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Anaerobic Co-Digestion of Cattle Slurry with Maize Stalk at Mesophilic Temperature

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Abstract: - Anaerobic digestion from batch digester containing varying ratio of mixture of cow slurry and maize stalk was studied at mesophilic temperature (37°C). Cattle slurry and maize stalks were co-digested at ratios 3:1, 1:1 and 1:3 using the percentage volatile solid of each substrate. The experiment was carried out in a laboratory scale batch digester. The digester was fed with cattle slurry-maize stalks mixtures calculated for the selected ratios based on the volatile solid (VS) concentration of the selected substrates. Co-digestion of cattle slurry with maize stalks at ratios 3:1, 1:1 and 3:1 at mesophilic temperature gave biogas yields of 0.426, 0.385 and 0.391m^3/kgoDM respectively while the methane yields were 0.297, 0.270 and 0.262m^3CH_4/kgoDM respectively. From the fresh mass of the substrate, biogas yields of 0.052, 0.059 and 0.090 m^3/kgFM were obtained for cattle slurry-maize stalks ratios of 3:1, 1:1 and 1:3 respectively while the methane yields from the fresh mass for the same ratios were 0.036, 0.043 and 0.060 CH_4/kgFM respectively. Co-digestion of cattle slurry with maize stalks was found to have methane concentrations of 69.66, 70.24 and 66.98% at cattle slurry/maize stalks combinations of 3:1, 1:1 and 1:3 respectively. The highest biogas yields (oDM) of 0.426 m^3/kgoDM was obtained at the mixing ratio of 3:1; therefore the mixing ratio of 3:1 is recommended as the optimal for the co-digestion of cattle slurry with maize stalks at mesophilic temperature.

Keywords: - *Co-digestion, cattle slurry, maize stalks, batch experiment, mesophilic temperature*

I. INTRODUCTION

The conventional energy sources in the world such as liquefied petroleum gas (LPG), benzene fuel, diesel fuel, and fire wood are rapidly reducing due to industrial and urban development. Renewables such as solar, wind, hydropower, and biogas are potential candidates to meet global energy requirements in a sustainable way [1, 2]. Also, there is a global energy crisis as a consequence of declining quantity of fossil fuels coupled with the unprecedented rising crude oil prices. The crisis demands greater attention to alternative energy sources and revision of existing technologies.

Biogas, the gas produced when organic matter of animal or plant ferments in an oxygen-free environment (anaerobic condition) occurs naturally in swamps and spontaneously in landfills containing organic waste. Anaerobic digestion (AD) offers a very attractive route to utilize certain categories of biomass for meeting partial energy needs. Also, proper functioning of AD systems can provide multiple benefits to the users and the community resulting in resource conservation and environmental protection [3]. It can also be induced artificially in digestion tanks to treat sludge, industrial organic waste, and farm waste [4]. The product of AD primarily are methane (CH_4) and carbon dioxide (CO_2), with varying amounts of water, hydrogen sulphide (H_2S), oxygen and other compounds [5, 6].

Millions of cubic metres of methane in the form of swamp gas or biogas are produced every year by the decomposition of organic matter, in form of both animals and vegetables. It is almost identical to the natural gas pumped out of the ground by the oil companies and used by many people for heating houses and cooking meals. In the past, however, biogas has been treated as a dangerous by-product that must be removed as quickly as possible, instead of being harnessed for any useful purposes. It is only in very recent times that a few people have started to view biogas, in an entirely different light, as a new source of energy for the future. High biogas yield can be achieved through co-digestion of manure with energy crops and / or their residues.

According to Agunwamba [7], co-digestion is the simultaneous digestion of more than one type of waste in the same unit. Co–digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. The most common situation is when a major amount of a main basic substrate (e.g. manure or sewage sludge) is mixed and digested together with minor amounts of a single, or a variety of additional substrates. Better digestibility, enhanced biogas production/methane yield arising from availability of additional nutrients, improved buffer capacity with stable performance as well as a more efficient utilization of equipment and cost sharing have been highlighted as part of the advantages of co-digestion [7, 8, 9,10, 11,12,13] Researchers have shown that co-digestion of banana and plantain peels, spent grains and rice husk, pig waste and cassava peels, sewage and brewery sludge, among many others, have resulted in improved methane yield by as much as 60% compared to that obtained from single substrates [14,15,16,17]. A wide variety of substrates, animal and plant wastes, as well as industrial wastes such as carbonated soft drink sludge and brewery wastes have been used for biogas production [18, 19, 20, 21, 22, 23, 24].

