

BIOGAS PRODUCTION FROM CHICKEN MANURE: CHARACTERIZATION AND KINETIC MODELS

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ABSTRACT

Characterizing chicken manure (CM) before anaerobic digestion (AD) and the knowledge of the kinetics of the process resulting in minimum and maximum biogas product is important. CM is a hazardous animal residue and kinetics is rarely studied without co-digesting with other feedstocks. Therefore, the objectives is to use POLYMATH 6.10 Educational Release and the Origin 2018 softwares to determine kinetic parameters in Modified Gompertz, Transfert, Cone and Logistic models used in biogas kinetic study and to propose the best model based on the characteristic of the CM used and the regression fitting. This was achieved by using regression parameters estimated by the two softwares using the Levenberg-Marquadt nonlinear technique. Findings shows that Logistic gave the best prediction, followed by Cone, Modified Gompertz, and Transfert model, in that order; though the above models puts biogas potential of CM at approximately 1m³ from 1:1 water-to-CM digestion with 63% methane, 29% carbondioxide, 5.8% hydrogen, 1.4% hydrogen sulphide, 0.6% ammonia, 0.1% nitrogen and 0.1% moisture.

Keywords: Chicken manure; Biogas potential; Biogas Kinetic Model; Characterization; Bioreactor

1. INTRODUCTION

One potential substrate for biogas production is chicken manure (CM), due to its availability as an agricultural waste material having high nitrogen content and carbon-nitrogen ratio (Eronmosele et al., 2020; Ulusoy et al., 2018; Wang et al., 2019). It is obtained generally from poultry farms and chicken processing industries as chicken processing waste (CPW) in form of legs, blood, heads, skin, bones, feathers, viscera, besides the whole carcasses if the bird is dead (Li et al., 2016). These contents makes CM an organic matter that is highly biodegradable and an important bioenergy source to derive improved fuel (Hakimi et al., 2021; Keskin et al., 2018; Tanczuk et al., 2019; Yilmaz & Sahan, 2020; Zahedi et al., 2020). Other significance could be poultry waste minimization when used as substrate for anaerobic digestion (AD) to manufacture biofertilizer, a co-product of the fermentation process (Hakimi et al., 2021; Ksheem, 2015; Li et al., 2016; Singh et al., 2018). Also, CM is a promising feedstock for slow pyrolysis (Tanczuk et al., 2019). Certain nutrient sources such as sulphur, nitrogen, potassium, phosphorus, fat, amino acids and protein can as well be recovered from the manure (Ksheem, 2015; Li et al., 2016; Oosterkamp & Oosterbeek, 2018; Selvaraj et al., 2018; Yilmaz & Sahan, 2020). Ammonia and/or

ammonium can also be recovered from CM by hydrothermal conversion of the high nitrogen content in it (Matsumura et al., 2021). A recent study done by Cheong et al. (2019), demonstrated the generation of electricity from the fluidized bed combustion of CM. Generally, utilization of CM fundamentally solves the environmental pollution problems (Abubakar, 2022; Wang et al., 2019).

CM alone is rarely used as feedstock in the production of biogas. Since the organic matter that make up what is known as CM are different and not all may be present in some sourced samples due to varying content, variation in nutrient composition is eminent. Notwithstanding, having CM specimen with right proportion of desired nutrient composition, will points to a successful AD and subsequent biogas production. To overcome this challenge, CM is often co-digested with other substrates that are nutrient deficient. Li et al. (2016), co-digested CM, chicken processing waste, miscanthus and seagrass, while Duan et al. (2018) and Jiang et al. (2021) co-digested CM and algal digestate and CM and corn straw respectively. The mentioned authors examined a combination of two kinetic models each for their multiple substrates, which are First Order and modified Gompertz, Logistic and modified Gompertz and Cone and modified Gompertz models

respectively, they estimated and compared their kinetic parameters. Several other authors studied biogas production from co-digested CM including Abdelhay et al. (2021) who worked on CM and algae, CM + corn stover (Li et al., 2013), CM + food waste and goat (Lohani et al., 2020), CM + poppy straw (Bayrakdar et al., 2016) and CM + oil refinery wastewater by Mehryar et al. (2017) among others without studying the kinetics of the biogas produced. Liu et al. (2018) and Ma et al. (2021) carried out kinetic study using CM as sole substrate by modified Gompertz model. However, their work explores a two-stage fermentation process and involves the addition of

biochar, of which kinetic parameter from sole CM utilization is presumed different. This work considered, 3 other models namely, Cone, Logistic and Transfert models for the same feedstock, comparing their respective maximum biogas potential (BP), lag phase (LP) and maximum biogas production rate (k). The experimental values obtained were fitted to the models. These parameters will facilitate the design and scale-up of a laboratory experiment into industrial size application. In addition, the characteristic of the CM sample was determined and compared to recent findings as relates to biogas production.

2. MATERIALS AND METHODS

Materials used are 55.3 cm high, metallic cylindrical digester, car tyre tube, ½ inch narrow pipe, pH/temperature meter (PH 2601), laboratory clamp (Fischer Scientific UK Ltd.), drying oven Nouvelle 6111 plus, electric furnace 20141, EDXRF spectrometer (model Rayny 720), GC-MS (ELGA Wycombe, UK), and weighing balance (Xiamen Jadever Scale Co. Ltd., China).

2.1 Substrate and Inoculum

Chicken manure was obtained from University of Maiduguri poultry farms. The inoculum used for the anaerobic digestion was fresh chicken droppings. The CM sourced from the contains feathers, dungs, moisture, and waste chicken feeds excluding chicken processing waste.

2.2 Physico-chemical Measurement

Dry matter content (DM) or Total solids (TS) and volatile solids (VS) content of the CM were measured by heating a given sample in a heating chamber at 105 °C (±2) for 24 hours as described by Najafi et al. (2019) and Abubakar & Yunus (2021), based on ASTM D1076-02 standard test method. The mass of CM remaining after heating was taken as the TS. Thereafter, the TS was heated in an incinerator at 550 °C (±50) for 2 hours. The difference between the TS and the mass remaining after incineration was taken as the VS following the method of Alghashm et al. (2018). Elemental composition (carbon and nitrogen) was determined using G4 ICARUS series 2 (Bruker, Massachusetts, USA).

