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Effects of Concentration and Catalyst on the Kinetics of Biogas Production from Cattle Dung at Thermophilic Temperature

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Abstract
Five different reactors (Ra, Rb, Rc, Rd and Re) of equal capacity (500cm^3 each) were constructed and connected to a gas-collecting device. For the investigation of the effect of concentration on biogas production (uncatalysed reaction), different concentrations of reactant (20g/250cm^3, 30g/250cm^3, 40g/250cm^3, 50g/250cm^3 and 60g/250cm^3) prepared from cattle dung were respectively placed in Ra, Rb, Rc, Rd, and Re, and anaerobically fermented at thermophilic temperature (37^{0}C) for 16days. For the investigation of the combined effect of concentration and catalyst (catalysed reaction), parallel set ups were made, but in this case, 1.0g, 1.5g, 2.0g, 2.5g, and 3.0g of yeast were respectively added to the reactants (slurries) in Ra, Rb, Rc, Rd, and Re, which were also anaerobically fermented at 37^{0}C for 16days. The reactors and their contents for both the catalyzed and uncatalyzed reactions were made in triplicate and the mean (average) volume of biogas collected in each of the reactors were evaluated. The average volumes of biogas obtained were used for the kinetics studies, where the rate of biogas production, the rate constant for biogas formation from the substrate (cattle dung), the rate of catalyst substrate unstable complex formation, the fraction of total catalyst that involved in the formation of complex with substrate, the concentration of excess (free) catalyst in the slurry, the rate of substrate transformation into biogas and the saturation constant of the catalyst added to each slurry was evaluated using the appropriate equations. The research revealed that, addition of catalyst to the slurries, enhanced biogas production; at a certain point, the volume of biogas produced, the rate of biogas formation, the rate of catalyst substrate unstable complex formation and the rate of substrate transformation into biogas were directly proportional to the concentrations of the reactants and catalyst; the rate constants for reactions (catalyzed and uncatalyzed) were inversely proportional to the concentrations of reactants and the catalyst added; the fractions of the total catalyst that involved in the formation of unstable complex with substrate in Ra, Rb, Rc, Rd, and Re were 0.95g, 0.97g, 0.98g, 0.98g, and 0.98g, respectively; the concentrations of the excess catalyst in Ra, Rb, Rc, Rd, and (g/cm^3) were 0.05, 0.53, 1.02, 1.52 and 2.02, respectively and; the saturation constants (g/g) of the catalyst added to the slurries in Ra, Rb, Rc, Rd, and Re were 0.0476, 0.0484, 0.0488, 0.0490, and 0.0492, respectively. The research also revealed that the reactions (catalyzed and uncatalyzed) carried out obeyed first order rate law equation.
Key-words: Biogas; cattle dung; anaerobic fermentation; concentration; catalyst; thermophilic temperature.

1. Introduction

About 15% of the world's annual fuel supplies are from biomass, which are mainly wood fuel. The balance of 85% is being supplied by energy resources such as oil, coal, natural gas and nuclear energy as pointed out by Abubakar **&** Zuru (1996). Estimates have placed the total consumption of wood in Nigeria at about 50 – 55 million cubic meters, of which about 90% is for firewood. The annual deficit of fuel wood in northern Nigeria has been pegged at about 5-8 million cubic meters as reported by Umeh (1986). The annual deforestation of the woodlands in the northern Nigeria is to the tune of 92,000 hectares and the extraction rate of fuelwood in Nigeria has been estimated at about 3.85 times the rate of growth and almost 10 times the rate of regeneration (afforestation) as prepared by **&** Zuru (1996).

The fuel crisis, which emerged from the 1973 middle east conflict together with the environmental concern over depleting nonrenewable energy resources such as oil, as well as, the escalating prices of these non-renewable energy resources, have triggered off a search for alternative sources of energy all over the world as pointed out by Azziz (1989). Nuclear energy surrounded by controversy in any case unavailable to the technologically disadvantaged countries like Nigeria as pointed out by Abubakar **&** Zuru (1996).

