Abstract

Optimum utilization of poultry droppings anaerobically for energy production and fertilizers for soil conditioning depend substantially on the right choice of the reactor, which is the heart of any chemical process plant. The performance evaluation of reactor types for the determination of the best contacting scheme for mesophilic anaerobic digestion of poultry droppings was carried out. The findings of our study were that anaerobic mesophilic digestion of poultry droppings is a first order reaction with a reaction rate constant of 0.035 day\(^{-1}\); using the same performance equation, the plug flow digester is preferred for large scale production while the batch digester is desirable for small scale production. Digesters in series with inter-stage feed injection or heating would not be necessary. A recycle reactor whose recycled stream serves as inoculum tremendously improves the digester performance and it’s the best option for the mesophilic anaerobic digestion of poultry droppings.

Keywords: Poultry Droppings, Mesophilic Anaerobic Digestion, Reactor Types, Performance Evaluation

1. Introduction

The captured solar energy in green plants by photosynthesis is stored in biomass. Biomass, a high energy density system, such as trees, grasses, agricultural crops, agricultural residues, animal wastes and municipal solid wastes can be used as a solid fuel. Anaerobic digestion can be used to convert biomass by microorganisms in the absence of air to produce either alcohol or methane gas, which themselves give energy on combustion. Since biomass is obtained from photosynthesis, biomass energy could be considered as another form of direct use of solar energy (Dara, 2006).

The conversion of biomass into energy has received increased attention in recent years. The upward spiral in the price of fossil fuels coupled with impending shortage has made biomass attractive as a supplemental source of energy. Biomass represents a renewable, low-sulphur energy source. Fossil fuels are likely to create environmental problems, whereas the production and use of biomass energy represents a balanced carbon cycle. In view of these, biomass energy will become the most useful energy source of the future (McKendry, 2001; Asadullah et al, 2007 and Mohapatra & Gadgil, 2013).

Anaerobic digestion has been deemed one of the most useful decentralized sources of energy supply by the United Nations Development Programme. With the Clean Development Mechanism (CDM) arrangement under the Kyoto Protocol, industrialized countries with a commitment to reduce their own greenhouse gas emissions, invest financially in the implementation of anaerobic digestion systems in developing countries (UNFCCC, 2007).

In the past decades, the consumption of poultry in Nigeria and in many other countries has been on the increase. As a result of this growing poultry demand, there has been a corresponding increase in the poultry industry and consequently increasing amounts of organic solids by-products and wastes. Poultry droppings can be considered as a sust-
a biologically available biomass; a broiler produces approximately 11 g DM (Dry Matter)/bird/day of poultry droppings while a layer generates 32.9 gDM/bird/day (FAO, 1984).

Biogas is produced from anaerobic digestion of poultry droppings which can be used in gas-engine electric generators and domestic cooking and the slurry from the digester could be converted into fertilizers. Amidst these opportunities, poultry waste management in most countries, especially the developing countries, can be best described as non-existence, or at best being ad hoc. Farmers decompose poultry waste in heaped piles which emit offensive odours, carbon dioxide, methane and leachate seepage and or run-off to water sources. Insects, aesthetic and other health & environmental problems are with its mishandling (Hetal, 2006). The development of better engineering systems for proper handling of poultry waste, rather than dumping them into the environment, is extremely important in protecting surface water, groundwater, soil, and maintaining air quality standards (Puyate & Yelebe, 2010).

Digesting poultry waste in anaerobic digesters is a well- known option for poultry waste management; however, a successfully operating one could scarcely be found (Hossain, 2005). A clear understanding of the performance of various digester types in anaerobic digestion of poultry waste is crucial to the design and successful operation of the digester (Levenspiel, 2006).

Biological treatment of solid waste is a cost effective alternative to other waste treatment techniques and many experts regard bio-treatment as the technology of the future (O’Mar, 1996). After recycling, anaerobic digestion of organic waste is most likely to be the next breakthrough in waste transformation technologies (Kiely, 1997).

There are various options of processing poultry droppings anaerobically in a single batch or flow reactor, in a chain of reactors possibly with inter-stage feed injection or heating, in a reactor with recycle of product stream and so on. Which scheme is most appropriate is yet to be determined (Levenspiel, 2006).