Moisture content (MC) in the original CM sample was determined using Equation 1.

$$DM(\%) = \frac{M_{dried}}{M_{wet}} \times 100 = 100 - MC(\%) \dots (1)$$

Percent ash content (AC) both dry and wet basis was computed based on Equation 2 and Equation 3,

$$\%AC(\text{dry basis}) = \frac{M_{ash}}{M_{dried}} \times 100 \dots (2)$$

$$\%AC(\text{wet basis}) = \frac{M_{ash}}{M_{wet}} \times 100 \dots (3)$$

Organic matter content (OM) was determined using Equation 4.

$$OM(\%) = \frac{M_{wet} - M_{ash}}{M_{wet}} \times 100 = 100 - AC(\%) \dots (4)$$

Equation 4 and 5 were used in accordance to the work of Ksheem (2015) where particle density (PD) was estimated taking value of %AC computed on wet basis.

$$PD(\text{g/cm}^3) = \frac{1}{\frac{OM}{1.55} + \frac{AC}{2.65}} \dots (5)$$

2.2.1 Carbon and Nitrogen Ratio

CM sample was experimented for % carbon content and % nitrogen content by separate methods. Nitrogen content was determined using the Kjeldahl method (Najafi *et al.*, 2019) involving 3 procedural steps, including digestion, distillation and titration. Carbon content was determined using the method explained by Schumacher (2002).

The C/N ratio was then calculated using Equation 6 given by Noori & Ismail (2019).

$$\frac{C}{N} = \frac{\% \text{Organic carbon in sample}}{\% \text{Nitrogen in sample}} \quad \dots \quad (6)$$

2.2.2 Elemental Composition

Elemental composition of the CM substrate was determined using EDXRF analyser.

2.2.3 Temperature and pH Measurement

Using a pH-temperature meter 2601, both pH and temperature inside the digester was read daily for 40 days. There wasn't any heating of sought of the biodigester. The process relies on the ambient temperature of the environment to digest the CM feedstock.

2.3 Bioreactor Setup and Cumulative Biogas Measurement

A cylindrical laboratory-scale anaerobic digester of height, 55.3cm, diameter, 27.5cm, thickness, 0.4cm and a working volume that covers 70% of the total volume (32850 cm³) was used as batch reactor, where 7kg of CM was fed once. The gas produced was channeled into a tube via a gas outlet pipe. Daily records of the weight of the tube was taken and subtracted from weight recorded in the previous day to obtain the weight of biogas produced daily. Using biogas density of 1.2 kg/m³, based on range reported by Teferra & Wubu (2018), the volume of biogas produced was calculated from which the cumulative biogas yield (CBY) was computed. This step is dissimilar to the liquid displacement technique explained by Syaichurrozi *et al.* (2018) and Uche *et al.*, (2020), but has the advantage of total recovery of gas generated.

2.4 Gas Chromatography-Mass Spectrometry (GC-MS) Analysis

Biogas sample was analyzed using GC-MS (ELGA Wycombe, UK) following the method described by Gallego *et al.* (2015) and Tetteh & Rathilal (2020).

2.5 Kinetic Parameter Estimation

Four kinetic models were used to fit the experimental CBY data of the AD of CM. These models were the modified Gompertz model, the Logistic mode, the Cone model and the Transfert model given in equations (7-10) respectively,

$$CBY = BPe^{-e^{\left[\frac{k_e}{BP}(LP-t)+1\right]}} \quad (7)$$

$$CBY = \frac{BP}{1+e^{\left[\frac{4k(LP-t)}{BP}+2\right]}} \quad (8)$$

$$CBY = \frac{BP}{1+(kt)^{-SF}} \quad (9)$$

$$CBY = BPe^{-e^{\left[1-\frac{k_e}{BP}(LP-t)\right]}} \quad (10)$$

where, BP = maximum biogas potential, LP = lag phase (day), SF = shape factor and k = maximum specific rate constant. Parameters from the equations were estimated using the POLYMATH software (version 6.10). The statistical indicators used to determine the more appropriate model that describe the experimental CBY were coefficient of determination (R²), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Residual Sum of Squares (RSS), Accuracy Factor (AF), Bias Factor (BF), AIC and BIC. These indicators are given in equations (11-14). RSS was determined according to equation (11)

$$RSS = \sum (|\text{Measured biogas}| - |\text{Predicted biogas}|)^2 \quad \dots \quad (11)$$

MAPE was calculated according to Equation (12) (Syaichurrozi *et al.*, 2018), where n = number of observations.

$$MAPE = \frac{1}{n} \sum \left(\frac{|\text{Measured biogas} - \text{Predicted biogas}|}{|\text{Measured biogas}|} \right) \times 100\% \dots (12)$$

BF and AF were computed according to Halmi *et al.* (2014) and Kang *et al.* (2021) using Equation 13 and 14 respectively.

$$BF = 10^{\frac{\sum \log(\text{Observed}/\text{Predicted})}{n}} \quad \dots \quad (13)$$

$$AF = 10^{\frac{\sum |\log(\text{Predicted}/\text{Observed})|}{n}} \quad \dots \quad (14)$$

3. RESULT AND DISCUSSION

3.1 Properties of Chicken Manure

The physico-chemical parameters of CM are listed in Table 1. The substrate is seen to have a high moisture content (MC) of 47%, which is higher than 39.73% reported by Singh *et al.* (2018) and 25.23% reported by Dede & Ozer (2018). Differences in MC of CM could be due to differences in type of feed (Hoeven-Hangoor *et al.*, 2013) and age of the substrate. However, the MC obtained in the present study is similar to 48.3%

obtained by Wedwitschka *et al.* (2020). A high MC of the fresh CM provides a good environment for metabolism. If moisture content is low (dry fermentation/high solid), mixing to ensure uniform composition inside the digester is difficult. The volatile solids content of 13.21 % is far below the range of 56.7 – 86.4% reported by Wedwitschka *et al.* (2020) and 25.6% reported by Cioabla *et al.* (2012). Again, factors like origin of bird can cause a significant difference in the VS of CM.

