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Effects of Organic Loading Rate on Biogas Yield in a Continuously Stirred Tank Reactor Experiment at Mesophilic Temperature

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Authors' contributions

This work was carried out in collaboration between all authors. Author AOA co-designed the study, performed the statistical analysis, wrote the first draft of the manuscript and managed literature searches. Authors SOJ and BL co-designed the study, supervised the project and corrected the draft to the final version. All authors read and approved the final manuscript.

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ABSTRACT

In this work, an attempt was made to study the effect of organic loading rate (OLR) on biogas yield using cow slurry as a single substrate at mesophilic (37℃) temperature in a long time experiment with Continuously Stirred Tank Reactor (CSTR). The reactor was loaded at OLR of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 goTS/l.d. Each OLR was maintained two (2) weeks before increasing it by 0.5 goTS/l.d. The experiment was run continuously for 140 days. It was observed that the biogas and methane yields decreased with increase in the organic loading rate after the reactor had attained stability. Both biogas yield and CH_4 in the biogas decreased with the increase in OLR. For OLR in the range of 2.0 g ($oTSl^{-1}d^{-1}$) – 5.0 g ($oTSl^{-1}d^{-}$)^{1}, biogas and methane yields obtained varied

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between 0.435 l_N/g - 0.300 l/g and 0.251 l_NCH_4/goS - 0.165l_NCH_4/goS, respectively at mesophilic temperature. The biogas produced by cow slurry was found to have an average methane (CH_4) content of 58%. It was concluded that organic loading rate has a decreasing effect on the biogas and methane yields in a continuously tank reactor experiment at mesophilic temperature. The kinetic model developed could be used for dimensioning CSTR digesting organic wastes.

Keywords: Organic loading rate; biogas yield; methane yield; CSTR and mesophilic temperature.

1. INTRODUCTION

Anaerobic digestion (AD) is a process of breaking down organic matter, such as manure, in the absence of oxygen by concerted action of various groups of anaerobic bacteria. The AD process generates biogas, an important renewable energy source that is composed mostly of methane (CH_4), and carbondioxide (CO_2) which can be used as an energy source (e.g., heat or electricity generation). Biogas originates from biogenic material and is therefore a type of biofuel.

To date 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. Several materials have been used in the past for the production of biogas [1-4].

The production of biogas involves the breaking down of complex polymers to soluble products by enzymes produced by fermentative bacteria which ferment substrate to short-chain fatty acids, hydrogen and carbon dioxide [5]. The production of biogas from biomass is a four step anaerobic digestion process, which is brought about by the complementary activities of several species of bacteria. The first step involves hydrolysis, second acidification and acidogenesis, third acetogenesis and the fourth step methanogenesis [Fig. 1]. All the described processes run almost simultaneously in a biogas plant. Nearly seventy percent of methane from biogas digesters fed with cattle dung is derived from acetate (Smith et al. [6] and Ramasamy et al. [7]). The quantity and quality of biogas depend on characteristics of feed materials (Calzada et al. [8]; Cuzin et al. [9]; Kalia et al. [10]; Zhang and Zhang [11]). The gas is generally composed of methane (55–65%), carbon dioxide (35–45%), nitrogen (0–3%), hydrogen (0–1%), and hydrogen sulfide (0–1%) (9). Table 1 shows the typical composition of biogas while Fig. 1 shows the stages in biogas production.

Table 1. Typical composition of biogas

Constituents	%composition
Methane, CH_4	55 – 65
Carbon dioxide, CO_2	35-45
Hydrogen sulphide H_2S	0-1
Nitrogen, N_2	0-1
Hydrogen, H_2	0-1
Carbon monoxide (CO)	0-3
Oxygen, O_2	0-2

Source: [10-12]

Organic Loading Rate (OLR) is an important operational parameter which represents the biological conversion capacity of an anaerobic digestion system. It is indeed a control parameter in continuous systems. It has been established that with low OLR, the anaerobic digester runs inefficiently, while with high OLR, there exists a risk of system failure due to overloading [8]. For example, according to Rincón et al. the OLR from 1.5 to 9.2 $kg \cdot m^{-3} \cdot day^{-1}$ during the digestion of olive mill solid residue in an anaerobic stirred tank reactor caused an increase in the methane productivity of more than 400%, while attempts to further increase the OLR led to process instability [14].

