yield

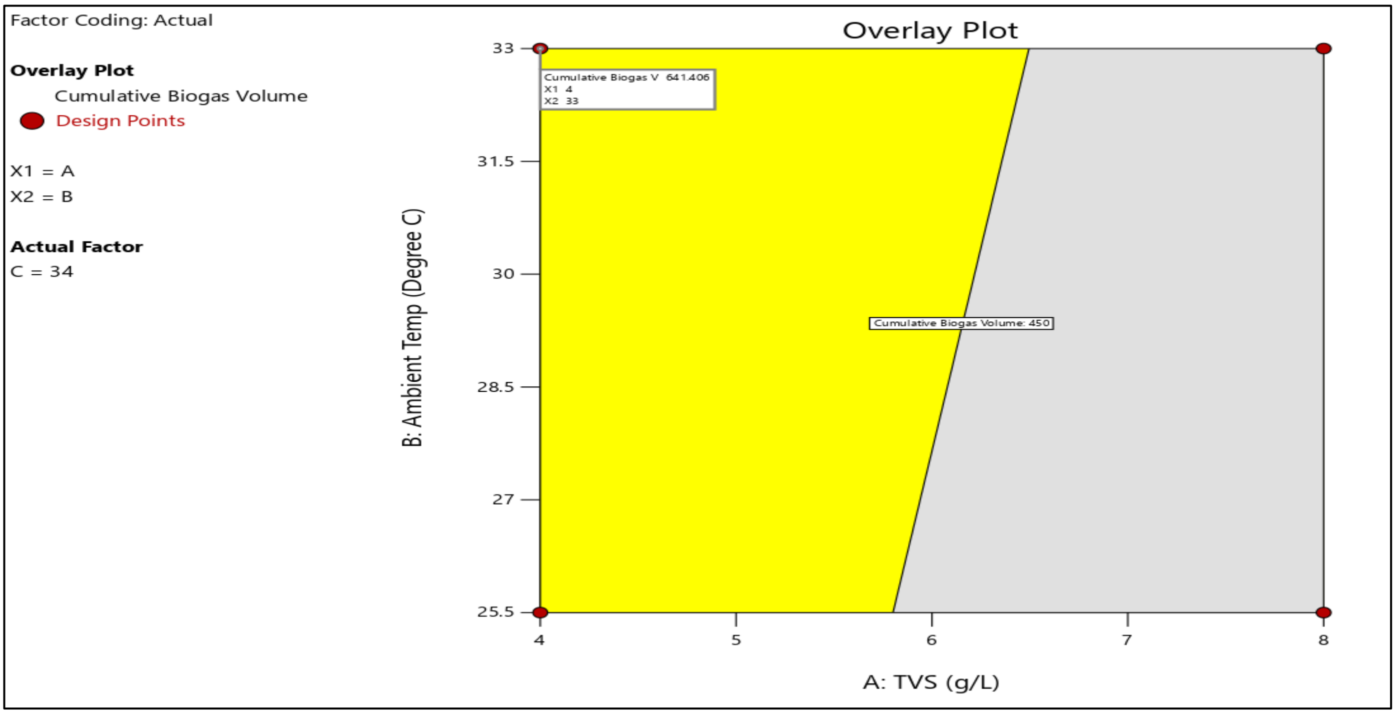

Fig 6: Optimization Overlay Plot of Cumulative Biogas Yield

Table 6: Optimize Point Prediction for Optimal Biogas Yield

Solution 1 of 70 Response	Predicted Mean	Predicted Median	Observed	Std Dev	n	SE Pred	95% PI low	Data Mean	95% PI high
Cumulative Biogas Volume	641.406	641.406		58.8363	1	69.3244	491.639	663	791.172
Conformation Location									
OLR (g VS/L)	4								
Ambient Temperature (°C)	33								
OLR (days)	34								

IV. CONCLUSION

The objectives of this study were to; determine some ultimate properties of CH and AH necessary for biogas production, produce biogas from the co-digestion of CD and AH at ambient conditions and optimize the process parameters of co-digesting CD and AH. Based on the finding of the study it can be concluded codigestion of CD and AH yields more biogas volume due to the synergy the N content of AH create in stabilizing the CD. The best result can be obtained by operating at the biodigester at OLR of 4 g VS/L at 33 °C for optimal yield.

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