Also, the addition of readily biodegradable organic matter into animal manure digester could significantly increase biogas production due to the changes of feedstock characteristics. Co-digestion of cassava peels with poultry, piggery and cattle waste has been found to result into increase in biogas production [25]. Several researchers have studied biogas generation from animal and agricultural wastes [26, 27, 28]. According to Callaghan *et al*. [29], co-digestion of cattle slurry with fruit and vegetable waste yielded more cumulative biogas production than the digestion of cattle slurry alone. This work studied the effect of co-digestion on anaerobic digestion of cattle slurry with maize stalks at mesophilic temperature (37°C).

II. MATERIALS AND METHODS

2.1 Sources of organic materials

Maize plants were harvested from the Institute for Animal Breeding and Animal Husbandry (ABAH), Ruhlsdorf / Grosskreutz, Germany and the stalks were separated for experimentation. Cattle slurry was also obtained from the same institute (ABAH).

2.2 Methodology

All samples were kept in the laboratory at a temperature of +3°C after size reduction prior to feeding into the digester. The amount of substrate and seeding sludge weighed into the fermentation bottles were determined in accordance to German Standard Procedure VDI 4630 [30] using the equation 1:

$$\frac{oTS_{substrate}}{oTS_{seeding\,sludge}} \leq 0.5 \qquad (1)$$

Where:

$oTS_{substrate}$ = organic total solid of the substrate and;

$oTS_{seeding\ sludge}$ = organic total solid of the seeding sludge (the inoculum)

Biogas production and gas quality from maize stalks (MS) and cattle slurry (CS) were analyzed in batch anaerobic digestion test at 37°C according to German Standard Procedure VDI 4630 (2004). Batch experiments were carried out in lab-scale vessels with two replicates as described by Linke and Schelle [31]. A constant temperature of 37°C was maintained through a thermostatic cabinet heater (Plate 1). Characteristic chemical and thermal properties of the substrates used are summarized in Table 1. Vessels (0.9 litre capacity) were filled with 800g of the stabilized inoculum. Two bottles were used for each of the combinations and the average yields found at the end of the experiment.

Plate 1: Experimental set up for batch digestion

Table 1: Chemical and thermal properties of substrates

Parameter	Analysis	
	Cattle Slurry	Maize Stalks
Dry Matter, DM (105°C)-%	11.77	45.54
Organic Dry Matter (oDM, %DM)	84.05	90.75
Organic Dry Matter (%FM)	9.89	41.33
NH_4-N (g/kgFM)	1.22	<2
Crude Fibre (%DM)	26.75	39.07
Fat (% DM)	-	1.61
Potassium (% DM)	2.05	1.22
Ethanol (g/l)	0.12	<0.04
Propanol	<0.04	<0.04
Total Acetic Acid	0.88	0.17
Ph	6.56	6.40
Conductivity (mS/cm)	9.98	0.744

At the beginning of the experiment, anaerobically digested material from a preceding batch experiment was used as inoculums for this study. The substrates fed into the digestion bottles were calculated using equation (2) and found to be 80.46g CS / 0MS (100% Cattle slurry with no maize stalk), followed by 41.53g CS / 3.31g MS (75%CS and 25%MS), 25.08gCS/ 6.00g MS (50%CS and 50%MS), 13.85gCS/9.94gMS and (25%CS and 75%MS). The calculated amount of the substrates (using equation 1) was added to 800g inoculum to ensure compliance of the $oDM_{feedstock}$ to $ODM_{inoculum}$ ratio being less or equal 0.5 as it is recommended in VDI 4630 (equations 1 and 2). Two digestion vessels were also filled with 800g of inoculums only as control.