The aim of the present study is to determine the effect of organic loading rate on biogas production from cow slurry in a continuously stirred tank reactor at mesophilic temperature and to establish a kinetic model that could be used to predict biogas and methane yields at any given OLR and vice versa.

1.1 Biogas Utilization

Biogas has found a wide range of applications. It is being used for meeting various fuel requirements in the household, agricultural and industrial sectors, domestic use such as cooking, lighting, heating, crop drying, running refrigerators, water pumps and generators [15], production of heat, Combined Heat and Power (CHP) and as vehicle fuel.

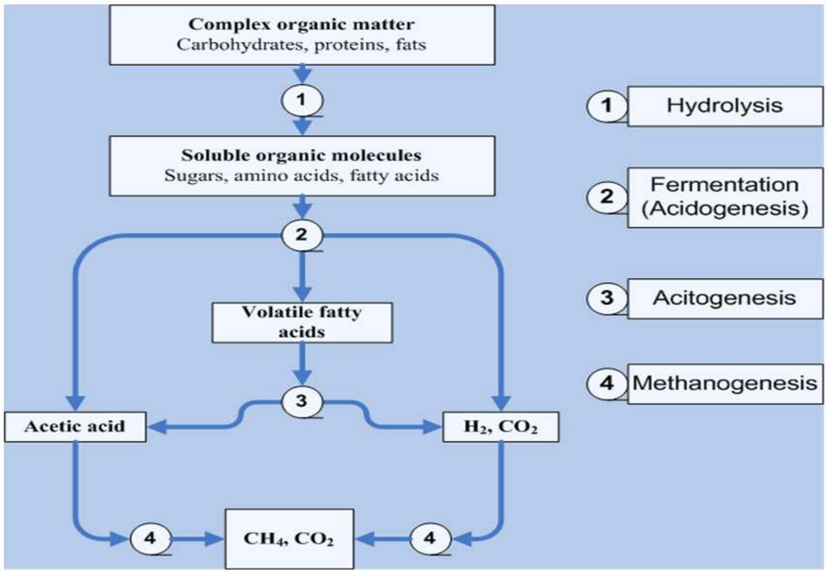

Fig. 1. Stages in biogas production
Source: [13]

Biogas could also be used as supplementary fuel in dual fuel engines and as well as in the drying, cooking, boiling and smoking of fish (especially catfish), taking into consideration the market value of smoked fish [16]. The effluent from the biogas process supplies essential nutrients which can also be utilized as fertilizer [17-20]. Biogas digestate has the advantages of producing energy, yielding high quality fertilizer and also preventing transmission of disease [21]. One essential requirement that needs to be fulfilled in a well-functioning biogas system is a suitable disposition of the large amount of digestate produced [19].

1.2 Factors Affecting Biogas Production

Several factors affect biogas production, and in turn bacterial activity. The regulation of these factors majorly leads to maintaining a suitable balance between volatile acids accumulation and methanogenic bacteria in a digester. These factors include feed stock properties (accessibility of the substrate), total suspended solid (TSS), volatile solids (VS), temperature, pH, hydraulic retention time (HRT), solid retention time (SRT), organic loading rate (OLR) of the digester, concentration of ammonia, co-digestion and digester type [22]. The volumetric Organic Loading Rate (OLR) is related to the retention time through the active biomass concentration in the bioreactor and is used to characterize the loading on anaerobic treatment systems. The OLR provides useful information for the design and operation of anaerobic processes as its knowledge is to quantify how effectively the reactor volume is being utilized. It can be expressed in terms of the mass of volatile solids applied and can be calculated using Equation 1,