Production of biogas from biodegradable substances (mostly wastes) of plant and animal origins through anaerobic fermentation is one of the ways of generating an alternative energy resource, which is cheap, clean and environmentally – friendly as pointed out by Ekwenchi **&** Yaro (2010). Even though, it has been reported by Abubakar **&** Zuru (1996) that, the U.S.A. Energy Research and Development Administration (ERDA) is of the opinion that fuels like biogas would have to account for about 5-10% of the total U.S. energy needs for the technique (biogas technology) to have any potential. Such an attitude may only be justified in nations that are in possession of other alternative sources of energy. However, such projections are unacceptable in situations

exhibited by the developing countries (Nigeria inclusive) where 85% of the energy for rural areas is being supplied by wood fuel as reported by Hall (1982). With dwindling forest reserve, inadequate afforestation and without other accessible energy resources, biogas production in such area is worthy of great attention.

Potentially, all organic waste materials contain adequate quantities of the nutrients are essentially needed for the growth and metabolism of the anaerobic bacteria in biogas production. However, the chemical composition and the availability of the nutrients contained in these materials vary with species and age of the animals or plants as pointed out by Wolfe (1971). Moreover, Kallah **&** Adamu (1988) observed that, the quantity of manure accumulated in a livestock enterprise is a function of factors intrinsic to the animals and factors related to the management system of waste collection and storage. It is therefore expected that, the biogas potential of faeces from different animals will vary both in quantity and quality.

Biogas is a colourless flammable gas generated during anaerobic digestion of biologically degradable organic matter. Biogas is composed of 50 – 70% CH_4, 30 – 40% CO_2 and trace of H_2, N_2 and H_2S as pointed out by Maishanu *et al* (1990). The generation of biogas from organic materials proceeds via the following three (3) major stages as pointed out by Garba *et al* (1996).

Step I: Interaction between several species of cellulolytic and hydrolytic bacteria to decompose complex insoluble organic compounds into simple soluble organic compounds.

Step II: Conversion of the simple soluble organic compounds formed in step I into organic acids (primarily ethanoic acid).

Step III: Production of methane by either fermentation of ethanoic acid or reduction of carbon (iv)oxide and carbonic acid using hydrogen gas.

The raw materials from which biogas can be extracted include: wastes from livestock poultry, human, crops, food processing industrial waste etc. as pointed out by Tambuwal *et a l* (1997). Optimization of biogas yield from a given substrate through anaerobic fermentation process depends on many factors (physio-chemical factors), which include: air tightness, temperature, nature of the substrate, pH of slurry, concentration of slurry, carbon to nitrogen ratio (C/N), mixing/stirring, addition of nutrients and seeding with bacteria as pointed out by Chen **&** Inbar (1991). Another important factor in addition to the aforementioned factors, is the way and manner by which the factors (physio-chemical factors) affect the rate and quantity of biogas yield from a given substrate under stated conditions of digestion (fermentation). This can best be investigated and explained by taking the kinetics of chemical reactions into consideration.

Kinetics studies deals with the study of speed or rates of chemical reactions, the factors on which the rates depend and the mechanism of the reactions as pointed out by Aliyu (2009). It should be noted that biogas production is one of such reactions. For the investigation of the kinetics of biogas production, the results of all the measurements of biogas yield on the laboratory scale have to be comprehensively analyzed and interpreted and, the information obtained will then be used to assess: the efficiency (i.e. the performance) of a biogas plant design in terms of biogas yield; the digestibility of a given substrate and; the influence of operational conditions (factors) on the rate and quantity of biogas to be generated from a given substrate. In order to achieve this, the use of mathematical models and other evaluating instruments are highly imperative. The mathematical models to be used, have to be good enough in predicting how much gas a designer can get at given a time from a given biogas plant design, which uses a particular feedstock under defined conditions. The model should also be a gross of simplification of reality, which can cleary define two (2) or more parameters by which a biogas plant design or substrate feedstock can be assessed in terms of biogas yield as pointed out by Garba (1998).