Table 1: Chicken Manure Characterization

Property	Amount	Property	Amount
Moisture content	47%	Volatile solid content	13.21%
Total Solids	53%	Fixed solid content	86.79%
Ash content (dry basis)	22.6%	VS/TS	0.25
Ash content (wet basis)	12%	Carbon content	66.17%
Organic matter content	88%	Nitrogen content	2.73%
Particle density	0.0163 g/cm ³	Crude Protein	17.06%
C/N Ratio	24:1		

PD is a determinant of the porosity and how easy bacteria breakdown the CM substrate or the weight of individual solid particle that make up the CM per unit volume. PD below 1.0 g/cm³ usually indicates high OM content. So, PD = 0.0163g/cm³ obtained here and 0.5438g/cm³ reported by Brunerová *et al.* (2020) are both within the expected range. The TS of 53% in the present study is higher than 74.77% reported by Dede & Ozer (2018). Nitrogen content between 2.6-5.7% had been reported for CM substrate (Adeyemo *et al.*, 2019, Dede & Ozer, 2018 and Singh *et al.* 2018), which are in consonance with 2.73% obtained in the present study. Carbon content of 66.17% in the present study is higher than 21.12-34.93% reported previously (Abubakar and Yunus 2021). A higher C/N ratio (24:1) reduces volatile fatty acid accumulation and increases the biogas potential of the substrate compared to substrate with lower C/N ratio (Dalk and Ugurlu 2015).

3.2 Effect of Metallic Nutrient of Manure on AD

AD of CM is influenced mostly by percentage or amount of organic matter, moisture and inorganic matter present in it. CM sample of compositional properties different from those shown in Figure 1 and Table 1 will give varying yield of biogas. Shown in Figure 1 are concentrations (in mg/Kg or ppm) of CM characterized for metallic ions using EDXRF.

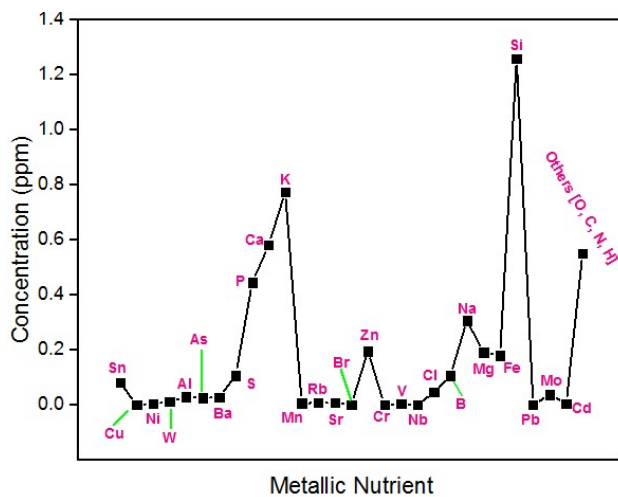


Figure 1: Metallic Nutrient Concentration in Chicken Manure

Twenty-four metals have been identified in the CM and are divided into heavy metals (macro-nutrient) and light metals (micro-nutrients). Heavy metals present are Fe, Ni, Mo, V, W, Cr, Cu, Zn, As, Sr, Ba, Pb, Cd and Sn in low concentrations ranging from 0-0.1956ppm. As stated by Mancini *et al.* (2018), heavy metals pose danger to microbial activity. Negligible concentrations obtained in the present study has far less potential of inhibiting the growth of bacteria during AD. The amount of some of the heavy metals in poultry manure, according to Zhang *et al.* (2012) is 65.6mg/kg dm of Cu, 3.3 mg/kg dm of As and 1.6 mg/kg dm of Cd. Microbes need preferably, light metals such as Ca, Fe, Mg, K, Na, Al and P for growth according to Sawyer *et al.* (2019) and Nsair *et al.* (2020). Moreover, most poultry manure contain 13 nutrients including S, Cl, B, N, P, K, Ca, Mg, Mn, Cu, Zn, Fe and Mo. The presence of these micro-nutrient in the CM substrates, especially Na (0.3071ppm), P (0.44494ppm), K (0.7742ppm), Fe (0.18ppm) and Mg (0.191ppm) makes the CM sample a suitable feedstock for AD. High Si (1.26ppm) content obtained was due the presence of bone, feather and soil particles in the CM. Non-metallic elements such as C, O, S, H and N are included in the plot, though oxygen is expected to be very less as the bacteria requires no oxygen. So, amount consist in elements tagged 'others' in Figure 4 is expected to be dominated by C, N, H and O in that order.

3.3 Fluctuation in pH and Temperature in the Digester

The temperature was not constant but it was within the mesophilic range – perfect for methanogenic activity. pH

also fluctuated and reduced with time of digestion (Figure 2). Fluctuation in pH during the AD of CM has also been reported by Wedwitschka *et al.* (2020), where pH fluctuated between 6.8 to 8.2. These fluctuations in pH can be attributed to a change in the volatile fatty acids content of the system. Since these volatile fatty acids are formed during the acedogenic stage of biogas production, the pH of the system reduces as shown in Figures 2 and 3. Above a pH of 6.0, biogas yield decreased significantly. At a pH above 7.5, methanogenic activity no longer existed.

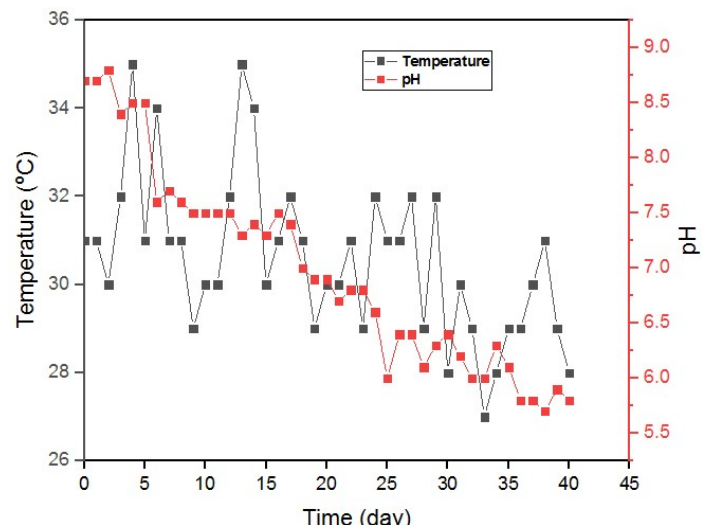


Figure 2: Daily pH and Temperature Record during Digestion Process

The pH range (5.7-8.8) of the CM slurry during AD was a little out of the survival range of micro-organism reported by Elalami *et al.*, (2019) (i.e. 6.0-8.0). The initial pH = 8.7 at $t = 0$ day for the CM agrees with Lohani *et al.* (2020), that CM is alkaline in nature.

