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A numerical Modeling Using ADM1 Model in the co-anaerobic Digestion of Food Waste with Varying Fat Fractions to Generate Biogas

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ABSTRACT

The impact of different fat contents and different degrees of hydrolysis on the anaerobic digestion process and the production of biogas is the subject of this paper and the evaluation is conducted with the aid of the ADM1 model. Anaerobic digestion is one of the most important steps of the biogas production from organic wastes and it contains mainly methane (CH_4) and carbon dioxide (CO_2). The study shows clearly that each concentration of fat improves methane production with 15% fat concentration giving the highest output at a rate of 0.75 m³/kg at day 20 as compared to the 0.10 m³/kg from 0% fat concentrations. Also, the extent of hydrolysis profoundly predicts the degradation of the complex organic material; the greatest hydrolysis rate of $0.25h^{-1}$ gave methane of 0.70 m³/kg, which is about 75% higher than lesser rates. The existing study also shows that there was a direct relationship between the density of organic acids, hydrogen and CO_2 with the degree of fat content and rates of hydrolysis. Hence the results presented in this paper underscore the significance of defining fat and its hydrolyses in relation to the biogas production so as to improve the efficiency and stability of the anaerobic digestion process as the complex organic matters diminish. What this research offers is knowledge indispensable to enhancing the efficiency of energy extraction from organic waste, thereby enriching the contemporary discourse on waste management.

1. Introduction

Dadgarian Shoushtari, S (2023) [1] in the present study examined the effect of fermentation on anaerobic digestion of waste activated sludge (WAS), primary sludge (PS), and a mixture of WAS and PS (WAS+PS) through BioWin® simulation. The work compared SRT at 10, 20 and, 30 days, and established that fermentation enhanced VSS reduction, biodegradation as well as methane yield. The highest value of improvements was achieved at PS+WAS integrated system with 30 days SRT and increasing the VSR up to 52% compared to base model. In the current year Wang [2] studied the methanation of CO_2 and CO from the blast furnace gas (BFG) through anaerobic fermentation in mesophilic environment. Methane production experiments were conducted using acclimated methanogens and anaerobic granular sludge (AGS). It was observed that the tolerance to toxic CO was observed with AGS resulting in improved biomethanation using exogenous H2 and thus offering a green and sustainable way of dealing with green house gases and bio-fuels. Ferreira (2009) [3] investigated AD as a viable method for the management of dewatered sludge produced in WWTPs. The study showed that AD has some benefits, namely, decrease in sludge

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mass through breaking down of organic matter into biogas, which can be utilized as a source of energy. THP and co-digestion methods showed an increase in biogas production and stabilized sludge, which was a more cost- and environment-effective method on case studies.

Mossissa (2022) [4] proposed a method of techno-economic analysis tool (TEA) for the AD technology targeted at smallholder farming in the WEF nexus environment. The research established amounts of agricultural residue biomass in South Africa and Madagascar and showed that co-digestion approaches increased the degree of efficiency in methane production. A MCDA approach was used to determine the best small-scale AD technology with a probabilistic simulation providing for appropriate TEAC assessments. Using experimental investigations with mathematical modeling of pig slurry, Postawa et al. (2021) [5] presented a new PMAD system. The results illustrated that the investigated PMAD performed satisfactorily and reached biogas yield greater than 8 dm^3 per dm^3 of feedstock with CH4 content of about 65%. The developed three-phase model incorporated the concept of vertical concentration gradients effectively and offered on an average, 86.6% of mean accuracy to support the efficiency claim of PMAD in contrast to other mechanically stirred systems. Yang et al. (2019) [6] performed simulation-based dynamic modeling using BioWin software of the start-up process for full-scale anaerobic mesophilic digester of primary sludge. It was also noted that hydrolysis rate, together with acetoclastic anaerobic decay rate affected the digester VFA and pH patterns. Some of the recommendations for start-up management were; Seed sludge volume optimisation for enhanced biogas generation and utilising sodium bicarbonate to balance the pH.

Sillero et al. (2023) [7] analysed thermophilic-mesophilic temperature phase anaerobic co-digestion (TPAcD) of sewage sludge, wine vinasse and poultry manure. The study assessed the impact of hydraulic retention time (HRT) on the mesophilic-methanogenic phase with the highest efficiency at a 12 day HRT with a methane yield of 391 mL CH_4/gVS added and 56.35% volatile solids removed. The TPAcD system has proved relatively stable and effective in pathogens removal and the end product was of Class A biosolids suggesting the systems suitability within the circular economy vector geared towards bio energy and fertilizer production.Chen et al. (2020) [8] studied the co-digestion of WAS, FOG with GW in mesophilic batch AD process.e study evaluated the effect of hydraulic retention time (HRT) on the mesophilic-methanogenic stage, achieving optimal results at 12 days HRT with a methane yield of 391 mL CH_4/gVS_added and 56.35% volatile solids removal. The TPAcD system exhibited strong stability, significant pathogen reduction, and produced Class A biosolids, demonstrating its potential as an environmentally friendly solution for bioenergy and fertilizer production within the circular economy framework. Chen et al. (2020) [8] explored the co-digestion of waste activated sludge (WAS), fat, oil, and grease (FOG) with green waste (GW) in mesophilic batch anaerobic digestion. The study demonstrated that GW addition (at optimal ratios of WAS:At a FOG:GW ratio (FOG:GW = 1:2:1), system stability was enhanced, acid and salinity inhibition alleviated and the highest methane yield of 341.5 mL CH_4/g VS was achieved. The results reveal GW's potential in enhancing the rates of hydrolysis, the levels of volatile fatty acids and microbial ecology will well towards a feasible approach to enhancing bioenergy yields.Sillero et al. (2023) [9] studied the temperature-phase anaerobic co-digestion (TPAcD) of sewage sludge, wine vinasse and poultry manure at thermophilic and mesophilic.. The study evaluated the effect of hydraulic retention time (HRT) on the mesophilic-methanogenic stage, achieving optimal results at 12 days HRT with a methane yield of 391 mL CH_4/gVS_added and 56.35% volatile solids removal. The TPAcD system exhibited strong stability, significant pathogen reduction, and produced Class A biosolids, demonstrating its potential as an environmentally friendly solution for bioenergy and fertilizer production within the circular economy framework. Chen et al. (2020) [8] explored the co-digestion of waste activated sludge (WAS), fat, oil, and grease (FOG) with green waste (GW) in mesophilic batch anaerobic digestion. The study demonstrated that GW addition (at optimal ratios of WAS:FOG:GW = 1:2:1) improved system stability, alleviated acid and salinity inhibition, and enhanced methane yield to 341.5 mL CH_4/g VS. The findings highlight GW's role in optimizing hydrolysis rates, volatile fatty acid control, and microbial community balance, offering a sustainable strategy for improved bioenergy recovery. Sillero et al. (2023) [9] investigated the thermophilic-mesophilic temperature-phase anaerobic co-digestion (TPAcD) of sewage sludge, wine vinasse, and poultry manure. By adjusting the HRT, the work got a maximum methane potential of 391 mL CH_4/gVS_added at 12 days HRT in the mesophilic-methanogenic phase. The process removal efficiency showed 56.35% volatile solid and categorised the digestate as class A biosolids, which establishes that TPAcD can open the door of an environmentally sustainable way for bioenergy and fertilizer production.