$$OLR = \frac{Q.C}{V} = \frac{C}{HRT} \tag{1}$$

where OLR is the volumetric organic loading rate (kgVS $m^{-3}d^{-1}$), Q the influent flow rate (m^3d^{-1}), C the concentration of volatile solids in the substrate (kgVS m^{-3}) and V the bioreactor volume (m^3). For completely mixed anaerobic reactors operated without solids recycling the hydraulic retention time (HRT) and the SRT are identical. The SRT was calculated using Equation 2

$$SRT = \frac{S_i}{OLR} \tag{2}$$

Where S_i is the organic matter concentration in the influent (%)

For digestion systems, which incorporates solids recycle, the SRT will be greater than the HRT and the OLR indicates both the anaerobic digester volume utilization efficiency and the overall process loading [23].

2. MATERIALS AND METHODS

2.1 Materials

The cow slurry used for this research was collected from the research farm of the Institute for Animal Breeding and Animal Husbandry, Ruhlsdorf / Grosskreutz, Germany. Other materials used were the reactor, gas measuring meter (RITTER), heater with pump incorporated for circulating heated water through the reactors' jackets, gas bag (LINDE), thermometer, barometer, pH meter with probe for measuring conductivity, vertical stirrer (electrically operated) and timer for timing the operation of the stirrers.

2.2 Methods

2.2.1 Substrates and analytical procedures

The sample of the selected substrate was investigated in the laboratory for Fresh Matter (FM), Organic Dry Matter (105℃), Organic Dry Matter in % fresh mass), Volatile fatty acids (VFA), pH, NH_4-N, Conductivity (LF) and Organic dry matter in % of fresh mass (oTS) (Table 2). The inoculum for the batch anaerobic digestion tests was also analyzed. Samples were also taken from the reactors weekly for analysis and thus monitoring what was going on inside the digester. All analyses were performed according to German standard methods [24,25].

2.2.2 Materials and process descriptions

Slurries obtained from the Institute for Animal Breeding and Animal Husbandry, Ruhlsdorf / Grosskreutz ,Germany were used as substrates in a Continuously Stirred Tank Reactor (CSTR). Plate 1 shows the experimental set up for CSTR. The temperature of the 8.0 litre electrically stirred reactor was kept at 37℃ for mesophilic by circulating heated water through the jackets.

The experiment was run at mesophilic temperature using cow slurry. The reactor was operated in a fill-and-draw mode with seven feedings per week and mixed slowly at a speed of about 100 rpm for 15 min every 1 hr. For start-up, the stirred tank reactor was filled with 8 litres of pre-cultivated adapted seeding sludge (inoculum) and addition of substrate was started at a low loading rate of 1.0 $goTSl^{-1}d^{-1}$. The mass of the substrate fed into the reactor was calculated (Equation 3).

$$M_s = \frac{OLR \times V_R}{C_s} \quad (3)$$

Where

Ms= mass of the substrate (g)
OLR= Organic Loading Rate (g $oTS.l^{-1}d^{-1}$)
V_R = Volume of the reactor in l

Plate 1. Set up of CSTR experiment

The experiment was started at an OLR of 1.0 g VS $l^{-1}d^{-1}$ (using cow slurry). This OLR was maintained for two weeks (14 days) after which it was raised by 0.5g VS l^{-1} d^{-1} (every 14 day) as recommended by VDI, 4630. The OLR of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 g VS $l^{-1}d^{-1}$ were used during the experiment. Within the experiments, three samples of slurries were analyzed. Samples in use were stored at 3°C while those to be used later were stored at -21℃. The experiment was run for 140 days with cow slurry at mesophilic temperature. The biogas produced was collected in a gas bag each (LINDE) and measured with a multi-chamber rotor gas meter (RITTER) and analyzed with an Infrared Gas Detector (PRONOVA). The biogas volume was calculated to standard conditions (0℃, 1013 mbar) and averaged weekly. The OLR was closely monitored until the OLR of 5.0 g VS l^{-1} d^{-1} was reached at which the reactor was failing.