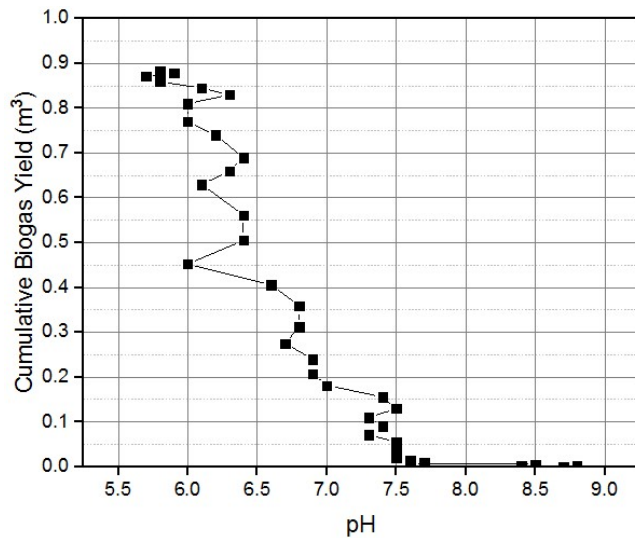


Figure 3: Cumulative Biogas Yield versus Daily Recorded pH

3.4 Biogas Yield

Total volume of biogas produced after 40 days of digestion was 0.883m^3 , an average of approximately $0.022\text{m}^3/\text{day}$. The maximum volume of gas (0.681m^3) was produced at the exponential phase (between day 9-35). A lag phase of about 7 days was observed during the process, an indication that the methanogens took a long time to adapt to the system. This lag phase may have been reduced if an inoculum from a biogas digester was added to the system. The CBY plotted against CM retention time is shown in Figure 4.

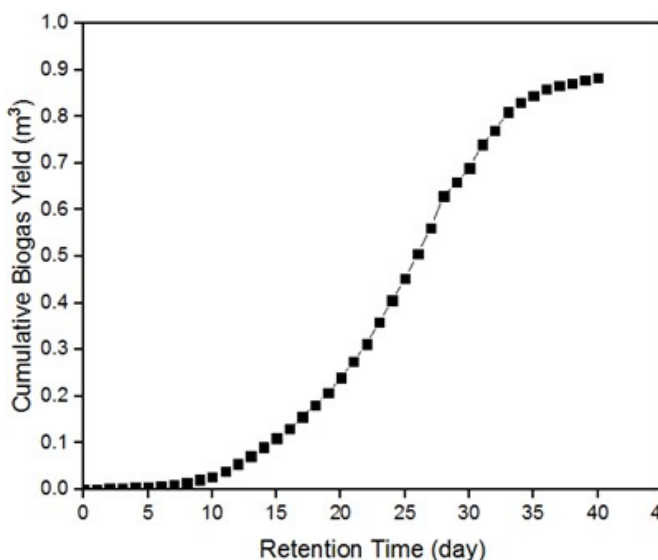


Figure 4: Cumulative Biogas Yield with Retention Time for the CM Substrate

According to AirFacts (2020), 100kg of chicken litter will generate $\cong 20\text{m}^3$ of biogas, corresponding with Bijman (2014) 200m^3 of biogas from 1000kg of chicken litter containing 55%DM and 42% OM in 30days. Biogas volume of 0.883m^3 produced here for 40 days digestion of 7.2kg of CM with 53%DM and 88%OM content is less than those obtained by the two authors. GC-MS analysis result where the component of the gas is displayed at different height versus run time is shown in Figure 5.

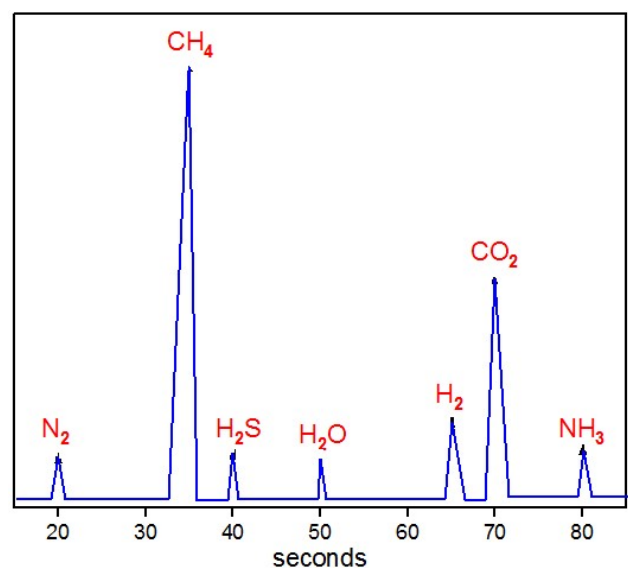


Figure 5: GC Biogas Analysis

The compositions of the gas were found based on peak areas occupied by CH_4 (178.87mm^2), CO_2 (82.34mm^2), H_2 (16.47mm^2), H_2S (3.97mm^2), NH_3 (1.70mm^2), N_2 (0.28mm^2) and H_2O (0.28mm^2) in the graph. Dividing the respective areas of the gas by the total area occupied gives the percentage of the component gases, which gives CH_4 (63%), CO_2 (29%), H_2 (5.8%), H_2S (1.4%), NH_3 (0.6%), N_2 (0.1%) and H_2O (0.1%). These percentage compositions are similar to the report of Abuabdou *et al.* (2020) and Granado *et al.* (2017).

3.5 Discussion on Biogas Kinetics Model Fitting

The Cone, Transfert, Modified Gompertz and Logistic models were fitted to the measured CBY versus retention time plot as shown in Figure 6. The four models gave a good fit of the experimental data as seen from the high

values of R^2 which were all close to unity and extremely low values of RMSE.