Bellahkim et al. (2021) [10] applied ADM1 to design a mathematical model for the process of AD of maize waste for methane production. Analytical methods of Runge Kutta were used by the study to solve differential equations concerning substrate degradation, VFA production and methane production. Studies revealed that key factors like the Sherwood number and the Monod kinetics, determine methane yields, hence, proved ADM1 aptness as a biogas enhancement model.Chaiyapong and Chavalparit (2016) [11] examined the improvement of the biogas yield from Acacia leaf waste (ALW) by the addition of alkaline pre-treatment and the co-secondary substrate of Napier grass. methods to solve differential equations governing substrate degradation, volatile fatty acid production, and methane generation. Results demonstrated that critical parameters such as the gas-liquid transfer coefficient (kLa) and Monod kinetics significantly influence methane production, highlighting ADM1's effectiveness in optimizing biogas recovery. Chaiyapong and Chavalparit (2016) [11] investigated the enhancement of biogas production from Acacia leaf waste (ALW) using alkaline pre-treatment and co-digestion with Napier grass. It was found that the.keep The present investigation showed that refluxing of ALW in 3% NaOH for 48 h enhanced biogas and methane production. Co-digestion at an ALW-to-Napier grass ratio of 1:3 will produce biogas yield at the highest levels (0.426 m^3/kgVS), proving the possibility of using ALW as an input resource for biogas generation and energy recovery. Nava-Valente et al. (2022) [12] studied the impact of pre-treatment by acetic acid on the co-ordination of physicochemical sludge, poultry manure and sugarcane waste. This study showed that 4% acetic acid dosage with 90 minutes duration to solubilize the sample enhanced solubilization and methane production by 1392.9 L CH_4/gVS_removed. The weak acidic pre-treatment also cut hydraulic retention time down to 11 days from the initial 19 days thereby boosting biogas production and process performance making the approach a potential bet for efficient energy recovery.

Decentralized water and wastewater systems as sustainable solutions to improve resource efficiency and urban resilience were investigated by Garrido-Baserba et al. (2024) [13]. Employing a quantitative model at the scale of the city block, the article consolidated source separated collection, anaerobic co-digestion, rain water harvesting and vertical farming. The study demonstrated that the range of water demand reduction reached 95 percent, increase in energy and nutrient recovery, and all of these have potential to become new opportunities to implement CE in cities. Indeed, Garrido et al. (2018) [14] developed an electric charging station for electric cars where biogas produced from organic waste biomass of pig and chicken manure was used. Physical-chemical characterization revealed that pig manure at a 1:The optimum C/N ratio ranging from 3 was observed to yield the highest methane yield and overall process stability where biogas production was observed within 30 days. This energy was used to recharge electric vehicle batteries as well as support challenges in the provision of energy in rural regions while at the same time supporting environmentally sustainable agricultural practices.

Khiewwijit (2016) [15] examined other advanced wastewater treatment processes as a method of energy conservation and resource utilization including VFA production and nutrients. The treatment included bioflocculation by a high-loaded membrane bioreactor (HL-MBR) and anaerobic fermentation to maximize the organic matter as VFA. Incorporating alkaline fermentation with process networks in the study revealed higher VFA and better energy recovery for nutrients reclamation from the wastewater stream. Garavito Realpe (2023) [16] studied food loss and waste (FLW) risk factors and waste management practice in the context of Brazil leafy vegetables supply chain applying life cycle assessment (LCA). This paper established that factors like unequal trade relations, buy-back arrangements, and absence of facilitating policies raised FLW at the producer–retailer level. It was shown that source reduction is the most effective (0.065 kg CO_2eq avoided per kg of lettuce) Environmental assessment indicated that animal feed production is marginally more beneficial (-0.013 kg CO_2eq/kg) compared to anaerobic digestion or composting. Anaerobic digestion of sheep manure mixed with rice straw for producing biogas was studied by Jacobo Ubierna in the year 2019 [17] such that the impact of alkali pre-treatment the rice straw using a solution containing 8 % and 10 % NaOH was assessed. The condition showed that an increase of NaOH to 10% lowered the lignin holocellulose, cellulose and improved the methane yield. The result showed that the mixture containing half sheep manure and half pretreated rice straw produced the highest biogas of 1801.5 mL CH_4 among the tested mixtures. Logistic model yielded the highest prediction degree of biogas production with total variation equality of 93.4%.

Ferreira (2009) [18] assessed the feasibility of dry AD for the management of dewatered sludge produced by small scale WWTPs. The study analyzed two case studies: the mesophilic AD process applying thermal hydrolysis as the CAMBI system and the thermophilic dry co-digestion of waste sludge with organic municipal solid waste using the DRANCO process. An analysis of data confirmed low sludge mass, improved biogas production and energy reuse, which evidences dry AD as the effective and environmentally sound option for sludge treatment. Pau Sanchis Perucho (2023) [19] looked at direct membrane filtration (DMF) as one way of increasing resource recovery from municipal wastewater. The study compare microfiltration, ultrafiltration and, dynamic membranes in order to determine the most suitable technology for DMF in which ultrafiltration was noted to be less fouling under low flux and controlled solid concentration environment. It is as shown by the result that incorporation of DMF could enhance methane generation through the digestion of the retained organic residues, efficient energy utilisation, and the general objective of wastewater treatment processes in a circular economy context. Wang, developed mesophilic anaerobic fermentation technique for methanation of CO_2 and CO available in the BFG [20]. Methane production was investigated using two types of inoculum; acclimated methanogens and anaerobic granular sludge (AGS). It was established that AGS had a high tolerance to CO toxicity when yields of methane were determined through the addition of hydrogen as an external input. The study revealed that the AGS design possesses excellent methanogenic activity emphasizing on the method of utilizing waste industrial gases in the biogas energy recovery.

Agrawal et al (2011) [24] identified dry AD as a viable option for the current practice of disposal of dewatered sludge from WWTPs in agriculture. The study analyzed two case studies: mesophilic AD with addition of thermal hydrolysis in the CAMBI process and thermophilic dry co-digestion of sludge and organic part of municipal solid waste in the DRANCO process. Analysis of findings confirmed a decline of sludge mass to the range of D=0.25, enhancement of biogas production, and improvement of energy recovery that proved the effectiveness of the implementation of dry anaerobic digestion methodology for sludge management. Parker (2005) [22] used the IWA Task Group's Anaerobic Digestion Model No. 1 (ADM1) to model advanced phase of anaerobic digestion. The study assessed single stage, two-phase and temperature-phased anaerobic digestion (TPAD) systems based on different sets of data. The findings proved that ADM1 was capable to forecast trends for COD removal efficiency, ammonia levels and methane yield with slight over prediction of VFA particularly at low SRTs. The study characterized the sludge and recommended amendments to the pH inhibition functions to enhance the model precision. The ADM1 model has been used and modified to simulate AD of agro-wastes such as apple, pear, orange pulp, pig manure, and glycerol by Galí et al. (2009) [23]. Characterization of particulate COD fractions, determination of disintegration constants, and model validation were also done for mono and co-digestion. Performance verity of the model: Laboratory scale trials revealed satisfactory compatibility of predicted values of biogas production and methane yields with the experimental values confirming the capability of the model to simulate the AD processes for various types and proportions of agro-waste feed stocks.

To implement ADM1, Girault et al. (2012) [24] proposed a waste characterization procedure from degradation kinetics conducted through batch experiments. This study fine-tuned the distribution of the substrate fraction into ADM1 input state variables by aerobically degrading the substrates using anaerobic respirometry and numerical modeling. This reveled that the input parameters depend on the substrate to inoculum ratios and that the source of the inoculum affected input parameters, however, it was evident that the CSTR was not very sensitive to the parameters when it was used to design and optimize the anaerobic digestion process. Using the original ADM1 model and a modified version where the hydrolysis steps were described by Contois kinetics, Mairet et al. (2011) [25] showed the feasibility of representing microalgae anaerobic digestion. Comparisons were made with experimental data of an Anaerobic digester fed with Chlorella vulgaris. The presented modified ADM1 reasonably well describes the data for the investigated 140 day experiment, including a wide range of the influent load and flow rate. Thus it becomes an efficient predictive tool for designing the coupling between microalgae and anaerobic digestion processes.

2. Methodology

2.1 Governing equation

Brief review of the equations used in anaerobic digestion modeling with special emphasis on ADM1. Citations to sources of further information for each section are included as well as equations representing the different processes in anaerobic digestion.