A lot of factors may be considered in the determination of the best contacting scheme for anaerobic digestion of poultry droppings; for example, the reaction order or type, planned scale of production, cost of equipment and operations, safety and flexibility of operations, equipment life expectancy, length of time that the product is expected to be manufactured, ease of convertibility of equipment to modified operating conditions or to new and different processes (Levenspiel, 2006).

Much work has been carried out on annexing waste for energy and soil conditioning. Yelebe & Puyate (2009) studied the biokinetics of aerobic digestion of municipal solid waste. In their work, Monod growth kinetics was used to model aerobic degradation of municipal solid waste in bio-augmented and non-bio-augmented batch reactors using a mixture of indigenous microorganisms isolated from the waste. Igioni et al (2006 and 2008) estimated the kinetic parameters during anaerobic digestion of MSW (Municipal Solid Waste) and investigated the suitability of either batch or continuous digester for anaerobic degradation of MSW in the production of biogas. However, their investigation does not take into consideration that a continuous reactor can either be plug flow or continuous stirred tank or recycle reactor with totally different kinetics and mode of operation. Jiraphon et al (2010) developed dynamic model for anaerobic digestion of shrimp culture pond sediment to study the variables that affect biogas production process and optimization. Garcia-Ochoa et al (1999) developed kinetic model for anaerobic digestion of beef cattle manure. Wauton & Gumus (2012) presented the biokinetics of mesophilic anaerobic digestion of poultry droppings. Wauton & Gumus (2013) studied the effect of bioaugmentation on biokinetics parameters in the mesophilic anaerobic digestion of poultry droppings. However, literatures are scarce on performance evaluation or studies of reactor types in mesophilic anaerobic digestion of poultry droppings.

In environmental engineering, particularly in wastewater and water treatment, reactor types are essentially batch, continuous stirred tank and plug flow reactors (Kiely, 1997). In this study, the performance evaluation of reactor types in mesophilic anaerobic digestion of poultry droppings was carried out in order to determine the optimum contacting scheme for the reaction.

2. Materials and Methods

Sample Preparation, digester experimental set-up, enumeration and isolation of bacteria and the phases of microbial growth; the change of Chemical Oxygen Demand (COD), pH and biomass with time has been extensively presented by Wauton & Gumus (2012 and 2013). Digester size, hydraulic retention time and COD removal efficiency were used as the measure for digester performance.

2.1. Order of Reaction

The relationship between the rate of substrate utilization, the concentration of substrate and reaction order in the mesophilic anaerobic digestion of poultry droppings is given as:

\[
\frac{dC}{dt} = KC^n
\]

Where:

- \( C \) = Rate of anaerobic digestion (mg/L. day)
dc/dt = Rate of substrate utilization (mg/L. day)
= Order of reaction
C = Chemical oxygen demand (mg/L)
K = Anaerobic digestion rate constant

For zero-order kinetics, Equation 1 could be expressed as:
\[ C = C_o = K_o t \] .................................2

For first-order kinetics, Equation 1 is written as:
\[ \ln \left( \frac{C_o}{C} \right) = K_o t \] .................................3

And for second-order kinetics, Equation 1 is expressed as:
\[ \frac{1}{C^2} - \frac{1}{C_o^2} = K_o t \] .................................4

2.2. Size of Reactor

2.2.1. Plug Flow (or Batch) Reactor

Assuming constant density for the fermentation broth, neglecting other density variations during reaction is of secondary importance compared to flow type (Levenspiel, 2006), the performance equation for a plug flow or batch anaerobic digester is (Foggler, 2005 and Levenspiel, 2006):
\[ \int_{V_{PLUG}}^- = \int_{V_{PLUG}}^\tau \frac{X_{COD}}{An} \frac{C_{O_{PLUG}}}{C_{Q}} \frac{V}{\tau} \] .................................5

Where:
- \( V_{PLUG} \) = volume of digester (L)
- \( Q \) = Feed rate (L/day)
- \( C_{O} \) = Influent concentration (mg/L)
- \( X_{COD} \) = Fractional conversion of COD
- \( \tau \) = Hydraulic retention time (Day)

2.2.2. Continuous Stirred Tank Digester

The performance equation for a continuous stirred tank digester is (Foggler, 2005 and Levenspiel, 2006):
\[ \int_{V_{CSTR}}^\tau \frac{X_{COD}}{An} \frac{C_{R_{CSTR}}}{C_{Q}} \frac{V}{\tau} \] .................................6