The biogas produced was collected in scaled wet gas meters for 35 days. This duration of the test fulfilled the criterion for terminating batch anaerobic digestion experiments given in VDI 4630 (daily biogas rate is equivalent to only 1% of the total volume of biogas produced up to that time). The volume of the gas produced was measured daily. Besides, other gas components, methane (CH_4) and carbon dioxide (CO_2) contents were determined at least eight times during the batch fermentation test using a gas analyser GA 2000. The tests were conducted in two replicates. Plate 1 shows the set up of the batch experiment conducted at mesophilic temperature (37°C).

Quantitative evaluation of the results gained in batch anaerobic digestion tests included the following steps: standardizing the volume of biogas to normal litres (1_N); (dry gas, t_0=273 K,p_0=1013hPa) and correcting the methane and carbon dioxide contents to 100% (headspace correction, VDI 4630). Readings were analysed using Microsoft Excel spread sheet together with "Table curve" computer software. Accumulated biogas yields over the retention time were fitted by regression analysis using Hill-Kinetic equation in order to determine the maximum biogas and methane potentials of the selected substrates.

The amount of substrate fed into the digester was calculated using equation (1).

$$\frac{oTS_{substrate}}{oTS_{seeding\,sludge}} \leq 0.5 \qquad 1$$

Where:

$oTS_{substrate}$ = organic total solid of the substrate and;

$oTS_{seeding\ sludge}$ = organic total solid of the seeding sludge (the inoculum)

Equation (1) can be modified to read

$$p_i = \frac{m_i . c_i}{m_s c_s} \qquad (2)$$

Where

p_i= mass ratio=2 ; m_i= amount of inoculum, g

c_i=Concentration of inoculum, oDM in % Fresh mass

m_s= amount of substrate,g

c_s= Concentration of substrate, oDM in % fresh mass

Readings of the gas production (ml), air pressure (mbar), gas temperature (°C) and time of the day were taken on daily basis throughout the period of the experiment. The gas was analysed at least twice per week for the four weeks of the experiments. The gas factor was calculated as well as the fresh mass biogas and methane yield with the volatile solid biogas and methane yields also determined on daily basis. The amount of gas formed was converted to standard conditions (273.15 K and 1013.25 mbar) and dry gas. The factor was calculated according to equation 3.

$$F = \frac{(p - P_{H_2O}).T_o}{(t + 273.15).p_o} \quad (3)$$

Where
T_o= 273.15 °C (Normal temperature)
t= Gas temperature in °C
P_o= 1013.25 mbar (standard pressure)
P= Air Pressure

The vapour pressure of water P_{H_2O} is dependent on the gas temperature and amounts to 23.4 mbar for 20°C. The respective vapour pressure of water as a function of temperature for describing the range between 15 and 30°C is given as in equation 4

$$P_{H_2O} = y_o + a.e^{b.t} \quad (4)$$

Where:
y_o = -4.39605; a = 9.762 and b= 0.0521
The normalized amount of biogas volumes is given as

$$Biogas[N\,ml] = Biogas[ml] \times F \quad (5)$$

Normalized by the amount of biogas, the amount of gas taken off of the control batch is given as

$$Biogas[N\,ml] = (Biogas[Nml] - Control[Nml]) \quad (6)$$

The mass of biogas yield in standard liters / kg FM fresh mass (FM) is based on the weight
The following applies:
1 standard ml / g FM=1 standard liters / kg FM = 1 m^3 / t FM

$$Mass\ of\ biogas\ yield = \sum \frac{Biogas[N\,ml]}{Mass[g]} \quad (7)$$

The oDM biogas yield is based on the percentage of volatile solids (VS) in substrate

$$oDM\ biogas\ yield = \sum \frac{Biogas[N\,ml).100]}{Mass[g].VS[\%FM]} \quad (8)$$

$$CH_{4corr.} = \frac{CH_4[vol\%].100}{(Mass[g] + CO_2[vol\%])} \quad (9)$$

$$Fresh\ Mass\ Methane\ yield = \frac{Fresh\ mass\ biogas\ yield \times CH_{4corr.}}{100} \quad (10)$$

$$oDM\ Methane\ yield = \frac{oDM\ biogas\ yield \times CH_{4corr.}}{100} \quad (11)$$

2.3 Substrates and Analytical Procedures

Sample of maize stalks (MS) was investigated for Fresh matter (FM), organic Dry Matter (105°C), Organic Dry Matter in % fresh mass, Volatile fatty acids (VFA), pH, NH_4-N, Conductivity (EC), Organic dry matter in % of fresh mass (oTS). All analyses were performed according to German standard methods [31].