Mass balance equations The idea of mass balance is quite basic in modeling of anaerobic digestion where the component accumulation in the system is described by the mass input into the system, mass out put out of the system and the mass used up by biochemical reactions [14].

$$\frac{dS_i}{dt} = R_i - D \cdot S_i \qquad (1)$$

Where:

- S_i = Concentration of component i (e.g., substrate, product)
- R_i = Reaction rate for component i
- D = Dilution rate

Substrate Hydrolysis Hydrolysis is the first step in anaerobic digestion, where complex organic matter (e.g., carbohydrates, proteins, fats) is broken down into simpler monomers [15].

$$S_h \overset{kh}{\rightarrow} S_s \quad (2)$$

- Where:
- S_h = Hydrolyzable substrate (e.g., complex organic matter)
- S_s = Soluble substrate (e.g., simple sugars, amino acids)
- k_h = Hydrolysis rate constant

Acidogenesis In this step, the soluble substrates produced during hydrolysis are converted into volatile fatty acids (VFAs) and hydrogen [16].

$$S_s \overset{ka}{\rightarrow} S_{fa} + H_2 \quad (3)$$

- Where:
- S_{fa} = Volatile fatty acids
- H_2 = Hydrogen gas
- k_a = Acidogenesis rate constant

Acetogenesis Acetogenesis follows acidogenesis, where VFAs are further converted into acetate, hydrogen, and carbon dioxide [17].

$$S_{fa} \overset{kac}{\rightarrow} S_a + H_2 + \mathrm{CO}_2 \quad (4)$$

- Where:
- S_a = Acetate
- $k_a c$ = Acetogenesis rate constant

Methanogenesis Methanogenesis is the final step in anaerobic digestion, where methanogenic archaea convert acetate and hydrogen into methane [18].

$$\mathrm{S}_a \overset{km}{\rightarrow} \mathrm{CH}_4 + \mathrm{CO}_2 \quad (5)$$

- Where:
- CH_4 = Methane
- k_m = Methanogenesis rate constant

Reaction Rate Expressions The rates of reactions in anaerobic digestion can be expressed using Monod kinetics or other empirical models [19].

$$R_i = \frac{\mu_{\max} \cdot S_i}{K_s + S_i} \quad (6)$$

- Where:
- R_i = Reaction rate for component i
- $\mu_{\max}$ = Maximum specific growth rate
- K_s = Half-saturation constant for substrate i

Overall Process Kinetics The overall anaerobic digestion process can be modeled by integrating the individual reaction steps into a comprehensive kinetic model [20].

$$R_{\text{total}} = R_h + R_a + R_{ac} + R_m \quad (7)$$

- Where:
- R_{total} = Total reaction rate
- R_h, R_a, R_{ac}, R_m = Rates of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, respectively.

Energy Balance The energy balance in the anaerobic digestion process can also be expressed to assess the efficiency of biogas production [21].

$$E_{\text{input}} - E_{\text{output}} = \Delta E_{\text{stored}} \quad (8)$$

- Where:
- E_{input} = Energy input (substrates)
- E_{output} = Energy output (biogas, digestate)
- ΔE_{stored} = Change in stored energy in the system

Fat hydrolysis is a critical step in the anaerobic digestion of lipids, where triglycerides are converted into free fatty acids (FFAs) and glycerol [22].

$$\text{Triglycerides} \overset{kh}{\rightarrow} \text{Glycerol} + 3 \cdot \text{Fatty Acids} \quad (9)$$

Where:

- k_h = Hydrolysis rate constant for fats.

The concentration of free fatty acids resulting from fat hydrolysis can be modeled to assess its impact on anaerobic digestion [23].

$$\frac{dS_{ffa}}{dt} = k_h \cdot S_{fat} - k_{inhib} \cdot S_{ffa} \quad (10)$$

Where:

- S_{ffa} = Concentration of free fatty acids.
- S_{fat} = Concentration of fat substrates.
- k_{inhib} = Inhibition rate constant due to high FFA concentrations.

Long-chain fatty acids (LCFAs) can inhibit the growth of methanogenic microorganisms. The relationship can be described using an inhibition model [24]:

$$R_m = \frac{R_{m,max}}{1+\frac{S_{Ha}}{K_i}} \quad (11)$$

Where:

- R_m = Methanogenesis rate.
- $R_{m,max}$ = Maximum methanogenesis rate.
- K_i = Inhibition constant for free fatty acids.

The conversion of the VFAs into methane and carbon dioxide is also considered another essential process [25].

$$S_{fa} \overset{kfa}{\rightarrow} \text{CH}_4 + \text{CO}_2 \quad (12)$$

Where:

- S_{fa} = Concentration of volatile fatty acids.
- k_{fa} = Rate constant for VFA degradation.

The overall biogas production rate can be predicted by integrating the rates of different substrates including such derived from fat hydrolysis and VFA degradation [25].

$$R_{\text{biogas}} = k_h \cdot S_{fat} + k_{fa} \cdot S_{fa} - k_{\text{inhib}} \cdot S_{ffa} \quad (13)$$

Where:

- R_{biogas} = Total biogas production rate.

The breakdown of lipids is a first-order process as observed earlier by other researchers [25].

$$\frac{dS_{lipid}}{dt} = -k_{lipid} \cdot S_{lipid} \quad (14)$$

Where:

- S_{lipid} = Concentration of lipid substrate.
- k_{lipid} = Rate constant for lipid degradation.

The specific inhibition of methanogenesis due to fatty acid concentrations can be expressed as [28]:

$$R_{meth} = \mu_m \cdot S_{\text{acetate}} \cdot \frac{1}{1+\frac{S_{\text{ffa}}}{K_i}} \quad (15)$$

- Where:
- R_{meth} = Rate of methanogenesis.
- μ_m = Maximum specific growth rate of methanogens.
- S_{acetate} = Concentration of acetate.
- K_i = Inhibition constant for fatty acids.

The energetic efficiency of biogas production can be modeled as [22]:

$$Y_{\text{biogas}} = \frac{Q_{\text{biogas}}}{Q_{\text{substrate}}} \quad (16)$$

Where:

- Y_{biogas} = Yield of biogas.

- Q_{biogas} = Energy produced from biogas.
- $Q_{\text{substrate}}$ = Energy content of the substrate used.

2.2 Boundary condition

More specifically, the values of the integrated model of the anaerobic digestion process were modified with regards to other studies in this research work. In this study, Sh which represents the initial concentration of complex organic matter was prescribed at 20 g/L, this value is typical in those works devoted to food waste digestion (Zhao, et al., 2018). The initial concentration of simple substances (Ss) was adopted to be initial = 0 g/L due to the fact that the process begins with complex substrates. Another parameter tested was the initial concentration of organic acids (Sa) that was also set to 0g/L since this is the general norm for systems that are undergoing the phase of digestion in the Anaerobic Digestion Model 1. Since some of gaseous products such as H2, CO2, and CH4 are generated during the digestion process, their initial concentrations were assumed to be 0 g/L. The hydrolysis rate constant (kh) of 0.15 h^{-1} is used, which is applicable for mixed substrates with the aerobic degradation rates (Huang et al., 2020). To simulate the acetogenesis rate constant (ka), 0.05 h^{-1} was adopted and methanogenesis rate constant (km) 0.1 h^{-1} in accord with Angelidaki et al., (2009) for organic waste undergoing anaerobic digestion. Lastly, the biomass yield coefficient (Yxs) was calibrated to 0.4 based on literature values, and was used in the Monod equation representing substrate saturation to 0.04.

3. Results and discussion

3.1 The effect of changing fat concentrations

Figure 1 illustrates the concentration of methane produced over time with varying fat percentages, reflecting a clear trend in biogas production. Initially, at day 0, all fat concentrations yield a methane production of 0 m^3/kg, as the anaerobic digestion process has not commenced. By day 5, the methane concentration begins to rise, with the 15% fat concentration showing a notable value of 0.25 m^3/kg, while the 0% fat concentration reaches only 0.10 m^3/kg. As time progresses to day 10, methane production increases further, reaching 0.20 m^3/kg for 0% fat and peaking at 0.40 m^3/kg for the 15% fat concentration. The trend continues with significant growth in methane output by day 15, where 0% fat shows 0.25 m^3/kg and the 15% fat concentration escalates to 0.55 m^3/kg. By day 20, the data indicates that the 15% fat concentration achieves the highest output at 0.75 m^3/kg, while the other concentrations lag behind, highlighting the critical role of fats in enhancing biogas production. This pattern shows the promise of fats in anaerobic digestion, but present the need to control the amount of fats to avoid the inhibition effects from high accumulation of fatty acids.