2.2.3 Analytical methods

The gas produced was analyzed twice a week by infrared gas detector (PRONOVA) for the gas components: CH_4, CO_2, O_2 and H_2S. All analyses were performed according to German standard methods [24,25]. The methane content of the gas obtained was averaged at 58% while the CO_2 and H_2S were averaged at 40% and 1.03% respectively as measured by the infrared gas detector. Values of OLR and biogas yield were average values of a seven-day period. The biogas yield was calculated from the biogas production derived from the VS-load of one week. Biogas was normalized at the standard temperature and pressure (0℃, 1013 mbar).

2.2.4 Development of kinetic model

Kinetic models were established for the CSTR experiment using the approach of Linke [24]. The model describes the biogas production pattern for a continuously stirred tank reactor (CSTR).

If the mass of biogas is neglected, the mass balance equation with equal mass flow of input and output m_o can be written as

$$V_R \frac{dc}{dt} = m_o.c_o - m_0.c + V_R.r(c) \tag{4}$$

r(c), the substrate removal rate which is a function of c is expressed as first order kinetic with

$$-\frac{dc}{dt} = r(c) = -k.c \tag{5}$$

$$V_R = m_o.HRT\ at\ steady\ \ state\ \ for\ V_R$$

k= first order reaction rate constant (d1)

$\frac{dc}{dt} = 0$, equations (4) and (5) can now be combined to give equation (6).

$$HRT = \frac{1}{k}.\left(\frac{c_o}{c} - 1\right) \tag{6}$$

According to Linke [24], the biodegradable fraction of the complex organic substrate is disintegrated to biogas following equation (7).

$$\frac{c_o - c(t)}{c_o} = \frac{y(t)}{y_m} \tag{7}$$

Where

y=VS biogas yield ($l.g^{-1}$)
$y_m = $ maximumVSbiogasyield($l.g^{-1}$)
c_o =VS-concentration of the input (gkg^{-1})

Equation (7) can be re-written as

$$\frac{c_o}{c} = \frac{y_m}{y_m - y} \tag{8}$$

By substituting equation (8) in equation (6), we have

$$HRT = \frac{1}{k}.\left(\frac{y}{y_m - y}\right) \tag{9}$$

$$y = \frac{HRT.k.y_m}{HRT.k + 1} \tag{10}$$

In CSTR experiments however, both the OLR and the HRT are the most applied parameters in practice. As a result, using the fact that $OLR = c_o / HRT$, equation (10) can be written as

$$OLR = \frac{k.c_o}{y/(y_m - y)} \tag{11}$$

By re-arranging equation (11), we have

$$y = y_m \frac{k.c_o}{k.c_o + OLR} \quad (12)$$

While y_m yields was obtained from a simple batch test, k was obtained from long-term experiments in a CSTR. The graph of $y/(y_m\text{-}y)$ was plotted against 1/OLR with slope $k.c_o$.

3. RESULTS AND DISCUSSION

Table 2 shows the result of the analysis conducted on the substrate (cow slurry) before the commencement of the experiment. Fig. 2 shows the variations in biogas rate, methane concentration, biogas yields and OLR with time at mesophilic temperature. It also showed the interactions between the parameters monitored for about 140 days that the experiment was run. The results revealed that, as the OLR increased from 1.0 oTSg/l.d, the yields were found to increase till OLR of 2.0 goTS/l.d (Fig. 2) after which a decrease in yields was noticed. This continued until the end of the experiment. This could also be seen clearly in Fig. 3 where the yield was plotted against organic loading rate. As OLR increased, the biogas and methane yields were found decreasing. The results obtained in this work were in agreement with previous findings where biogas productions decreased with increase in OLR [24,26].