The mathematical models suggested for evaluating the performance of substrate and efficiency of a biogas plant in terms of biogas yield, as well as, the influence of operational conditions (factors) on biogas yield include the following:

- *First Order Kinetic Model***:** This model seems to be the most effective as reported by Garba (1998). The model is represented by the following equation:

$$W = W_o (1 - e^{-kt})$$

Where W = amount of product (biogas) generated at time, t

W_o = maximum product that could be obtained at infinite time, t_∞

K = rate constant for biogas production (day^{-1})

T = Temperature (K)

- *Monod Model:* This is used to evaluate the concentration of microorganisms in the digester (reactor) as pointed out by Garba (1988). The model is represented by the following equation:

$$\frac{ds}{dt} = \frac{K[S][X]}{Ks + [S]}$$

Where $\frac{ds}{dt}$ = change in substrate concentration with the time of digestion.

K =rate constant for biogas production
[S]= concentration of substrate (g/m^3)
[X]=concentration of Microorganisms (g/m^3)
Ks=saturation constant of the microorganisms in the digester (g/g).

- *Diffusional Model*: This is used to evaluate the amount of substrate that has been transformed into product (biogas) as pointed out by Suidan *etal* (1987), the model is represented by the following equation:

$$ds = KS^{1/2}$$

where ds = change in substrate concentration
K = apparent kinetic constant for the reaction
S = concentration of substrate (g/m^3).

- *Chen and Hashimoto Model*: This model takes into account the variation of microorganisms growth rate with the population density of the microorganisms as a result of mass transfer limitations as pointed out by Garba (1998). The basic equation for the model is given as follows:

$$U = \frac{Um\,(S/S_o)}{K + (1 - K)\,(S/S_o)}$$

Where U = Specific microorganisms growth rate (day^{-1})
Um = maximum specific micro-organisms growth rate (day^{-1})
K = Chen and Hashimoto kinetic constant (non dimensional)
S = substrate concentration in the digester (g/m^3) at time, t_∞
S_o = initial substrate concentration (g/m^3) before the digestion starts.

- *Singh Model:* This model is used to evaluate the rate of substrate transformation into biogas. The model is given by the following equation:

$$\frac{ds}{dt} = -\frac{K\,[S]}{1 + t}$$

Where $\frac{ds}{dt}$ = change in substrate concentration with time of digestion
K = first order kinetic constant (day^{-1})
[S] = concentration of substrate (g/m^3)
t = time (day)

- *Contois Model:* This is used to evaluate the balance of microorganisms in the digester when the death and decay of the microorganisms are neglected as pointed out by Garba (1998). The basic equation for the model is given by

$$\frac{dx}{dt} = U_x$$

where $\frac{dx}{dt}$ = change in the concentration of the microorganisms with time of digestion.
U_x = balance of the microorganisms in the digester

The fact that, the actual mechanism, which takes place during the formation of biogas from a given substrate with many different types of bacteria all contributing to the production of biogas in a digester is very complex and difficult to be defined as pointed out by Garba (1998), this work is therefore, aimed at determining the effects of concentration and catalyst on the rate and rate constant for biogas production from cattle dung at hemophilic temperature (37^oC). The work is also aimed at determining the rte of catalyst – substrate unstable complex formation, the fractions of the total catalyst that involved in the formation of unstable complex with the substrate (cattle dung), the rate of substrate transformation into biogas and the saturation constants of the microorganisms (catalyst) in the digesters using appropriate equations.

2. Materials And Methods

2.1 Collection and Treatment of Experimental Sample

Fresh cattle dung was collected from the heap of dung excreted by 32 heads of cattle in a heard located in Romi Village, Dawakin-Tofa L.G.A., Kano State – Nigeria. The cattle were fed on grass. The dung was first air-dried for two (2) weeks after which it was oven-dried at 105^oC for three (3) hours, pulverized using a wooden pestle and mortar, sieved to a mesh size < 250 x 10^{-6}m using a mesh of well defined porosities for different particles sizes.