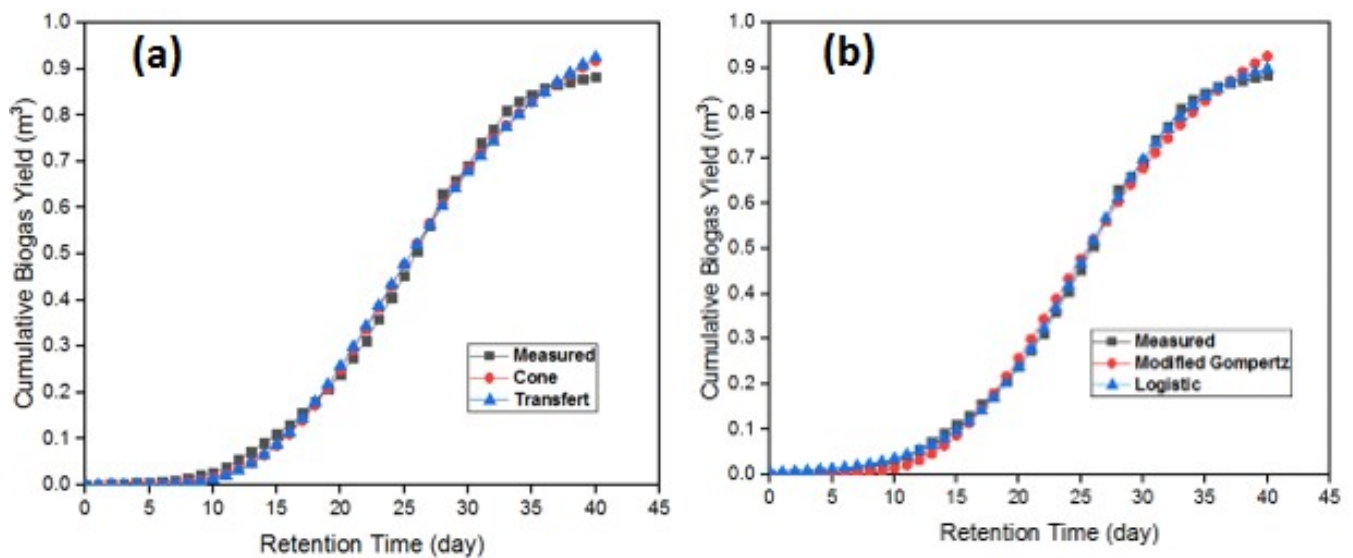


Figure 6: Model Fitting(a) Cone and Transfert (b) Modified Gompertz and Logistic to Measured CBY

However, other statistical indicators like the AIC and BIC (Table 4) show that the logistic model gave the best fit of the experimental data..

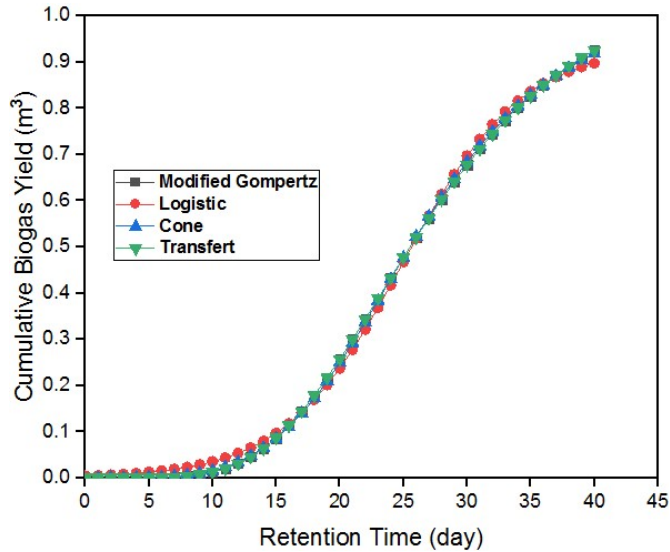


Figure 7: Plots of all Kinetic Models Together

Square root of the variance of the residuals or RMSE values ranges from 0.009375-0.137137, as shown in Table 4.

Table 4: Regression Parameter Estimated from Fitted Biogas Kinetic Model

Model	Parameter	R²	Adj. R²	RSS	AIC	BIC
Modified Gompertz	BP = 1.073076 m ³	0.99632	0.99613	0.01681	-310.66405	-304.92087
	k = 0.0447788 day ⁻¹					
	LP = 14.32809 day					
Cone	BP = 1.06351 m ³	0.99723	0.99708	0.01266	-322.27873	-316.53555
	k = 0.03814 day ⁻¹					
	SF = 4.36841					
Logistic	BP = 0.9325659 m ³	0.99921	0.99917	0.0036	-373.8043	-368.06112
	k = 0.0503514 day ⁻¹					
	LP = 15.71288 day					
Transfert	BP = 1.073082 m ³	0.99632	0.99613	0.01681	-310.66402	-304.92084
	k = 0.0447783 day ⁻¹					
	LP = 14.32796 day					
Model	MAPE	RMSE	AF	BF		
Modified Gompertz	24.38987	0.020248	1.980345	1.90345		
Cone	34.21464	0.137137	3.907264	3.907264		
Logistic	-38.5674	0.009375	1.215339	0.8822816		
Transfert	24.38968	0.020248	1.980317	1.980317		

BP = maximum biogas potential, LP = lag phase (day), SF = shape factor and k = maximum specific rate constant

Venkateshkumar *et al.* (2020) report that lower RMSE indicate a better fit, also confirms the selected models based on the R^2 criteria and Syaichurrozi *et al.* (2018) who based model selection on MAPE. An MAPE < 20% can be taken as a good model, hence Logistic is favored compared to other models. A 100% fit imply a $BF=AF=1$ according to (Kang *et al.*, 2021), whereas $BF>1$ in modified Gompertz, Cone and Transfert models are considered a fail-safe model and $BF<1$ in Logistic model is considered a fail-dangerous model according to Halimi *et al.* (2014). The AF estimates are > 1 , where higher values suggests a less precise prediction (as in Cone model).

To select the best biogas kinetic model, in this case, AIC, BIC and F-test were compared using values obtained from Origin Version 95E statistical analysis software. According Origin Pro, the data are too small to make conclusions on F-test for the models analyzed. Logistic function model has lower AIC value compared to modified Gompertz, Cone and Transfert model and so is more likely to be correct. Cone model has lower AIC compared to modified Gompertz and Transfert model and is therefore more likely to be correct. AIC comparison also favours modified Gompertz model over Transfert model. BIC difference >10 ranks the models, starting from the most correct model as; Logistic, Cone, modified Gompertz and Transfert model, just in a similar fashion as AIC, but a BIC difference < 2 obtained by comparing modified Gompertz and Transfert model renders the result inconclusive. In the literature, modified Gompertz model was reported to have lower AIC = 39.41 compared to AIC = 43.48 of Cone model estimates from CM and corn straw digestion according to Dinh *et al.* (2018), making it the correct model.