2.4 Model Formulation

Models were formulated for the prediction of the biogas and methane yields at selected ratios of the substrates co-digested using the design expert computer software.

III. RESULTS AND DISCUSSION

Table 1 shows the results of the chemical and thermal properties of the selected substrates before digestion. The cumulative biogas and methane productions obtained from batch digesters are shown in Figures 1-4.

3.1 Substrates

The dry matter (DM), organic dry matter (oDM), NH_4-N, Crude Fibre, N, P, K, pH, and the conductivity of the selected substrates determined are as shown in Table 1 [32,33].

3.2 Co-Digestions of Cattle Slurry with Maize Stalks

Figures 1-4 show the fresh mass biogas yields, fresh mass methane yields, organic dry matter biogas yields and organic dry matter methane yields from the co-digestion of Cattle Slurry (CS) with Maize Stalks (MS) respectively. In the co-digestion of cattle slurry with maize stalk under mesophilic condition (37^{o}C), the fresh mass biogas yields at ratios 3:1, 1:1 and 1:3 were found to be 0.052, 0.059 and 0.090 m^3/kg_{FM} respectively while the fresh mass methane yields for the same combinations were found to be 0.036, 0.043 and 0.060 m^3CH_4/kg_{FM} respectively (Figures 1 and 2). In the same vein, the biogas yields (oDM) of cattle slurry co-digested with maize stalk at the same ratios were found to be 0.426, 0.385 and 0.391 m^3/kg_{oDM} while the methane yields (oDM) were respectively found to be 0.297, 0.270 and 0.212 $m^3/CH4/kg_{oDM}$ when experimented at mesophilic temperatures (Figs. 3 and 4).

Higher biogas and methane yields were obtained at ratio 3:1 (75% VS of cattle slurry co-digested with 25% VS of maize stalk). The reason for this is that higher mixing ratios meant higher quantity of maize stalks in the mixture which also implied increased lignin content and this made digestion activities to be more difficult for the anaerobic bacteria. Thus, co-digestion of cattle slurry with maize stalks showed increase in the yields both from fresh mass and the organic dry matter contents of the selected substrates. This agrees with the results of previous researches that co-digestion aids biogas and methane yields [25, 29, 13, 11].

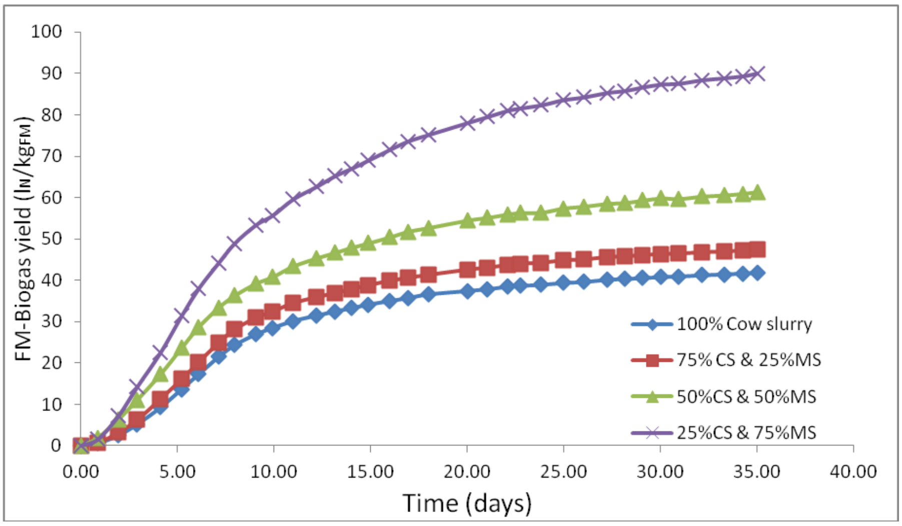

Figure 1: Fresh-Mass biogas Yields of Co-digestion of Cattle slurry with Maize-Stalks