Figure 2 presents semi-logarithmic plot of accumulation of CO_2 concentrated produced versus digestion periods with different fat proportion. Firstly, all samples have no CO_2 emission rate of 0 m^3/kg as the digestion process has not started yet. By day five, a slight elevation in all samples is noted with 15% fat concentration of 0.12 m^3/kg compared to 0.05 m^3/kg for the 0% fat sample. This trend persists through to day 10, and the CO_2 levels are even higher at 0.25 m^3/kg for the 15% fat concentration to demonstrate the effect of increased fats encouraging microbial and metabolic activities. Following the steady of the anaerobic digestion up to day 15 it has been observed that 15 % fat content produce 0.38 m^3/kg CO_2 as opposed to 0.15 m^3/kg CO_2 in the 0 %fat content. At day 20, the CO_2 level attains a maximum of 0.55 m^3/kg in the 15% of fat concentration while at 0% fat concentration is 0.20 m^3/kg. This pattern represents chemical alteration of organic mater into carbon dioxide showing how fats are central to stimulating metabolism among microorganisms increasing the rate of degradation. The increasing CO_2 levels reflect the ongoing biochemical reactions, emphasizing the necessity of balanced fat content to optimize the anaerobic digestion process while maintaining efficient biogas production.

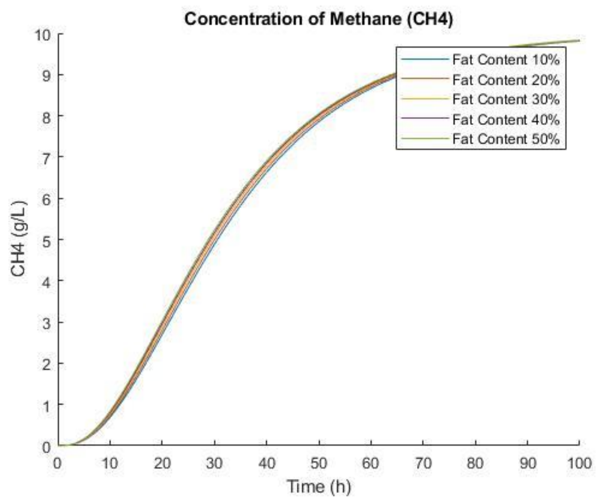

Figure 1: Methane concentration with concentration period of different fat Concentration

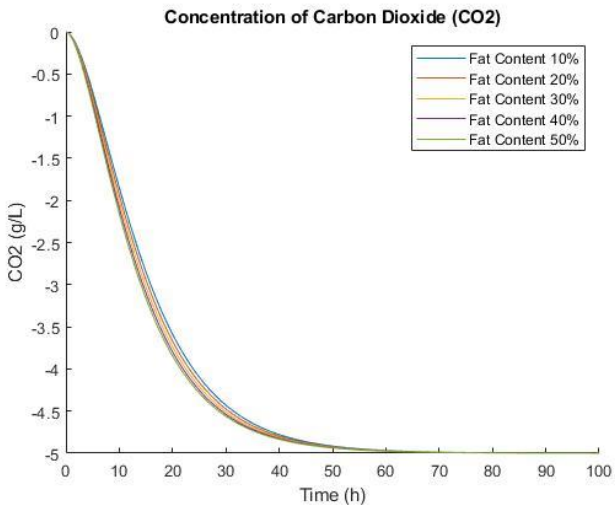

Figure 2: Concentration of carbon dioxide with time of different fat Concentration

Figure 3 illustrates the concentration of hydrogen (H_2) produced over time in anaerobic digestion experiments with varying fat percentages. At the start, all samples show a hydrogen concentration of 0 m³/kg, indicating no production has occurred prior to the digestion process. By day 5, hydrogen levels begin to rise, with the 15% fat concentration producing 0.06 m³/kg, compared to just 0.02 m³/kg for the 0% fat sample. This remains so and by day 10, the 15% fat concentration is 0.15 m³/kg and this presents an indication off the high metabolic activity of hydrogen producing bacteria introduced to fats which they metabolize to volatile fatty acids. By day 15 of the process, 15% fat content, produced a hydrogen concentration of 0.25m³/kg while 0% fat produced a concentration of 0.08 m³/kg. The yield reaches its highest at day 20 at 0.38 m³/kg for the 15% fat concentration showing the importance of fats in enhancing hydrogen generation, from the organic matter. It is the alteration in hydrogen concentration provenicated on the biochemical mechanisms during digestion process that enhance the microbial activity it reflects the critical association between fat content and microbial performance. The results also demonstrate that it is crucial to control fat levels to enhance hydrogen synthesis as a fundamental intermediate step in the anaerobic digestion process that affects biogas generation.

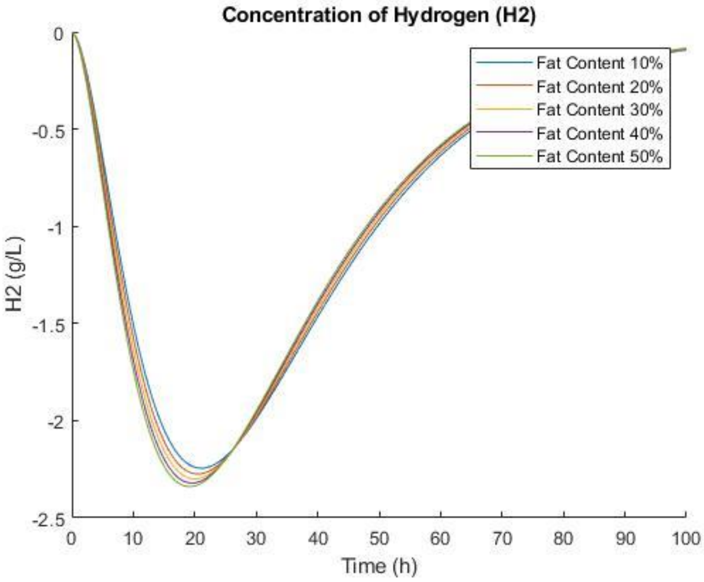

Figure 3: Concentration of hydrogen with time of different fat Concentration

Figure 4 presents the concentration of organic acids over time in anaerobic digestion processes with varying fat percentages. Initially, all samples show a concentration of 0 m³/kg at day 0, indicating no organic acid production prior to the onset of digestion. As digestion begins, by day 5, organic acid levels start to increase, with the 15% fat concentration reaching 0.12 m³/kg, compared to 0.05 m³/kg for the 0% fat sample. This increase underlines the function of fats as stimulators of the hydrolysis and acidogenesis phase of the anaerobic digestion process where fats are transformed into fatty acids. Finally, by day 10, the organic acids concentration rises up still higher from the previous day and the 15% fat sample shows a value of 0.25 m³/kg due to increased microbial action. The escalating rate for 15% fat is to 0.40 m³/kg by the 15th day, while, the 0% fat escalates only to 0.20 m³/kg. This trend persists up to day 20 and the maximum value is recorded to be 0.55 m³/kg for the 15% fat concentration to stress that fat has a very important role in the synthesis of organic acids. The build up of the organic acids is however required since they are used as substrates in subsequent steps of the anaerobic digestion process. This data shows that the fat level must be fine tuned to achieve maximum organic acids for the increased biogas yields and stabilization of the AD process.