Table 2. Chemical and thermal properties of selected cow dung

Parameters	Cow dung
Dry Matter, DM (%)	11.77
Organic dry matter, oDM (%DM)	84.05
Organic dry matter (%FM)	9.89
DM (60º-105ºC)	96.89
NH_4-N (g/kgFM)	1.22
N_{kjel}, g/kgFM	3.87
P mg/kg TS60°	1082.7
K %DM	2.05
Crude fibre (%DM)	26.75
pH	6.56
Conductivity (mS/cm)	9.98
Ethanol (g/l)	<0.04
Propanol	<0.04
Total acetic acid	8.12

Also, biogas rate increased with increase in OLR for about 90 days after which it began to fluctuate and later became relatively constant indicating a gradual failure of the reactor at 37°C. The methane concentration of cow slurry when subjected to a long time digestion as was the case in this research was found to be 58% on the average. The SRT was found to reduce from 10days (in the 20th week) to 2 days at the commencement of the experiment.

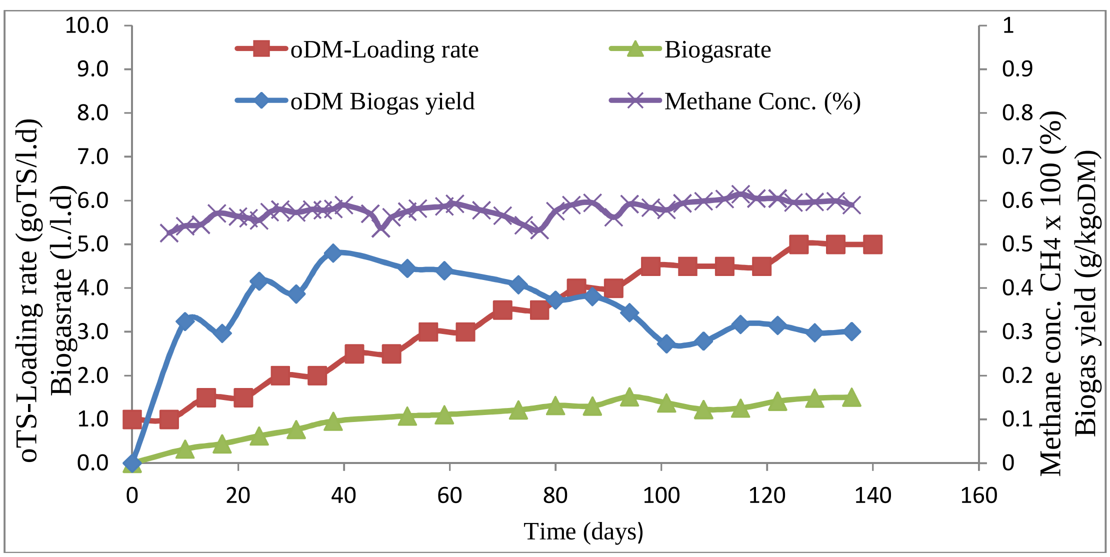

Fig. 2. Continuously stirred tank reactors performance data for cow slurry at mesophilic temperature