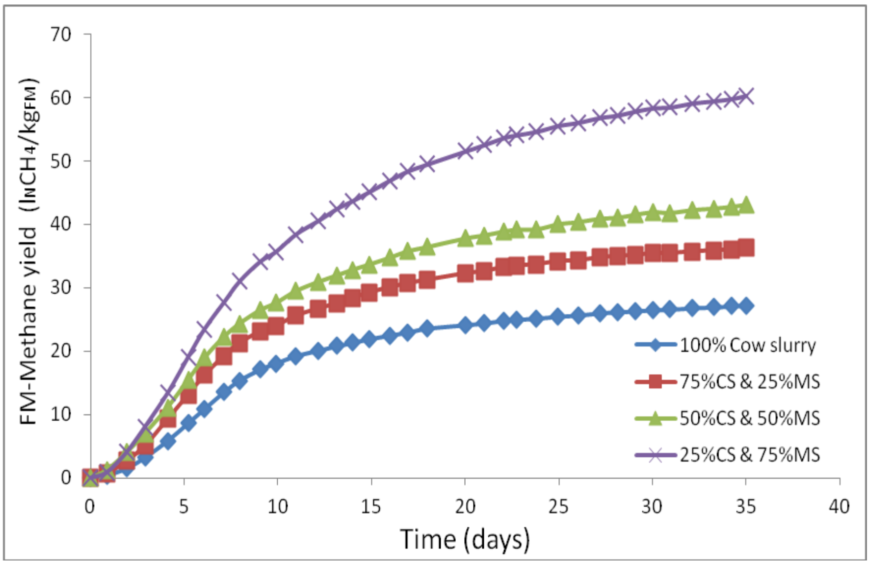

Figure 2: Fresh-mass methane yields of cattle slurry co-digested with maize-stalks