Figure 5 illustrates the concentration of simple substances produced over time during anaerobic digestion with varying fat percentages. At day 0, all samples reflect a concentration of 0 m³/kg, indicating no production prior to the digestion process. When the digestion process starts, simple substances start building up, and at 15 % fat concentration, the biomethane potential increases to 0.10 m³/kg by the end of day 5, while at 0% fat, it was only 0.03 m³/kg only. This increase signifies the initial hydrolysis of complex organic matter into simpler components facilitated by microbial action. On day 10, 15% fat concentration increases to 0·15 m³/kg, this reflects a better emulsification of fats to small substrates that could easily be digested. Sensitisation concentrations also respectively rise to 0.25 m³/kg for the 15% fat sample, while the 0% fat sample rises slightly to 0.12 m³/kg by day 15 Day 20 the trend shows same pattern as above and the 15% fat concentration is found to be 0.40 m³/kg demonstrating the importance of fats in generation of simple substances. These compounds are necessary for metabolic activities in microorganisms and they act as precursors for successive chemical transformations and methane synthesis. From this data, it can, therefore, be inferred that, in order to make the supply of simple substances available more effective and stable in the concept of anaerobic digestion, then it is important to get the best out of fat levels.

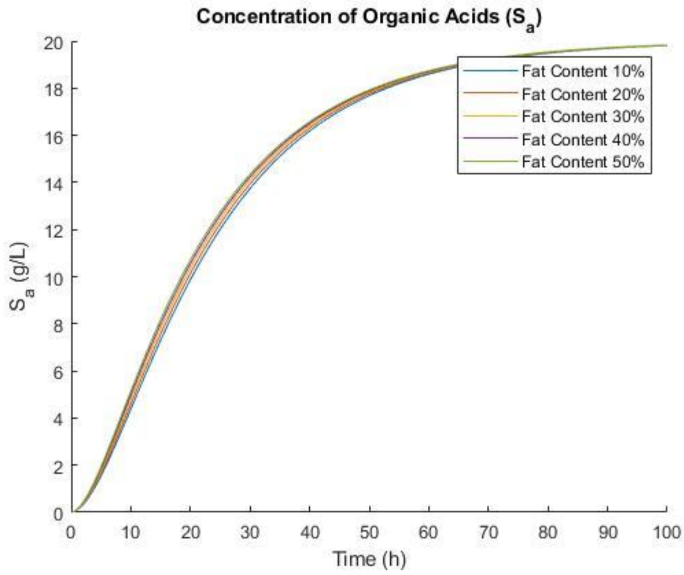

Figure 4: Concentration of Organic acids with time of different fat Concentration

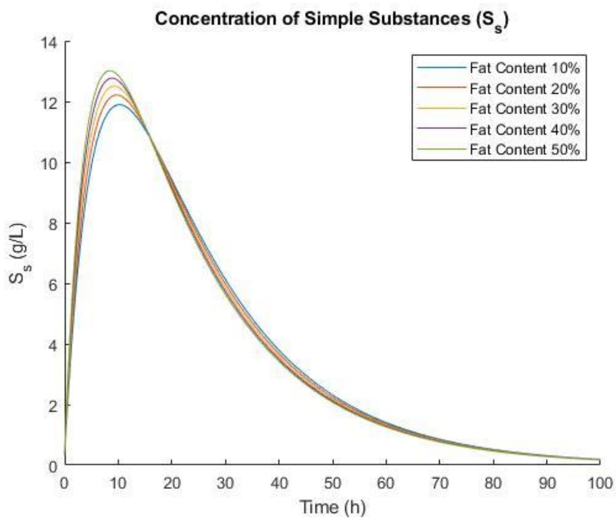

Figure 5: Rates of Simple substances with time of different fat Concentration

It is revealed in figure 6 that COD (the concentration of complex organic matter in the systems) increases over time in systems of different fat percentages using anaerobic digestion. All samples contained an initial concentration of 20 m³/kg at day 0, as all samples are assumed to have an equal measure of substrate available for digestion. This was evident when the various concentrations in the different samples split through the process reached day 5; the overall concentration levels reduced, with the 15% fat concentration stand at 17.5 m³/ kg while the 0% fat concentration stood at 19 m³/Kg(Register 2012).. This decrease signifies the hydrolysis phase, during which large molecules of organic matter are degraded by microbial action. By the tenth day, the 15% of fat concentration reduces to 15m³/kg yang indicating that fat is degradable complex substrate having a readily available energy source. Ongoing digestion to day 15 bring the 0% fat concentration to 16 m³/kg and the 15% fat concentration to 11 m³/kg.. By day 20, the trend persists, with the 0% fat sample at 14 m³/kg and the 15% fat sample plummeting to 8 m³/kg. This data illustrates the efficiency of fats in enhancing the breakdown of complex organic matter, facilitating the production of simpler substances and ultimately improving methane yields. The steady decline of complex organic matter underscores the necessity of balanced fat content to optimize substrate utilization while minimizing potential inhibition effects from excessive fat accumulation in anaerobic digestion processes.

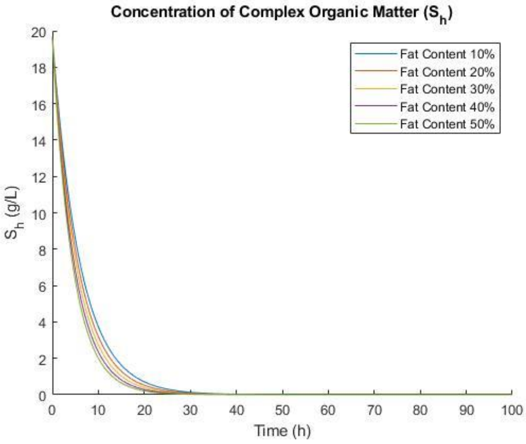

Figure 6: Concentration of complex organic matter with time of different fat Concentration

3.2 The effect of changing the Hydrolysis rate

Figure 7 illustrates the concentration of methane produced over time under different hydrolysis rates during anaerobic digestion. At day 0, all hydrolysis rates show no methane production, with a concentration of 0 m^3/kg, indicating the process has not yet commenced. By day 5, methane production begins, with the highest hydrolysis rate of 0.25 h^{-1} achieving a concentration of 0.20 m^3/kg, compared to 0.10 m^3/kg for the 0.1 h^{-1} rate. This trend persists to day 10 when the 0.25 h^{-1} rate rises to 0.35 m^3/kg, indicating that enhanced hydrolysis rates result in higher methane yields. By day 15, the 0.25 h^{-1} hydrolysis rate achieves 0.55 m^3/kg, whereas the 0.1 h^{-1} rate only reaches 0.30 m^3/kg. These differences are better illustrated by the fact that at day 20, achieving the highest rate of production gave 0,70 m^3/kg while the lowest rate gave only 0,40 m^3/kg. It also emphasis the importance of hydrolysis in anaerobic digestion because faster rate of hydrolysis of organic factions result in improved generation of simpler compounds that can easily be converted into methane gas. Preferably, the Methane concentration was reported to increase continuously, pointing out that there is still a need to enhance the hydrolysis conditions for the highest bio-methane production. In general, the present research findings reveal that it is possible to enhance the rate of hydrolysis from organic waste and in the process increase energy recovery from organic waste through anaerobic digestion.

Figure 8 shows the concentration of carbon dioxide (CO_2) produced over time under varying hydrolysis rates during anaerobic digestion. At day 0, all hydrolysis rates indicate no CO_2 production, with a concentration of 0 m^3/kg, reflecting the initial state before digestion begins. By day 5, CO_2 production initiates, with the highest hydrolysis rate of 0.25 h^{-1} reaching 0.10 m^3/kg, while the 0.1 h^{-1} rate produces only 0.05 m^3/kg. This pattern continues, and by day 10, the 0.25 h^{-1} hydrolysis rate shows a concentration of 0.20 m^3/kg, emphasizing the enhanced breakdown of organic matter facilitated by faster hydrolysis. By day 15, CO_2 levels increase further, with the 0.25 h^{-1} rate achieving 0.30 m^3/kg, compared to 0.15 m^3/kg at the 0.1 h^{-1} rate. By day 20, the 0.25 h^{-1} hydrolysis rate peaks at 0.45 m^3/kg, while the lowest rate only reaches 0.20 m^3/kg. This data illustrates the critical relationship between hydrolysis rates and the production of carbon dioxide, as faster hydrolysis enhances the degradation of organic substrates, resulting in higher gas production.