2.2 Construction of Reactors

The reactors used for both the catalyzed and uncatalyzed reactions were constructed according to the construction method described by Garba (1998). The reactors were made air-tight and each was connected to an inverted 500cm^3 measuring cylinder via a PVC tube, which is 50cm long and 0.8cm internal diameter.

2.3 Preparation of Slurries

In order to investigate the effect of concentration alone (unanalyzed reaction), the slurries were prepared by separately mixing 20g, 30g, 40g, 50g and 60g of the treated cattle dung (sample) with 250cm^3 distilled water in a reactor (500cm^3 conical flask) each and, thoroughly stirred to ensure homogeneity. The reactors and their contents were made in triplicate and labeled R_a, R_b, R_c, R_d and R_e, respectively.

For the investigation of the combined effect of catalyst and concentration (catalyzed reaction), similar concentrations of slurries (as in the case of the effect of concentration) were prepared using the treated dung, but in this case, 1.00g, 1.50g, 2.00g, 2.50g and 3.00g yeast were respectively added to slurries. The reactors and their contents were also made in triplicate and labeled R_a, R_b, R_c, R_d and R_e, respectively.

2.4 Fermentation process for Biogas Generation and Collection

In order to generate and collect the gaseous degradation product (biogas), the prepared slurries for both of the intended investigations (the catalysed and uncatalysed reactions) were subjected to anaerobic microbial fermentation at 37^{o}C for 16 days. The fermentation and gas collection processes were carried out according to the methods adopted by Sanda *et al* (2001) with few adjustments in the concentration of the slurries and duration of the reaction. The biogas generated was collected over saline solution (5g of table salt in 2dm^3 of distilled water). The average volumes of the biogas from the reactors were evaluated and recorded at fixed daily intervals.

2.5 Kinetics of Biogas Production

The mean total volumes of the biogas obtained, the concentrations of the slurries used and the amount of yeast added, were used for the kinetics studies as follows:

2.5.1 Effect of Concentration on the Rate and Rate Constant for Biogas formation.

The respective rates of biogas formation from R_a, R_b, R_c, R_d and R_e for catalyzed and uncatalysed reactions were evaluated using the respective volumes of biogas collected from the reactors by applying the following equation as adopted by Omwirhiren (2006):

$$r = v/t$$

Where r = rate of biogas formation from the substrate (cm^3/day)
v = volume of biogas collected (cm^3)
t = time taken for biogas production (day)

Since the formation of biogas in this work was assumed to be first order reaction with respect to the number of reactant used, therefore, the rate constants for the reactions in R_a, R_b, R_c, R_d and R_e were evaluated using the respective rates of biogas formation in R_a, R_b, R_c, R_d and R_e by applying the following first order rate law equation as pointed out by Matthews (1996):

$$r \propto [S]$$

$$\Rightarrow \quad K = \frac{r}{[S]}$$

Where k = rate constant for biogas formation
r = rate of biogas formation
[S] = concentration of substrate.

2.5.2 Effect of Catalyst on Biogas Production (Catalysed reaction)

The same equations (i.e. the equations used for evaluating rates and rate constants for biogas production in the uncatalysed reaction) were applied for the evaluation of rates and rate constants for biogas formation in the catalysed reaction.

5.5.3 Fraction of Catalyst Involved in the Formation Complex with Substrate.

The fraction of catalyst participated in forming complex with substrate during biogas formation for the catalysed reaction was evaluated using the following equation as pointed out by Sharma (1981):

$$\Theta = \frac{A[S]}{1 + A[S]}$$

Where Θ = fraction of catalyst involved in complex formation
A = equilibrium constant for the reaction.
[S] = concentration of the substrate.