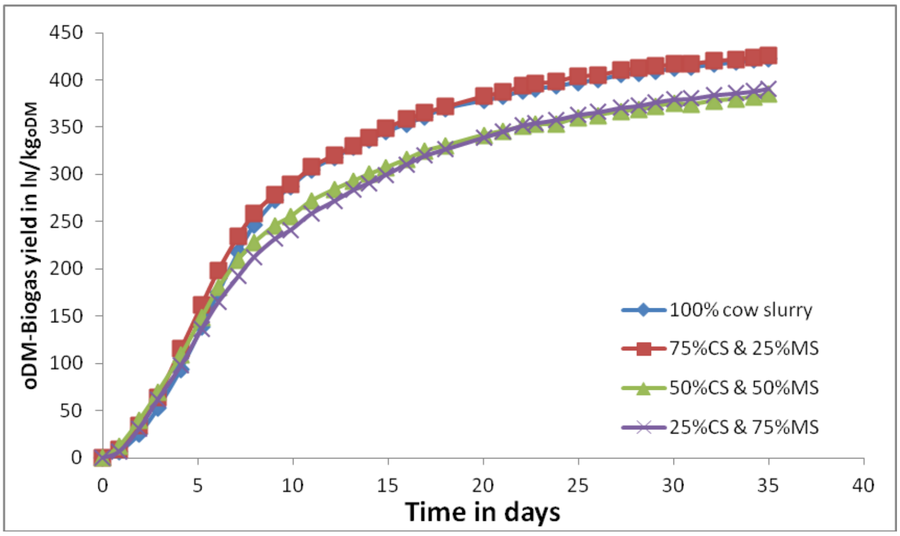

Figure 3: oDM biogas yields of cattle slurry co-digested with maize-stalks

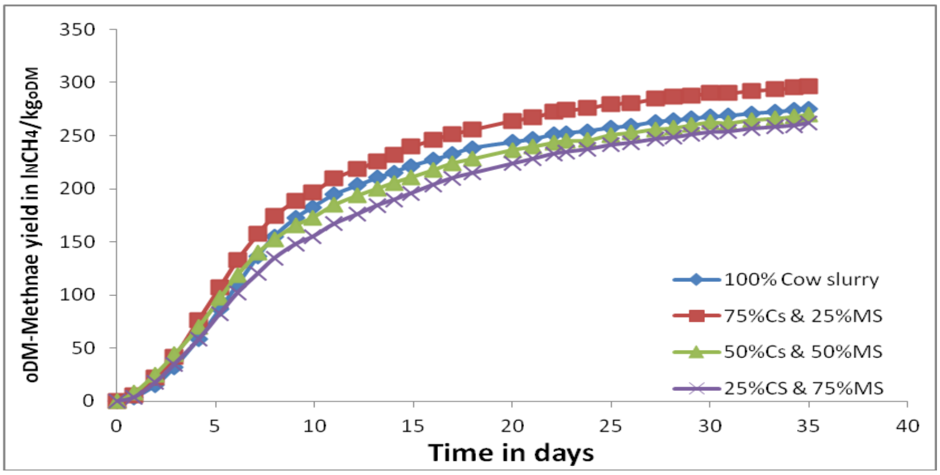

Figure 4: oDM methane yields of cattle slurry co-digested with maize-stalks

Also, since the biogas yield of maize stalk (0.357 m^3/kg_{oDM}) was lower than the results obtained from all the co-digestions at the selected ratios [34], it means that co-digestion has lowered the C/N ratio of maize stalk and thus enhancing biogas production. For biogas production from the co-digestion of cattle dung and maize stalk, mixing in ratio 3:1 will be adequate for enhanced biogas production. Also, the analysis of the results of the co-digestion of cow slurry with maize stalks revealed that there was a significant difference between the yields at 95% level of significance while the substrate ratios indicated no significant difference (Table 2).

Figures 5 and 6 show the relationships and interactions between the biogas and methane yields of the selected substrates when co-digested at different ratios. From the response surface methodology (RSM), it can be deduced that increase in %VS of CS and MS resulted in a corresponding increase in biogas yield.

Table 2: Anova: Two-Factor Without Replication at 95% Confidence Limit for Co- Digestion 2

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	4	878.84	219.71	42800.43
Row 2	4	856.2	214.05	34118.6
Row 3	4	930.12	232.53	29445.62
Column 1	3	218.93	72.97667	646.7294
Column 2	3	1299.6	433.2	339.1804
Column 3	3	165.55	55.18333	373.5977
Column 4	3	981.08	327.0267	38.41003

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Substrate ratios	717.1979	2	358.5989	1.035098	0.410962	5.143249
Yields	317015.3	3	105671.8	305.0222	6.03E-07	4.757055
Error	2078.637	6	346.4396			
Total	319811.1	11				

Response: Methane
ANOVA for Response Surface 2FI Model
Analysis of variance table [Partial sum of squares]