Where:
- \( R \) = Recycle Ratio
- \( V_R \) = Volume of Reactor

And
\[ X_{COD} = \left( \frac{R}{R + 1} \right) X_{COD} \] .................................10

2.2.3. Digesters in Series

For \( N \) plug flow digesters connected in series, the performance equation could be written as (Foggler, 2005 and Levenspiel, 2006):
\[ \int_{V_{COD}}^\tau \frac{X_{COD}}{X_{COD} \ldots X_{COD}} \frac{C_{COD}}{\tau_{COD} \ldots \tau_{COD}} \] .................................7

Where:
- \( X_{COD}, X_{COD} \ldots X_{COD} \) are the fractional conversion of the COD of the poultry droppings leaving digester 1, 2… N

Whereas for continuous stirred bioreactors in series, the performance equation is (Levenspiel, 2006):
\[ \frac{V}{Q} \int_{V_{COD}}^\tau \frac{X_{COD}}{X_{COD} \ldots X_{COD}} \frac{C_{COD}}{\tau_{COD} \ldots \tau_{COD}} \] .................................8

2.2.4. Recycle Digesters

Wauton & Gumus (2013) discovered that inoculation or bioaugmentation would increase the yield for the mesophilic anaerobic digestion of poultry droppings by 97% and hence recommended inoculation in digester design. de la Rubia et al (2002) in their study of anaerobic mesophilic and thermophilic municipal sludge digestion conducted a pilot-scale digester placed in Guadalete River WWTP using digested mesophilic sludge (containing 17.14 gL\(^{-1}\) VS (Volatile Solids)) as inoculums and raw sludge as feed to enhance digestion.

The performance equation for a recycle reactor, assuming negligible changes in density is given by Levenspiel (2006):
\[ \int_{V_{COD}}^\tau \frac{X_{COD}}{X_{COD} \ldots X_{COD}} \frac{C_{COD}}{\tau_{COD} \ldots \tau_{COD}} \] .................................9

Where:
- \( R \) = Recycle Ratio
- \( V_R \) = Volume of Reactor

And
\[ X_{COD} = \left( \frac{R}{R + 1} \right) X_{COD} \] .................................10

3. Results and Discussion

The result of substrate utilization with time for anaerobic digestion of poultry droppings is presented in Figure 1. Detailed biokinetics of anaerobic digestion of poultry droppings presenting growth phases of anaerobes, biokinetics parameters and rate models is available in literature (Wauton & Gumus, 2012).

Figure 1 is also a plot of Equation 2 whereas Equations 3 and 4 are as shown in Figures 2 and 3 respectively. From a careful examination of the plots of the reaction orders, Figure 2 have the highest value of the coefficient of determination (\( R^2 \)), the order of the reaction is 1; which indicates that the rate of reaction is directly proportional to the concentration of the substrate. This is in agreement with the order of reactions of most biological systems reported in literatures (Reynold & Richards, 1996 and Kiely, 1997). Hence, the rate equation for the anaerobic digestion of
poultry droppings could be written as:

\[-r_{as} = -\frac{dC}{dt} = 0.035 C = 0.035C(1 - X_{COD}) \] \text{11}

Integrating Equation 12 yields:

\[\tau_{\text{PLUG}} = -\ln(1 - X_{COD})/0.035 \] \text{13}

And

\[V_{\text{HOG}} = -Q \frac{\ln(1 - X_{COD})}{0.035C_{o}} = \phi \tau_{\text{HOG}} \] \text{14}

Where:

\[\phi = \frac{Q}{C_{o}}\]

And for the stirred tank digester, substituting Equation 11 into Equation 6 yields:

\[V_{\text{CSTR}} = \frac{\tau_{\text{CSTR}}}{C_{o}} = \frac{\Delta X_{\text{COD}}}{0.035C_{o}(1 - X_{\text{COD}})} \] \text{15}

Equation 15 can be written as:

\[\tau_{\text{CSTR}} = \frac{X_{\text{COD}}}{0.035(1 - X_{\text{COD}})} \] \text{16}

And

\[V_{\text{CSTR}} = \frac{QX_{\text{COD}}}{0.035(1 - X_{\text{COD}})} = \phi \tau_{\text{CSTR}} \] \text{17}