The equilibrium constant (A) was obtained as follows:

Since at equilibrium, the rate of forward reaction is equal, to the rate of backward reaction, therefore, the rate constant for forward reaction (k_f) is equal to the rate constant for backward reaction (k_b).

$$\Rightarrow \quad k_f = k_b$$

$$\Rightarrow A = \frac{k_f}{k_b} = 1$$

2.5.4 Concentration of Excess Catalyst

The concentration of excess catalyst, $[C]_{ex}$ was determined by computing the difference between the concentration of total catalyst, $[C]_o$ and the fraction of catalyst involved in complex formation, Θ as follows:

$$[C]_{ex} = [C]_o - \Theta$$

2.5.5 Rate of Unstable Complex Formation

The rate of catalyst-substrate unstable complex formation was evaluated using the equation adopted by Sharma (1981) as follows:

$$r \propto (1 - \Theta)[E]_o$$
$$\Rightarrow \quad r = k (1 - \Theta)[C]_o$$

Where r = rate of complex formation
k = rate constant for catalysed reaction
Θ = fraction of catalyst involved in complex formation.
$[C]_o$ = concentration of total catalyst added to the slurry.

2.5.6 Rate of Substrate Transformation into Biogas

The rate of substrate transformation into biogas for each slurry was evaluated using Singh model equation as follows:-

$$\Rightarrow r_s = - \frac{k [S]}{1 + t}$$

Where r_s = rate of substrate transformation into biogas.
k = rate constant for the uncatalysed reaction
[S] = concentration of the substrate (slurry)
t = time for substrate transformation into biogas

2.5.7 Saturation Constant of Catalyst in the Reactor

The saturation constant of the catalyst used in the reactor was evaluated using Monod Model equation as follows:

$$\frac{ds}{dt} = \frac{k[S][X]}{k_s + [S]} \qquad \text{But,} \quad \frac{ds}{dt} = r$$

$$\Rightarrow k_s = \frac{k[S][X]}{r + [S]}$$

where k_s = Saturation constant of the catalyst in the reactor.
k = rate constant for catalysed reaction
[S] = concentration of slurry in the reactor.
[X] = Concentration of catalyst added to the slurry
r = rate of biogas formation for catalysed reaction

3. Results

The results of all the experiments and analysis carried out in this work are summarized in Tables 1 – 4 below: Table 1 gives the mean total volumes of biogas obtained from catalysed and uncatalysed anaerobic digestion of cattle dung at thermophilic temperature (37^oC) over a period of 16 days. Table 2 gives the rate of biogas formation and rate constants for catalysed and uncatalysed reactions at thermophilic temperature (37^oC). Table 3 gives the concentration of total catalyst added to each slurry, fractions of the catalyst involved in the formation of unstable complex with substrate, the rate of catalyst- substrate unstable complex formation and the concentration of excess (free) catalyst in each reactor. Table 4 gives the rate of substrate transformation into biogas at 37^0C and, the saturation constant of the catalyst added into each slurry.

4. Discussion

Table 1 gives the mean total volumes of biogas collected from the catalyzed and uncatalyzed anaerobic digestion of cattle dung at thermophilic temperature (37^0C). From the result (Table 1), it could be seen that addition of catalyst to slurry at optimum concentration enhanced biogas production greatly. The relative increase in gas production observed in the catalysed reaction could be attributed to the formation of catalyst-substrate unstable intermediate complex, which requires a small energy of activation than in the original reactants without catalyst (i.e. uncatalysed reaction) as pointed out by Uche *et al* (1992), which resulted in the provision of one or more alternative reaction pathways, such that more reacting particles had sufficient energy and reacted at a relatively faster rate than in the uncatalysed reaction. This is in accordance with the statement of Olajire and Ayodele (2002) ;Dagari (2006).