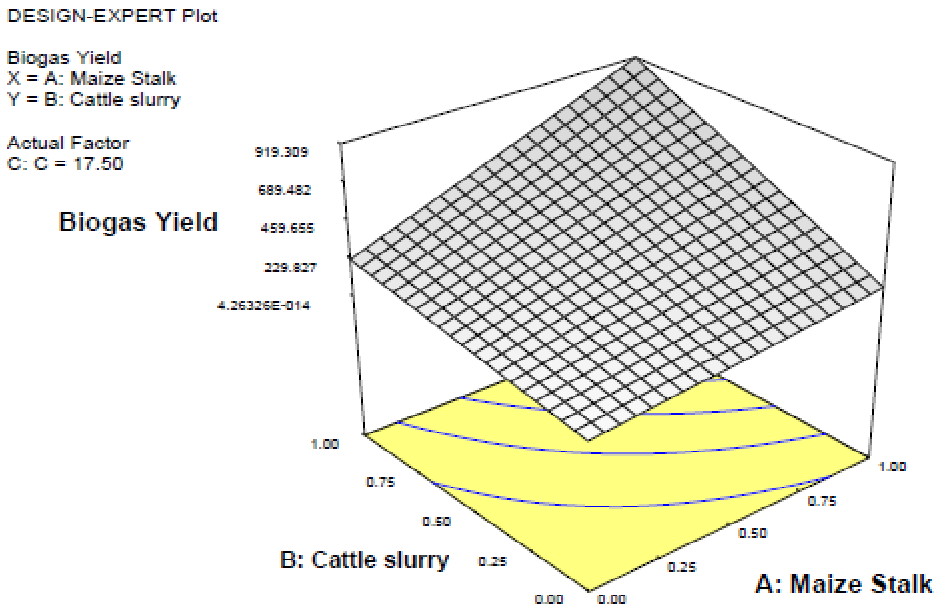

Figure 5: Interactions between cattle slurry and maize stalks (biogas yields)

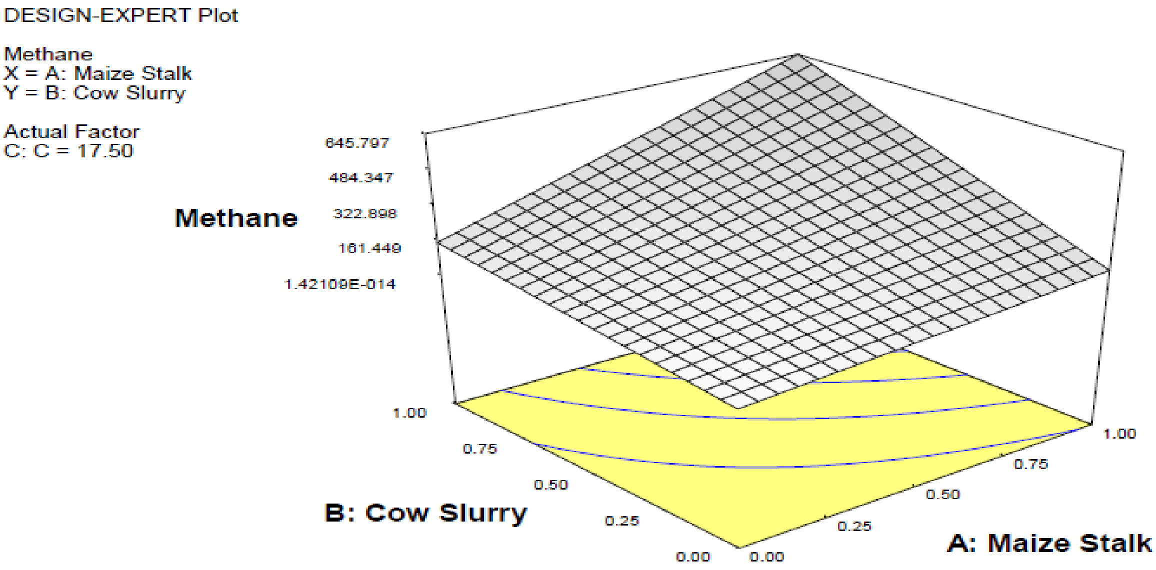

Figure 6: Interactions between cow slurry and maize stalks (methane yields)

The model developed from the RSM for the prediction of biogas and methane yields of cow slurry and maize stalks when co-digested are different ratios are as shown in equations 12 and 13.

Final Equation in Terms of Coded Factors:

$$Biogas\,Yield = +332.33 + 218.00*A + 241.66*B + 191.72*C + 127.33*A*B + 85.29*A*C + 106.42*B*C \quad (12)$$

$$Methane\ Yield = +228.03 + 150.97*A + 171.93*B + 125.82*C + 94.87*A*B + 53.61*A*C + 72.21*B*C \quad (13)$$

Where A=Maize stalks
B= Cow Slurry
C= Time (days)

IV. CONCLUSION

The study has shown that co-digesting cattle slurry with maize stalks at different ratios result into an increase in both biogas and methane yields.

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