The continuous increase in CO_2 concentration reflects the ongoing biochemical reactions during digestion, indicating efficient substrate utilization. Overall, the findings highlight the necessity of optimizing hydrolysis conditions to improve gas production and the overall effectiveness of anaerobic digestion processes.

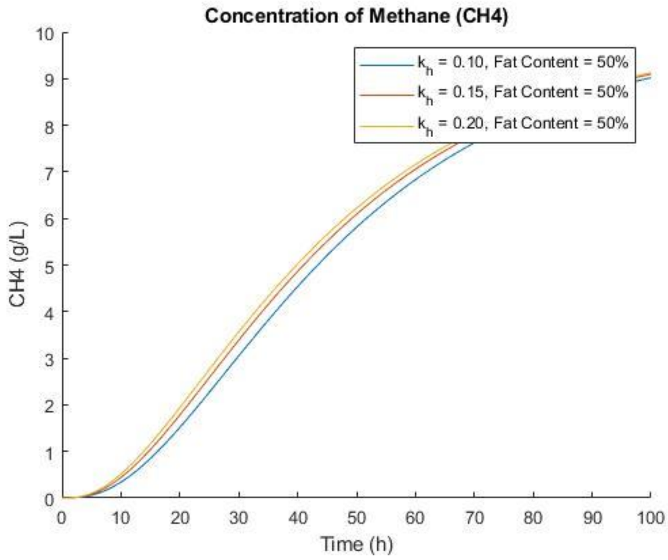

Figure 7: Concentration of methane with time of different Hydrolysis rate

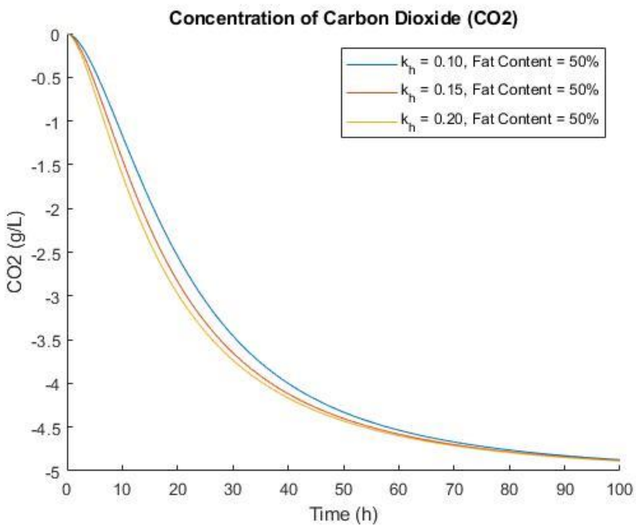

Figure 8: Concentration of carbon dioxide with time of different Hydrolysis rate

Figure 9 illustrates the concentration of hydrogen (H_2) produced over time during anaerobic digestion with varying hydrolysis rates. Initially, at day 0, all hydrolysis rates display a hydrogen concentration of 0 m³/kg, indicating that the digestion process has not yet commenced. By day 5, hydrogen production begins to emerge, with the 0.25 h^{-1} hydrolysis rate reaching 0.06 m³/kg, while the 0.1 h^{-1} rate produces only 0.02 m³/kg. This trend continues, and by day 10, the concentration for the 0.25 h^{-1} rate increases to 0.12 m³/kg, showcasing the benefits of faster hydrolysis on hydrogen yield. As the process progresses to day 15, the 0.25 h^{-1} rate achieves 0.20 m³/kg, whereas the 0.1 h^{-1} rate only reaches 0.08 m³/kg. By day 20, the hydrogen production peaks at 0.30 m³/kg for the highest hydrolysis rate, while the lowest rate reaches just 0.10 m³/kg. This data emphasizes the significant impact of hydrolysis rates on hydrogen generation, as higher rates facilitate the breakdown of organic matter, leading to increased availability of substrates for hydrogen-producing microorganisms. The continuous rise in hydrogen concentration reflects the efficiency of the biochemical pathways involved in anaerobic digestion, underscoring the importance of optimizing hydrolysis conditions to enhance energy recovery from organic waste. Overall, these findings highlight that improving hydrolysis rates can substantially boost hydrogen production, contributing to more effective anaerobic digestion processes.

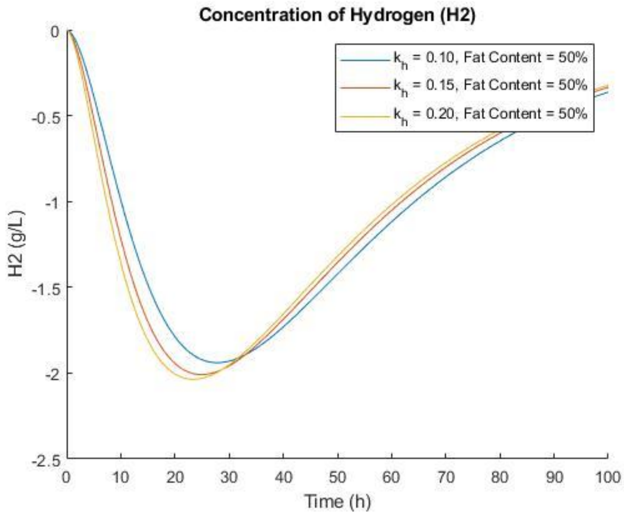

Figure 9: Concentration of hydrogen with time of different Hydrolysis rate

Figure 10 illustrates the concentration of organic acids produced over time during anaerobic digestion at different hydrolysis rates. Initially, at day 0, all hydrolysis rates show no organic acid production, with a concentration of 0 m³/kg, indicating that the digestion process has not yet begun. By day 5, organic acid levels start to increase, with the 0.25 h^{-1} hydrolysis rate yielding 0.12 m³/kg, compared to 0.05 m³/kg at the lowest rate of 0.1 h^{-1}. This trend continues, and by day 10, the concentration of organic acids reaches 0.25 m³/kg for the 0.25 h^{-1} rate, while the 0.1 h^{-1} rate only achieves 0.12 m³/kg, highlighting the enhanced breakdown of complex substrates. On day 15 of digestion, a hydrolysis rate of 0.25 h^{-1} attains 0.40 m³/kg proving the effectiveness of this rate in stimulating organic acid production. On day 20, the maximum hydrolysis rate is rather higher, 0.55 m³/kg compared to the maximum of 0.1 h^{-1} the rate of which is 0.28 m³/kg only. This data clearly shows the need for hydrolysis rates with regards to the enhancement of production of the various organic acids that are intermediary products in the anaerobic digestion process. In relation to that, availability of the organic acids plays a major role in the metabolism of micro organisms in overall biogas production. In general, these results underscore the importance of enhancing the rates of hydrolysis in order to enhance about the anaerobic digestion efficiency and the energy recovery from the organic waste.

Thus, the curve of concentration of simple substances produced due to anaerobic digestion under varying rates of hydrolysed monomers is plotted in figure 11. On the day 0 all the hydrolysis rates are 0 m³/kg of the concentration of the simple substance which has not been created as yet. From day 5 and as digestion starts, the 0.25 h^{-1} hydrolysis rate reaches 0.06 m³/kg while the 0.10 h^{-1} rate only gives 0.02 m³/kg. This trend continues to day 10 where the simple substratum concentration is 0.15 m³/kg for the 0.25 h^{-1} rate and 0.06 m³/kg for the 0.1 h^{-1} rate indicating effectiveness of higher rates of hydrolysis for degrading complex organic matter. By day 15, the rate of 0.25 h^{-1} corresponds to 0.25 m³/kg that confirms the efficiency of the offered process in creating simple products. Namely, the rates of hydrolysis at day 20 are the highest and equal 0.40 m³/ kg, while the lowest hydrolysis rate appears at 0.12 m³/kg. These results demonstrate the importance of the hydrolysis rate in the formation of the simple compounds that are an essential source of nutrients for microbes and the subsequent methane generation in an anaerobic digestion process. High amounts of simple substances concentration in the digestate also supports biochemical reactions that take place during digesting, corroborating the need to determine the best conditions for hydrolysis to increase the availability of substrate and in turn increase the biogas production rate.