The first-order kinetic constant, k estimated in from all the models were not significantly different ($p=0.05$) and varied between 0.038 – 0.050 /day. The lag phase obtained from the Modified Gompertz, Transfert and Logistic models were not significantly different but were about twice the experimental value of 7 days. Lag phases during AD can be affected by nature or source of inoculum as well as inoculum to substrate ratio. If an inoculum that is rich in methanogens is used, a lag phase of zero may be obtained (Undiandeye *et al.*, 2022). The estimated lag phase compares with the

values obtained by Duan *et al.* (2018) which are between 11.37-15.73 days for modified Gompertz model and 11.48-15.8 days for Logistic model for CM plus algal digestate substrate used. Though, the author's data cannot be used to compare estimates in Table 4 as they are gotten from co-digested AD process, Liu *et al.* (2018)'s LP = 14.29 days for CM substrate estimated from modified Gompertz model is approximately identical to LP obtained in this work. But Ma *et al.* (2021)'s LP = 5.20 days for layer CM from modified Gompertz model and Dinh *et al.* (2018)'s LP = 7.0328 days from Cone model for CM plus corn straw AD are around the 7 days experimental LP period in this work. Maximum specific biogas production rate, $k = 0.0688 \text{ day}^{-1}$ according to Dinh *et al.* (2018) from modified Gompertz model for CM versus corn straw processed, almost satisfy 3 models given positive k in Table 4 for CM. Negative value of k in Transfert model makes it the worst performing model. But RSS values used during F-test suggest Logistic model as the preferred model because it has a small RSS value.

4. CONCLUSION

Considerable amount of biogas is present in CM due to its rich nutrient content supporting bacterial growth. Out of the four kinetic models used, the Logistic model best predicted the biogas kinetic parameters compared to the others. Estimated kinetic parameters ranged from 0.93-1.73 m^3 , 14.3-15.7 days, and 0.038-0.050 day^{-1} for the maximum biogas potential, lag phase and first-order kinetic constants respectively, and are within reported ranges obtained for mono- or codigestion of CM with other feedstock. It is important to have a CM substrate with desired proximate data since biogas yield is influenced by it, which in turn makes model fitting difficult. It has been observed that, hardly any analogy on works carried out on CM biogas production are the same, even with mono- or co-digested feedstock. This could be attributed to microorganisms degrading the feedstock, which are capable of dictating the entire anaerobic digestion process.

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REFERENCES

- Abdelhay, A., Al-Hasanat, L., & Albsoul, A. (2021). Anaerobic co-digestion of cattle manure and raw algae: Kinetic study and optimization of methane potential by RSM. *Pol. Journal of Environmental Studies*, 30(2), 1029–1037. <https://doi.org/10.15244/pjoes/125523>
- Abuabdou, S. M. A., Ahmad, W., Aun, N. C., & Bashir, M. J. K. (2020). A review of anaerobic membrane bioreactors (AnMBR) for the treatment of highly contaminated land fill leachate and biogas production: Effectiveness, limitations and future perspectives. *Journal of Cleaner Production*, 255(120215), 1–12. <https://doi.org/10.1016/j.jclepro.2020.120215>
- Abubakar, A. M. (2022). Biodigester and feedstock type: Characteristic, selection, and global biogas production. *Journal of Engineering Research and Sciences (JENRS)*, 1(3), 170–187. <https://doi.org/https://doi.org/TBA>
- Abubakar, A. M., & Yunus, M. U. (2021). Reporting biogas data from various feedstock. *International Journal of Formal Sciences: Current and Future Research Trends (IJFSCFRT)*, 11(1), 23–36. <https://doi.org/https://doi.org/10.5281/zenodo.6603733>
- Adeyemo, A. J., Akingbola, O. O., & Ojeniyi, S. O. (2019). Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded alfisols in southwestern Nigeria. *International Journal of Recycling of Organic Waste in Agriculture*, 8(1), 73–80. <https://doi.org/10.1007/s40093-019-0273-7>
- AirFacts. (2020). Manure digestion for biogas from cow/pig/chicken manure. *Are Volume of Gas and Solid Equivalent*, 1–2. www.Gazpack.nl/biogas-from-cow-dung-pig-and-chicken-manure
- Alghashm, S., Qian, S., Hua, Y., Wu, J., Zhang, H., Chen, W., & Guoqing, S. (2018). Properties of biochar from anaerobically digested food waste and its potential use in phosphorus recovery and soil amendment. *Sustainability*, 10(4692), 1–11. <https://doi.org/10.3390/su10124692>
- Bayrakdar, A., Molaey, R., Onder, R., Sahinkaya, E., & Calli, B. (2016). Biogas production from chicken manure: Co-digestion with spent poppy straw. *International Biodeterioration & Biodegradation*, 1–6. <https://doi.org/10.1016/j.ibiod.2016.10.058>
- Bijman, T. (2014). Biogas from poultry waste – A case. *Nijhuis Water Technology*, June, 1–12.
- Brunerová, A., Müller, M., Gürdil, A. G. K., Slegler, V., & Brozek, M. (2020). Analysis of the physical-mechanical properties of a pelleted chicken litter organic fertiliser. *Research in Agricultural Engineering*, 66(4), 131–139. <https://doi.org/https://doi.org/10.4491/eer.2018.081>
- Cheong, D., Kim, J., & Lee, C. (2019). Improving biomethanation of chicken manure by co-digestion with ethanol plant effluent. *International Journal of Environmental Research and Public Health*, 16(5023), 1–10. <https://doi.org/10.3390/ijerph16245023>
- Cioabla, A. E., Ionel, I., & Dumitrele, Gabriela-Alina Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. *Biotechnology for Biofuels and Bioproducts*, 5(39), 1–9. <http://www.biotechnologyforbiofuels.com/content/5/1/39>
- Dalk, K., & Ugurlu, A. (2015). Biogas production from chicken manure at different organic loading rates in a mesophilic-thermophilic two stage anaerobic system. *Journal of Bioscience and Bioengineering*, xx(xx), 1–8. <https://doi.org/10.1016/j.jbiosc.2015.01.021>
- Dede, O. H., & Ozer, H. (2018). Enrichment of poultry manure with biomass ash to produce organomineral fertiliser. *Environmental Engineering Research*, 23(4), 449–455. <https://doi.org/https://doi.org/10.4491/eer.2018.081>
- Dinh, P. V., Fujiwara, T., Phu, S. T. P., & Hoang, M. G. (2018). Kinetic of biogas production in co-digestion of vegetable waste, horse dung, and sludge by batch reactors. *IOP Conference Series: Earth and Environmental Science*, 1–9.
- Duan, N., Ran, X., Li, R., Kougiyas, P. G., Zhang, Y., Lin, C., & Liu, H. (2018). Performance evaluation of mesophilic anaerobic digestion of chicken manure with algal digestate. *Energies*, 11(1829), 1–11. <https://doi.org/10.3390/en11071829>
- Elalami, D., Carrere, H., Monlau, F., Abdelouahdi, K., Oukarroum, A., & Barakat, A. (2019). Pretreatment