Substituting Equation 11 into Equation 9 and integrating yields:

\[\frac{0.035}{R + 1} = \ln \left[ \frac{C_{o} + RC_{r}}{(R + 1)C_{r}} \right] \] \text{18}

Equation 18 could be written as:

\[\tau_{\text{S}} = \frac{C_{o}V_{S}}{Q} = \frac{R + 1}{0.035} \ln \left[ \frac{C_{o} + RC_{r}}{(R + 1)C_{r}} \right] \] \text{19}

Where \(\lambda\) is a factor which accounts for the modified reaction rate constant due to the addition of inoculum from recycle stream into the digester

Also,

\[V_{S} = \frac{Q}{C_{o}} \left( \frac{R + 1}{0.035} \right) \ln \left[ \frac{C_{o} + RC_{r}}{(R + 1)C_{r}} \right] = \phi \tau_{\text{S}} \] \text{20}

The value of \(R\) used is the yield for the anaerobic digestion of the poultry droppings for the recycle stream to serve as inoculum and it lies between 0.08 and 0.2 for anaerobic digestion (Kiely, 1997).
Equations 14, 17 and 20 indicate that the volume of digester is directly proportional to the hydraulic retention time. Figure 4 presents the performance of reactor types in anaerobic digestion of poultry droppings. It shows that when the COD conversion is small, the digester performance is only slightly affected by flow type. The performance ratio increases very rapidly at high COD conversions. Consequently, a proper choice of contacting scheme becomes very important.

In plug flow, batch and recycle digesters, the concentration decreases progressively through the system whereas in mixed flow, the concentration drops immediately to a low value (Fogler, 2005 and Levenspiel, 2006). This sudden change in properties of the system is not favourable for biological reactors. The effect of the shock of a sudden change in environment to microbes in a biological system has been extensively discussed by Reynold & Richards (1996), Kiely (1997) and Yelebe & Puyate (2009).

From Equations 7 and 8, \( N \) digester in series with a total volume, \( V \), gives the same conversion of COD as a single digester of volume, \( V \). This arrangement (i.e. multiple digesters) is preferred in a reaction that requires inter-stage feed injection or heating or both. Anaerobic digestion of poultry droppings taking place in a mesophilic temperature of 32 °C, is a ‘very sensitive’ reaction and does not require interstage heating or feed injection for optimum operations. However, optimum hook up of plug flow digesters connected in parallel or in any parallel-series combination will require the fluid streams that meet to have the same concentration and \( \tau \) must be the same for each parallel line. \( N \) mixed flow digesters connected in series, though the concentration in each digester is uniform, stepwise drop in concentration from digester to digester obtained and the larger the number of units in series, the closer should the behaviour of the system to plug flow (Levenspiel, 2006).

Figure 4 depicts that continuous stirred digester has the least performance. The performance of the recycle digester, which is a convenient way for approaching mixed flow with what is essentially a plug flow device, (Levenspiel, 2006) lie between the plug flow digester and the continuous stirred digester. However, the introduction of biomass from the recycle stream as an inoculum gives the best performance i.e. it increases the digester performance tremendously and is highly recommended. But for small scale production, the batch digester is preferred which has the advantage of small instrumentation cost and flexibility of operation (Levenspiel, 2006), however, the larger the digester, the better the economics (Jim, 2001) which makes flow digesters imperative.

4. Conclusion

The performance evaluation of reactor types, in order to determine the best contacting scheme for the mesophilic anaerobic digestion of poultry droppings was carried. The COD conversion efficiency, reactor size and hydraulic retention time were used as the measure of performance. Anaerobic mesophilic digestion of poultry droppings takes place in first-order kinetics with reaction rate constant of 0.035 day\(^{-1}\). When COD conversion is small, the digester performance is only slightly affected by flow types. The performance ratio increases very rapidly at high COD conversions. The CSTR has the least performance. Recycled digester lies between the plug flow digester and the CSTR. However, the introduction of biomass from the recycle stream as an inoculum gives the best performance; it tremendously increases the digester performance and is highly recommended. For small scale production, the batch digester is preferred which has the advantage of small instrumentation cost and flexibility of operation; however, the larger the digester, the better the economics.

Acknowledgement

The authors are thankful to Mr. Suoyo Diete-Spiff, the Chief Laboratory Technologist, Department of Chemical Sciences, Niger Delta University.

References