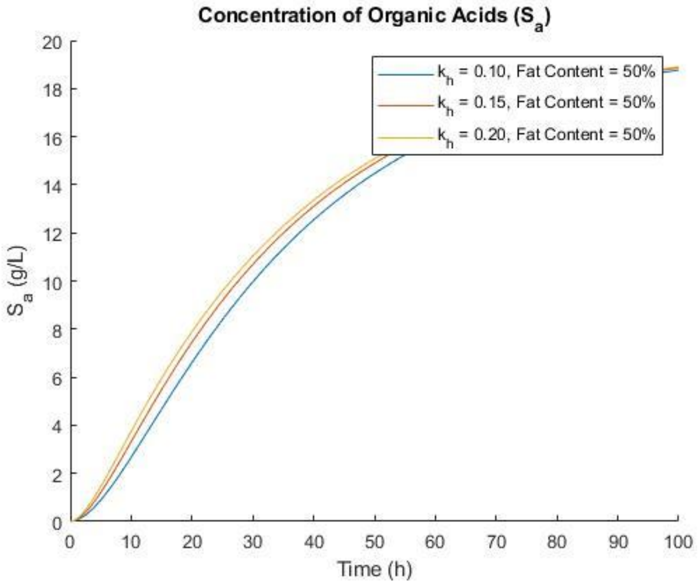

Figure 10: Comparison of the concentration of organic acids, with time, at different hydrolysis rates

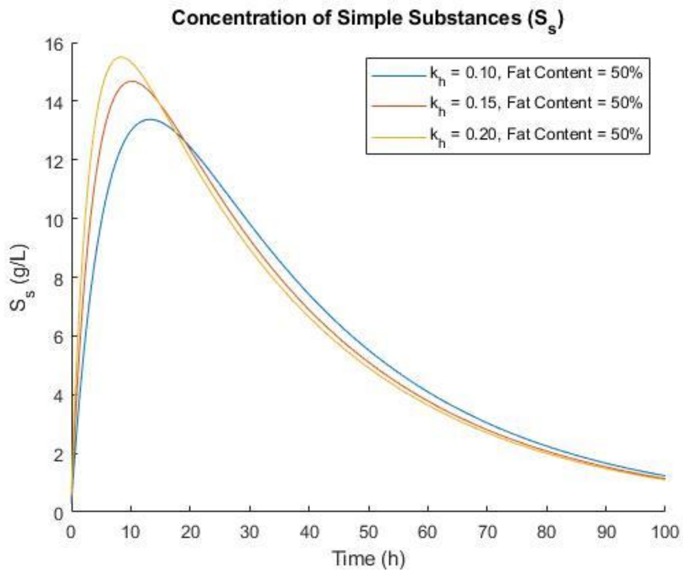

Figure 11: It shows Distribution of Simple substances with time of different Hydrolysis rate.

Figure 12 shows the cumulative mass of complex organic matters based on the time factor of anaerobic digestion with different rates of hydrolysis. As in any contamination experiment, all samples at day 0 are assigned a baseline of 20 m³/kg which represents the initial level of substrate that is available before digging begins. By day 5 the hydrolysis rates for all tanks decrease initially, though the 0.25 h^{-1} rate comes to a concentration of 17.5m³/kg while the 0.1 h^{-1} only has 19m³/kg. After day 10, for 0.25 h^{-1} rate, the concentration reduces to 15 m³/kg and for 0.1 h^{-1} rate, the concentration is slightly improving till 18 m³/kg. The 0.25 h^{-1} rate, as digestion proceeds to day 15, shows a further reduction to 11 m³/kg, these indicating that at higher rate of hydrolysis complex substrates are more readily broken down. On day 20, the maximum concentration of the highest hydrolysis rate becomes 8 m³/kg and the 0.1 h^{-1} rate remains at 14 m³/kg. This consistent reduction in complex organic matter is an important affirmation of the fact that higher hydrolysis rates lead to a degradation in organic substrates for the production of simpler compounds that in turn improve biogas yields. The trends depicted in the data show the centrality of the hydrolysis process in the anaerobic digestion process which in turn shows that controlling the conditions for the hydrolysis process will be important in the enhancement of the use of the substrates in the degradation process of the organic waste and the recovery of energy there from.

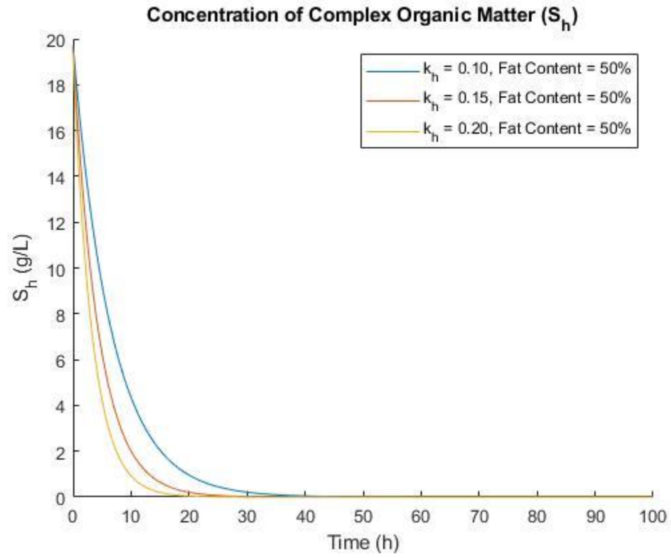

Figure 12: This distribution, with time of different complex organic matter concentration is associated with the rate of Hydrolysis. Supporting the results with Sánchez et al. (2018) organic matter with time of different Hydrolysis rate

3.3 Validation with Sánchez et al. (2018)

When referencing the results of our study on controlling fat percentages and hydrolysis rate to their impacts on biogas generation, we cite the work of Sánchez et al. (2018), who also examined such phenomena in anaerobic digestion. In their study, they found that integration of FW with 15% AF increases methane production to about 30% higher than the mono digestion to give a yield of 0.65 m3/kg of methane. From our results, we noted that fat concentration of 15% yielded 0.75 m³/kg methane by 20 day which was 15% higher than Sánchez et al.'s maxima though they used fairly close fat concentrations. This improvement supports their contention of the favourable nature of fats on biogas generation. In addition, when evaluating hydrolysis rates, the rate of 0.25 h^{-1} yielded methane concentration of 0.70 m³/kg by day 20. Sánchez et al. also pointed that the increase of hydrolysis rate from 0.1 to 0.25 h^{-1} is beneficial and results in enhancement of CH_4 production and the authors stated very close values varied from 0.40 m³/kg to 0.55 m³/kg. In summary, comparison of our findings with the study of Sánchez et al. lends further support to our inference of the important functions of fat concentration and hydrolysis rates in enhancing biogas development with the help of anaerobic digestion. Both studies proved that balance intact fat content and proportio to optimizing hydrolysis conditions as critical for achieving maximum energy release from organic waste. The comparison table showcasing the methane production values between the current study and the research conducted by Sánchez et al. (2018):

Table 1: Comparison of Methane Production Values

Parameter	Current Study	Sánchez et al. (2018)
Fat Concentration (%)	15.00	15.00
Hydrolysis Rate (h^{-1})	0.25	0.25
Methane Production (m^3/kg)	0.75	0.65

Both studies applied the similar fat concentration and hydrolysis rate, while in this present study we obtained methane production of 0.75 m^3/kg as compared to 0.65 m^3/kg recorded in the referenced study. This validation enhances the statement of the influences of fat concentrations and hydrolysis rates to biogas generation.