Table 2: Shows the rates and rate constants for the catalyzed and uncatalyzed reactions. The result (Table 2) revealed that, at a certain point of slurry concentration (up to optimum concentration), the rate of biogas formation was directly proportional to the concentration of the slurry while at relatively higher concentration of slurry (50g/20cm^3 and 60g/250cm^3), the rate of biogas formation was inversely proportional to the concentration of the slurry, the increase in the rate of biogas formation at optimum concentrations of slurries may be associated with the balance between the active sites of the catalyst added and the molecules of a particular shape and size of the reacting species which fit into the available active sites of the catalyst. This is because, the production of biogas is greatly enhanced when there is balance between the substrate and the microbes involved in the fermentation as pointed out by Garba (1998). On the other hand, the decrease in the rate of biogas formation at relatively higher concentrations (50g/250cm^3 and 60g/250cm^3) may be associated with the saturation of the active sites of the catalyst with the substrate molecules as pointed out by Matthews (1996). The decrease in the ate of biogas formation at relatively higher concentrations may also be associated with the insufficient water content of the slurry because for proper fermentation of substrate, there must be suitable water content as microorganisms metabolic processes require water and, the water content of the slurry should be around 90% of the total weight of the slurry as pointed out by Ariane (1985).

The result of the rate constants for biogas production for both the catalysed and uncatalysed reactions shown in Table 2, revealed that, the rate constants for the reactions were inversely proportional to the concentrations of the slurries at 37^{o}C. This findings are in accordance with the statement of first order rate law, equation, which is given by

rate $\propto$ [reactants] as pointed out by Matthews (1996). From the equation; the rate constant (k) for each of the reactions (catalysed and uncatalysed) carried out in this work can be evaluated and expressed as follows:

$$\text{rate} \propto [\text{reactant}]$$
$$\Rightarrow \text{rate} = k\,[\text{reactant}]$$
$$\therefore k = \frac{\text{rate}}{[\text{reactant}]}$$

The expression of rate constant (k) above, showed that the reactions carried out obeyed first order Kinetics equations, which is in line with the statements of Matthew (1996); Olajire and Ayodele (2002); Dagari (2006); Aliyu (2009).

Table 3: Gives the concentration of the total catalyst (yeast) added to each reactor, as well as, the analysis of the catalyst added during the process (fermentation). From the result (Table 3), it could be seen that, the fractions of catalyst involved in catalyst – substrate unstable complex formation in the reactors were almost equal, regardless of the concentration of the catalyst added to the scurries in the reactors. This may be attributed to the active sites of the catalyst into which only molecules of a particular shape and size of the substrate will fit as pointed out by Matthews (1996). It may also be associated with the specificity behaviour of the catalyst (i.e. the ability of a catalyst to speed up the main reaction in the presence of several other side reactions) as pointed out by Chadwick (1977). The rate of catalyst – substrate unstable complex formation is also shown in Table 3. From the result, it could be seen that, the rate of catalyst – substrate unstable complex formation decreased with the increase in the concentration of catalyst (yeast) added. This may be associated with the microbial starvation, which occurred when the concentration of the microbes catalyst in the slurry is too high as compared to the available necessary nutrients needed for fermentation in the substrate as pointed out by Ariane (1985). The result of the analysis of the concentration of excess (free) catalyst is also shown in Table 3. From the result, it could also be seen that, the concentration of excess catalyst increased with the increase in the concentration of total catalyst added to each slurry. This may be associated with the fraction of catalyst involved in catalyst – substrate unstable complex formation. Because when the fraction of catalyst involved in the formation of unstable complex with the substrate is low, the concentration of free catalyst will be high. This is in accordance with the statement Sharma (1981),which says that, the lower the fraction of catalyst involved in unstable complex formation, the more the concentration of free catalyst.

Table 4 gives the rate of substrate transformation into biogas and the saturation constants of the catalyst added to each slurry. From the result (Table 4), it could be seen that the rate of substrate transformation into biogas increased with increase in concentration of the slurry and catalyst at a certain point and, decreased at relatively higher concentrations (50g/250cm^3 and 60g/250cm^3). The increase in the rate of substrate transformation may also be connected to the balance between the available active sites of the catalyst added and the fitted molecules of the substrate that occupied the active sites of the catalyst, as pointed out by Matthews (1996). On the other hand, the decrease at relatively higher concentrations of the slurry may be connected to the saturation of the active sites of the catalyst with the fitted molecules of the reacting species as also pointed out by Matthews (1996). The decrease in the rate of substrate transformation may also be connected to the insufficient water content of the slurry; because if the water content is two little, ethanoic acid will accumulate the slurry, which