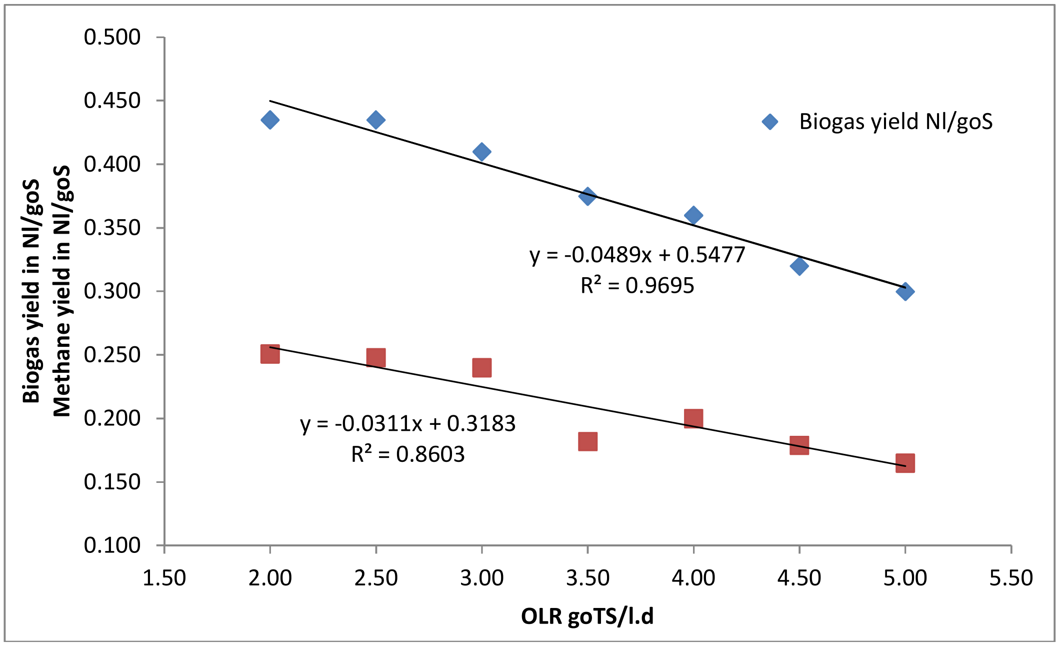

Fig. 3. Biogas and methane yields against OLR for CSTR experiment with cow slurry at mesophilic temperature

Similarly, in Fig. 2, the biogas rate increased from 0.42 Nl/l.d to 1.79 Nl/l.d as the OLR increased from 1.0 goTS/l.d to 5.0 goTS/l.d. This supports the fact that increases in OLR causes a corresponding increase in biogas rate. The results obtained were also subjected to statistical analysis. The t-test carried out on both biogas and methane yields revealed that there was no significant difference in biogas and methane yields at 95% confidence limit. From the results obtained, studying the trend between the OLR and the yields (for both biogas and methane yields), it was found that after the system has been stabilized, the yields were found to be decreasing with increase in OLR. For instance, in the mesophilic medium, as OLR increased from 1.0 to 5.0 goTS/l.d, the biogas yield, the system stabilized at 2.0 goTS/l.d at which the biogas yield was 0.435 m^3/kg oTS and then gradually decreased until 0.300 m^3/kg at 5.0 goTS/l.d.

3.1 Reaction Rate Constant, k for CSTR Experiments

The maximum yield, y_m and the reaction rate constant, k which are important factors in determining the fermenter size by means of organic loading rate (OLR) were determined. To obtain y_m, a simple batch test was conducted using the substrate in question.

(y_m=0.49 l_N/kgoDM) [27].

3.2 The Kinetic Models for the CSTR Experiments

The kinetic model developed for the CSTR experiments is of the form stated in Equation 12. For cattle slurry at mesophilic temperature, the kinetic model that describes the digestion process in terms of the OLR is given as in Equation 13

$$y = 0.490\frac{0.176.c_o}{0.176.c_o + OLR} \quad (13)$$

The methane yields followed the same trend. It decreased from 0.251 m^3/kgoTS at OLR of 2.0 goTS/l.d to 0.165 m^3/kgoTS at OLR of 5.0 goTS/l.d.

4. CONCLUSION

The study has shown that biogas and methane yields decreased with increase in OLR in a long time experiment at mesophilic temperature. The R^2 values of both biogas and methane production for OLR of 2.0 to 5.0 goTS/ld were found to be 0.9695 and 0.8603 respectively. The methane concentration was averaged at 58%. Kinetic model were established for the CSTR experiment on the basis of mass balance equations and a first order kinetic in a long term experiments (140 days) in order to obtain reliable data for the reaction rate constant k. The simple model equation obtained may be used for predicting the yield of continuously stirred tank reactors (CSTR) digesting organic wastes.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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