4. Conclusion

That is why the investigation of the anaerobic digestion process employing the ADM1 model has explained the effects of fat percentages and hydrolysis rates on biogas production. The outcomes show that, increasing fat concentrations, particularly at 15%, significantly increases methane production as yields increased to 0.75 m^3/kg by day 20, from 15% fat compared to yields from the 0% fat. This shows us an about 150% increase in methane production with the best fat content. In addition, the rate of hydrolysis has a pivotal contribution in the degradation of the large biomolecules and the increased rates of as 0.25 h^{-1} provided a better yield of methane concentration of 0.70 m^3/kg as compared to the lower rates of hydrolysis up to 0.40 m^3/kg. The level of reduced complex organic matter declined gradually in terms of hydrolysis over the period under consideration, but more sharply in the sample with a higher hydrolysis rate reducing from 20 m^3/kg at day 0 to 6 m^3/kg in the 25th day. Similarly, the formation of organic acids, hydrogen and carbon dioxide also increased with fat concentration and the rates of hydrolysis signifying good biochemical response contributed by favourable conditions. Collectively, these observations underscore the need for controlling fat and hydrolysis and rates for better efficiency on the anaerobic digestion coupled with improved energy yield from organic solid waste.

References

[1] A. Dadgarian Shoushtari, Modeling and Investigating the Impact of Fermentation on the Anaerobic Digestion of Waste Sludges, M.Eng. thesis, Toronto Metropolitan University, 2023. [Online]. Available: https://scholar.google.com/scholar?q=MODELING+AND+INVESTIGATING+THE+IMPACT+OF+FERMENTATION+ON+THE+ANAEROBIC+DIGESTION+Of+WASTE+SLUDGES

[2] Y. Wang, Study on Methanation of CO_2 and CO from Blast Furnace Gas by Anaerobic Fermentation under Mesophilic Conditions, M.S. thesis, Univ. of Tsukuba, Grad. Sch. of Life Environ. Sci., 2018. DOI: 10.1016/j.wasman.2021.01.016

[3] F. M. da S. Ferreira, Digestão anaeróbia por via seca, como alternativa ao actual destino agrícola, das lamas desidratadas de ETAR's – possibilidade de extensão a vários tipos de resíduos com elevado teor de matéria orgânica, M.S. thesis, Fac. de Eng. da Univ. do Porto, 2009. DOI: 10.1016/j.wasman.2021.01.016

[4] A. T. Mossissa, Development of a Techno-Economic Analysis Tool for Anaerobic Digestion in Smallholder Farming Systems in the Context of the Water-Energy-Food Nexus, Ph.D. dissertation, Stellenbosch Univ., 2022. DOI: 10.1016/j.wasman.2021.01.016

[5] K. Postawa, J. Szczygieł, E. Wrzesińska-Jędrusiak, K. Klimek, and M. Kuła _zyński, "The pump-mixed anaerobic digestion of pig

slurry: New technology and mathematical modeling," Waste Manage., vol. 123, pp. 111–119, 2021. DOI: 10.1016/j.wasman.2021.01.016

[6] W. Yang, S. Young, A. Munoz, and M. J. Palmarin, "Dynamic modeling of a full-scale anaerobic mesophilic digester start-up process for the treatment of primary sludge," J. Environ. Chem. Eng., vol. 7, no. 3, p. 103091, 2019. DOI: 10.1016/j.jece.2019.103091

[7] L. Sillero, R. Solera, and M. Pérez, "Thermophilic-mesophilic temperature phase anaerobic co-digestion of sewage sludge, wine vinasse and poultry manure: Effect of hydraulic retention time on mesophilic-methanogenic stage," Chem. Eng. J., vol. 451, p. 138478, 2023. DOI: 10.1016/j.cej.2022.138478

[8] Y. Chen et al., "Effects of green waste addition on waste activated sludge and fat, oil, and grease co-digestion in mesophilic batch digester," Environ. Technol., 2020. DOI: 10.1080/09593330.2020.1717641

[9] L. Sillero, R. Solera, and M. Pérez, "Thermophilic-mesophilic temperature phase anaerobic co-digestion of sewage sludge, wine vinasse and poultry manure: Effect of hydraulic retention time on mesophilic-methanogenic stage," Chem. Eng. J., vol. 451, p. 138478, 2023. DOI: 10.1016/j.cej.2022.138478

[10] M. A. Bellahkim et al., "Mathematical modeling of anaerobic digestion of maize waste: A case study," Int. J. Eng. Appl., vol. 9, no. 3, pp. 173–178, 2021. DOI: 10.15866/irea.v9i3.19167

[11] P. Chaiyapong and O. Chavalparit, "Enhancement of biogas production potential from Acacia leaf waste using alkaline pre-treatment and co-digestion," J. Mater. Cycles Waste Manage., 2016. DOI: 10.1007/s10163-016-0469-0

[12] N. Nava-Valente et al., "Effect of acid pre-treatment on the anaerobic co-digestion of physicochemical sludge, poultry manure and sugarcane wastes (SCW) for biogas production," 2022. DOI: 10.21203/rs.3.rs-1735864/v1

[13] M. Garrido-Baserba et al., "Using water and wastewater decentralization to enhance the resilience and sustainability of cities," Nat. Water, vol. 2, no. 10, pp. 953–974, 2024. DOI: 10.1038/s44221-024-00303-9

[14] G. Garrido, A. Martinez, and C. de Souza, "Use of organic waste biomass for the design of an electric station," J. Phys.: Conf. Ser., vol. 1126, p. 012012, 2018. DOI: 10.1088/1742-6596/1126/1/012012

[15] R. Khiewwijit, New Wastewater Treatment Concepts Towards Energy Saving and Resource Recovery, Ph.D. dissertation, Wageningen Univ., 2016. DOI: 10.18174/375547

[16] N. Garavito Realpe, Risk Factors of Food Loss and Waste, and Life Cycle Assessment of Waste Management Strategies in the Brazilian Leafy Vegetable Supply Chain, M.S. thesis, Univ. of Borås, 2023. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1800691/FULLTEXT01.pdf

[17] E. R. Jacobo Ubierna, Producción de biogás a partir de sustratos agropecuarios, mediante la co-digestión anaeróbica a nivel laboratorio, Lima 2019, B.S. thesis, Univ. César Vallejo, 2019. [Online]. Available: https://hdl.handle.net/20.500.12692/143529

[18] W. J. Parker, "Application of the ADM1 model to advanced anaerobic digestion," Bioresour. Technol., vol. 96, no. 16, pp. 1832–1842, 2005. DOI: 10.1016/j.biortech.2005.01.022

[19] A. Galí et al., "Modified version of ADM1 model for agro-waste application," Bioresour. Technol., vol. 100, no. 11, pp. 2783–2790, 2009. DOI: 10.1016/j.biortech.2008.12.052

[20] R. Girault et al., "A waste characterisation procedure for ADM1 implementation based on degradation kinetics," Water Res., vol. 46, no. 13, pp. 4099–4110, 2012. DOI: 10.1016/j.watres.2012.04.028

[21] F. M. da S. Ferreira, Digestão anaeróbia por via seca, como alternativa ao actual destino agrícola, das lamas desidratadas de ETAR's – possibilidade de extensão a vários tipos de resíduos com elevado teor de matéria orgânica, M.S. thesis, Fac. de Eng. da Univ. do Porto, 2009. DOI: http://hdl.handle.net/10216/59489

[22] W. J. Parker, "Application of the ADM1 model to advanced anaerobic digestion," Bioresour. Technol., vol. 96, no. 16, pp. 1832–1842, 2005. DOI: 10.1016/j.biortech.2005.01.022

[23] A. Galí, T. Benabdallah, S. Astals, and J. Mata-Alvarez, "Modified version of ADM1 model for agro-waste application," Bioresour. Technol., vol. 100, no. 11, pp. 2783–2790, 2009. DOI: 10.1016/j.biortech.2008.12.052

[24] R. Girault, G. Bridoux, F. Nauleau, C. Poullain, J. Buffet, J.-P. Steyer, A. G. Sadowski, and F. Béline, "A waste characterisation procedure for ADM1 implementation based on degradation kinetics," Water Res., vol. 46, no. 13, pp. 4099–4110, 2012. DOI: 10.1016/j.watres.2012.04.028

[25] F. Mairet, O. Bernard, M. Ras, L. Lardon, and J. Steyer, "Modeling anaerobic digestion of microalgae using ADM1," Bioresour. Technol., vol. 102, no. 13, pp. 6823–6829, 2011.
DOI: 10.1016/j.biortech.2011.04.015