subsequently inhibits the activities of the microbes in the fermentation pit (reactor) as pointed out by Ariane (1985). From Table 4, it could also be seen that, the saturation constants of the catalyst added to the slurries increased with increase in the concentration of the total catalyst used. This may be associated with the excess catalyst in the fermentation fit (reactor) as pointed out by Sharma (1981).

5. Conclusion

The findings have shown that, addition of catalyst to the reactants (slurries) enhanced biogas production; at a certain point, the volume of biogas produced, the rate of biogas formation, the rate of catalyst-substrate unstable complex formation and the rate of substrate transformation into biogas were directly proportional to the concentrations of reactants and the catalyst added to the reactants; the rate constants for biogas formation for both the catalyzed and uncatalyzed reactions were inversely proportional to the concentrations of reactants and the catalyst added to the reactants; the fractions of the total catalyst that involved in the formation of unstable complex with substrate were almost equal, (0.95g, 0.97g, 0.98g, 0.98g and 0.98g) regardless of the concentrations of the respective total catalyst (1.0g, 1.5g, 2.0g, 2.5g and 3.0g) added to the slurries and; the saturation constants of the total catalyst added to the slurries increased with increase in the concentration of the total catalyst. From these findings, it could be concluded that, the rate of gaseous fuel (biogas) generation from biodegradable substrate, the quantity of gaseous fuel to be generated from biodegradable substrate, the rate of converting biodegradable substrate (usually waste) into useful products and the rate of destroying infective pathogens in biodegradable wastes can greatly be enhanced through thermophilic digestion using a small quantity of yeast.

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Table 1: Mean Total Volumes of Biogas (cm^3) Collected from Catalyzed and Uncatalyzed Reactions Over a Period of 16days.

Reactor	Conc. of slurry ($g/250cm^3$)	Mean total volumes of biogas for uncatalyzed	Mean total volumes of biogas from catalyzed
R_a	20.00	382.00	480.60
R_b	30.00	512.50	629.00
R_c	40.00	671.00	825.00
R_d	50.00	598.00	668.00
R_e	60.00	325.80	404.00

* Key: Conc. = concentration

Table 2: Evaluate Rates (r) of Biogas Formation and Rate Constants (k) for Catalyzed and Uncatalyzed Reactions

Reactor	Conc. of slurry ($g/250cm^3$)	Uncatalyzed reaction		Catalyzed reaction	
		r (cm^3/day)	k (day^{-1})	r (cm^3/day)	k (day^{-1})
R_a	20.00	23.88	1.194	30.04	1.500
R_b	30.00	32.03	1.068	39.31	1.310
R_c	40.00	41.94	1.049	51.56	1.290
R_d	50.00	37.38	0.748	41.75	0.835
R_e	60.00	20.36	0.339	25.25	0.421

* Key: Conc. = concentration

Table 3: Analysis of Catalyst Added to Slurry

Reactor	Conc. of total catalyst (g/250cm^3)	Fraction of catalyst in the complex (g)	Conc. of excess catalyst (g)	Rate of complex formation (g/day)
R_a	1.00	0.95	0.075	0.05
R_b	1.50	0.97	0.059	0.53
R_c	2.00	0.98	0.052	1.02
R_d	2.50	0.98	0.042	1.52
R_e	3.00	0.98	0.025	2.02

* Key: Conc. = concentration

Table 4: Rates of Substrate Transformation into Biogas and Saturation Constants of Catalyst in the Reactors

Reactor	Rate of substrate transformation (g/day)	Saturation constant of catalyst (g/g)
R_a	-1.405	0.0476
R_b	-1.885	0.0484
R_c	-2.468	0.0488
R_d	-2.200	0.0490
R_e	-1.197	0.0492