- and co-digestion of wastewater sludge for biogas production: Recent research advances and trends. *Renewable and Sustainable Energy Reviews*, 114(109287), 1–23.
<https://doi.org/10.1016/j.rser.2019.109287>
- Eronmosele, P., Thelma, A. E., & Essienubong, A. I. (2020). Comparative study of the kinetics of biogas yield from the codigestion of poultry droppings with waterleaf and poultry droppings with elephant grass. *Engineering Sciences (NWSAENS)*, 15(3), 139–150.
<https://doi.org/http://dx.doi.org/10.12739/NWSA.2020.15.3.1A0457>
- Gallego, E., Javier, F., Francisco, J., Guardino, X., & Gadea, E. (2015). Development of a method for determination of VOCs (including methylsiloxanes) in biogas by TD-GC/MS analysis using Supel TM Inert Film bags and multi-sorbent bed tubes. *International Journal of Environmental Analytical Chemistry*, 95(5), 291–311.
<https://doi.org/10.1080/03067319.2015.1016012>
- Granado, R. L., Antune, A. M. S., Fonseca, F. V., Sánchez, A., Barrena, R., & Font, X. (2017). Technology overview of biogas production in anaerobic digestion plants: A European evaluation of research and development. *Renewable and Sustainable Energy Reviews*, 80, 44–53.
<https://doi.org/10.1016/j.rser.2017.05.079>
- Hakimi, M., Shamsudin, M. R., Pendyala, R., Aminah, S., & Gunny, A. A. N. (2021). Co-anaerobic digestion of chicken manure and selected additives for biogas production. *IOP Conference Series: Earth and Environmental Science*, 1–8.
<https://doi.org/10.1088/1755-1315/765/1/012055>
- Halmi, M. I. E., Shukor, M. S., Johari, W. L. W., & Shukor, M. Y. (2014). Mathematical modeling of the growth kinetics of *Bacillus* spp. on tannery effluent containing chromate. *Journal of Environmental Bioremediation & Toxicology (JEBAT)*, 2(1), 6–10.
<http://journal.hibiscuspublisher.com>
- Hoeven-Hangoor, E. van der, Paton, N. D., Linde, I. B. van de, Verstegen, M. W. A., & Hendriks, W. H. (2013). Moisture content in broiler excreta is influenced by excreta nutrient contents. *Journal of Animal Science*, 91(12), 5705–5713.
<https://doi.org/https://doi.org/10.2527/jas.2013-6573>
- Jiang, H., Shen, Y., Ma, C., Zhao, J., Wang, Y., Li, Y., & Zhou, H. (2021). Solid-state anaerobic digestion of chicken manure and corn straw with different loading amounts. *Polish Journal of Environmental Studies*, 30(3), 2117–2125.
<https://doi.org/10.15244/pjoes/124180>
- Kang, M. S., Park, J. H., & Kim, H. J. (2021). Predictive modeling for the growth of *Salmonella* spp. in liquid egg white and application of scenario-based risk estimation. *Microorganisms*, 9(486), 1–12.
<https://doi.org/https://doi.org/10.3390/microorganism9030486>
- Keskin, T., Arslan, K., Karaalp, D., & Azbar, N. (2018). The determination of the trace element effects on basal medium by using the statistical optimization approach for biogas production from chicken manure. *Waste and Biomass Valorization*, 0(0), 1–10.
<https://doi.org/10.1007/s12649-018-0273-2>
- Ksheem, A. M. A. (2015). *Optimising nutrient extraction from chicken manure and compost* [University of Southern Queensland].
<https://doi.org/10.13140/RG.2.1.1973.3842>
- Li, C., Strömberg, S., Liub, G., Nges, I. A., & Liu, J. (2016). Assessment of regional biomass as co-substrate in the anaerobic digestion of chicken manure: Impact of co-digestion with chicken processing waste, seagrass and *Miscanthus*. *Biochemical Engineering Journal*, 1–38.
<https://doi.org/http://dx.doi.org/doi:10.1016/j.bej.2016.11.008>
- Li, Y., Zhang, R., Chen, C., Liu, G., He, Y., & Liu, X. (2013). Biogas production from co-digestion of corn stover and chicken manure under anaerobic wet, hemi-solid, and solid state conditions. *Bioresour Technol*, 149, 406–412.
<https://doi.org/http://dx.doi.org/10.1016/j.biortech.2013.09.091>
- Liu, X. Y., Wang, J. J., Nie, J. M., Wu, N., Yang, F., & Yang, R. J. (2018). Biogas production of chicken manure by two-stage fermentation process. *E3S Web of Conferences (ICEMEE 2018)*, 38(01048), 5–8.
<https://doi.org/https://doi.org/10.1051/e3sconf/20183801048>
- Lohani, S. P., Acharya, A., Koirala, R., Koirala, A., Lamsal, B., & Khanal, S. N. (2020). Anaerobic co-digestion of food waste, goat and chicken manure for sustainable biogas production. *International Journal of Energy Applications and Technologies*, 7(4), 120–125.
<https://doi.org/10.31593/ijeat.748982>
- Ma, J., Chen, F., Xue, S., Pan, J., Khoshnevisan, B., Yang,

- Y., Liu, H., & Qiu, L. (2021). Improving anaerobic digestion of chicken manure under optimized biochar supplementation strategies. *Bioresource Technology*, 325(124697), 124697. <https://doi.org/10.1016/j.biortech.2021.124697>
- Mancini, G., Papirio, S., Lens, P. N. L., & Esposito, G. (2018). Increased biogas production from wheat straw by chemical pretreatments. *Renewable Energy*, 119, 608–614. <https://doi.org/10.1016/j.renene.2017.12.045>
- Matsumura, Y., Suganuma, Y., Ichikawa, T., Kim, W., Nakashimada, Y., & Nishida, K. (2021). Reaction rate of hydrothermal ammonia production from chicken manure. *ACS Omega*, 1–5. <https://doi.org/10.1021/acsomega.1c03418>
- Mehryar, E., Ding, W. M., Hemmat, A., Hassan, M., Bi, J. H., Huang, H. Y., & Kafashan, J. (2017). Anaerobic co-digestion of oil refinery wastewater and chicken manure to produce biogas, and kinetic parameters determination in batch reactors. *Agronomy Research*, 15(5), 1983–1996. <https://doi.org/https://doi.org/https://doi.org/10.15159/AR.17.072>
- Najafi, B., Ardabili, S. F., Shamshirband, S., & Chau, K. (2019). Development of a modified kinetic method for modelling of biogas produced from biomass. *Energies*, 1–16.
- Noori, N. A., & Ismail, Z. Z. (2019). Process optimization of biogas recovery from giant reed (*Arundo donax*) alternatively pretreated with acid and oxidant agent: Experimental and kinetic study. *Biomass Conversion and Biorefinery*, 1–15. <https://doi.org/https://doi.org/10.1007/s13399-019-00481-7>
- Nsair, A., Onen Cinar, S., Alassali, A., Abu Qdais, H., & Kuchta, K. (2020). Operational parameters of biogas plants: A review and evaluation study. *Energies*, 13(15), 1–27. <https://doi.org/10.3390/en13153761>
- Oosterkamp, W. J., & Oosterbeek, O. (2018). Chicken manure digestion. *Current Biochemical Engineering*, 3(April), 1–2. <https://doi.org/10.2174/2212711903666160831141935>
- Sawyer, N., Trois, C., Workneh, T. S., & Okudoh, V. (2019). An overview of biogas production: Fundamentals, applications and future research. *International Journal of Energy Economics and Policy*, 9(2), 105–116. <https://doi.org/10.32479/ijeep.7375>
- Schumacher, B. A. (2002). *Methods for the determination of total organic carbon (TOC) in soil and sediments*.
- Selvaraj, B., Krishnasamy, S., Munirajan, S., Alagirisamy, S., Dhanushkodi, M., & Gopalsamy, S. (2018). Kinetic modelling of augmenting biomethane yield from poultry litter by mitigating ammonia. *International Journal of Green Energy*, 00(00), 1–7. <https://doi.org/10.1080/15435075.2018.1529580>
- Singh, G., Shamsuddin, M. R., & Lim, S. W. (2018). Characterization of chicken manure from Manjung Region. *OP Conf. Series: Materials Science and Engineering*, 1–7. <https://doi.org/10.1088/1757-899X/458/1/012084>
- Syaichurrozi, I., Suhirman, S., & Hidayat, T. (2018). Effect of initial pH on anaerobic co-digestion of *Salvinia molesta* and rice straw for biogas production and kinetics. *Biocatalysis and Agricultural Biotechnology*, 1–33. <https://doi.org/10.1016/j.bcab.2018.10.007>
- Tanczuk, M., Junga, R., Kolasa-Wiecek, A., & Niemiec, P. (2019). Assessment of the energy potential of chicken manure in Poland. *Energies*, 12(1244), 1–18. <https://doi.org/10.3390/en12071244>
- Teferra, D. M., & Wubu, W. (2018). *Biogas for clean energy*. InTech Open. <https://doi.org/http://dx.doi.org/10.5772/intechopen.79534>
- Tetteh, E. K., & Rathilal, S. (2020). Kinetics and nanoparticle catalytic enhancement of biogas production from wastewater using a magnetized biochemical methane potential (MBMP) system. *Catalysts*, 10(1200), 1–19. <https://doi.org/10.3390/catal10101200>
- Uche, A. M., Emmanuel, O. T., Paul, O. U., Olawale, A., Frank, K. B., Rita, O. O., & Martin, O. S. (2020). Design and construction of fixed dome digester for biogas production using cow dung and water hyacinth. *African Journal of Environmental Science and Technology*, 14(1), 15–25. <https://doi.org/10.5897/AJEST2019.2739>
- Ulusoy, Y., Ulukardesler, A. H., Arslan, R., & Tekin, Y. (2018). Energy and emission benefits of chicken manure biogas production: A case study.

- Environmental Science and Pollution Research*, 1–7.
<https://doi.org/10.1007/s11356-018-3466-0>
- Undiandeye, J., Gallegos, D., Lenz, J., Nelles, M., & Stinner, W. (2022). Effect of novel *Aspergillus* and *Neurospora* species-based additive on ensiling parameters and biomethane potential of sugar beet leaves. *Applied Sciences*, 12(2684), 1–14.
<https://doi.org/https://doi.org/10.3390/app12052684>
- Venkateshkumar, R., Shanmugam, S., & Veerappan, A. R. (2020). Anaerobic co-digestion of cow dung and cotton seed hull with different blend ratio: Experimental and kinetic study. *Biomass Conversion and Biorefinery*, 1–111.
<https://doi.org/https://doi.org/10.1007/s13399-020-01006-3>
- Wang, F., Pei, M., Qiu, L., Yao, Y., Zhang, C., & Qiang, H. (2019). Performance of anaerobic digestion of chicken manure under gradually elevated organic loading rates. *International Journal of Environmental Research and Public Health*, 16(2239), 1–17.
<https://doi.org/10.3390/ijerph16122239>
- Wedwitschka, H., Gallegos Ibanez, D., Schäfer, F., Jenson, E., & Nelles, M. (2020). Material characterization and substrate suitability assessment of chicken manure for dry batch anaerobic digestion processes. *Bioengineering*, 7(106), 1–16.
<https://doi.org/10.3390/bioengineering7030106>
- Yilmaz, S., & Sahan, T. (2020). Utilization of pumice for improving biogas production from poultry manure by anaerobic digestion: A modeling and process optimization study using response surface methodology. *Biomass and Bioenergy*, 138(105601), 1–10.
<https://doi.org/10.1016/j.biombioe.2020.105601>
- Zahedi, S., Mart, C., Solera, R., & Perez, M. (2020). Evaluating the effectiveness of adding chicken manure in the anaerobic mesophilic codigestion of sewage sludge and wine distillery wastewater: Kinetic modeling and economic approach. *Energy & Fuels*, 1–8.
<https://doi.org/10.1021/acs.energyfuels.0c01852>
- Zhang, F., Li, Y., Yang, M., & Li, W. (2012). Content of heavy metals in animal feeds and manures from farms of different scales in Northeast China. *International Journal of Environmental Research and Public Health*, 9, 2658–2668.
<https://doi.org/10.3390/ijerph9082658>