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Experimental Investigation and Numerical Modelling of Anaerobic Digestion Process Using De-Oiled Cakes

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Abstract

Energy crises emerging due to the depletion of fossil fuels and the management of solid wastes of all categories are the problems that should be addressed in the present scenario. This is done by converting these solid waste materials into valuable energy, reducing fossil fuel dependency. The conversion of solid wastes into valuable biogas is performed through the anaerobic digestion (AD) process. In this work, the solid wastes considered were de-oiled cake (DOC), such as rapeseed cake (RC), neem cake (NC) and ground cake (GC), obtained after removing the oil from the seeds. The anaerobic digestion process is simulated using the Simulink tool of MATLAB. Comparison of biogas produced, digest pH value, and temperature inside the digester were done. Experimentation is also performed with a floating drum digester of a 300-litre gas-holding floating dome made of fibre material. The obtained results are compared with the simulation results, and it is found that the experimental values coincide with the simulation results. The maximum biogas production was obtained experimentally with RC (1.366 litres), followed by NC (0.992 litres) and GC (0.938 litres). The difference among the experimental and simulation results for biogas production is 7.04% for NC, 6.39% for GC and 2.51% for RC. The average pH and temperature maintained inside the digestor for RC is 7.06 and 48.35°C, 7.02 47.46°C for GC, and 7.05 and 46°C for NC. The chemical oxygen demand (COD) is higher for RC (93767.69 mg/L), with a 0.42% variation from the simulation result.

1. Introduction

The worldwide energy consumption is increasing and will likely continue for the next few decades. Using fossil fuels continues to be a major contributor to the production of greenhouse gases, which constitute a major threat to the climate and are even more worrisome [1]. Since biomass is a renewable, cheap, and useful energy source with a broad range of potential product uses, it is heralded as a green energy source that will surely gain traction in the present energy landscape [2]. One promising alternative to conventional fuels for recuperating energy and adding product value is agricultural leftovers, which comprise a large amount of lignocellulosic biomass [3]. The waste disposal dilemma has widespread support, and one technology that has the potential to alleviate it is anaerobic digestion (AD). It lessens organic matter and provides energy that is good for the environment [4,5]. From the perspective of waste treatment, AD decreases the trash's volume and mass while decreasing its organic content and biodegradability. This allows for the better use of the leftover residue as a soil amendment and fertilizer [6]. AD has several positive effects on the environment. It helps to remove harmful odours, gases like methane, and volatile organic compounds. Additionally, it eliminates harmful microorganisms in the waste through the digester. Many variables will influence AD; for example, the rate of degradation and the quantity of methane produced by various feedstocks will vary [7]. That is conditional on the source material's moisture level, carbon and nutrient availability, biodegradability, and methane potential. Digestion of solids is more time-consuming than that of soluble feedstocks. The makeup of the bacteria in the digester affects how efficient it is. Throughout the fermentation process, it is essential to maintain the proper balance of bacteria and methanogens [8]. The environmental parameters and operating elements of the digester exhibit oscillations. Comprehending the total solids (TS) and volatile solids (VS) in the feeds, figuring out the best retention periods, and ensuring enough mixing are all critical. These elements are important to the procedure. One operational consideration is how much and what kind of feedstocks are fed into the digester. Additionally, the operation depends on maintaining the population of microorganisms and the organic loading in the reactors, regardless of whether it is a batch or continuous reactor [9]. The significance of mixing cannot be overstated in any reaction. Its primary objective is facilitating a close and continuous interaction between microorganisms and the feed and nutrients involved. Additionally, mixing prevents the creation of a floating crust layer, which might impede the percolation of biogas from the slurry. Because mixing makes it easier for volatile materials to break down, it is essential for increasing biogas output. It is important to consider the energy costs involved in mixing, which necessitates carefully balancing the advantages and costs [10]. Several factors, including temperature, pH, and the concentrations of various materials, determine a reactor's environmental conditions. These materials encompass volatile fatty acids, ammonia, salt, and cationic ions. Methanogens, responsible for biogas production, exhibit distinct reactions within specific temperature ranges. Among the different types of methanogens, thermophiles yield the highest biogas output. However, the digester must maintain a 40-70°C temperature to ensure optimal performance. Additionally, methanogens thrive in environments with a neutral pH, typically 6.5 to 8.2 [11]. Agricultural waste originates from various sources, including livestock, agro-industrial, crop residues, and aquaculture; hence, appropriate management is essential. Developing and implementing solid strategic plans is essential to successfully meeting the expectations of the agriculture industry. Moreover, lignocellulosic biomass may provide a long-term response to the problems brought on by the depletion of fossil fuels and global warming. Biomass may be used to produce a variety of biofuels and bioenergy, such as biodiesel, bioethanol, biogas, and biohydrogen. By producing value-added goods such as bio-fertilizers, bio-bricks, bio coal, bioplastics, paper, industrial enzymes, and organic acids, lignocellulosic wastes have a major potential to shape the economy [12,13]. Deshmukh et al. [14] considered Thionyl chloride pretreatment at 35 °C for a 25-minute residence period was required to use de-oiled castor bean cake (CBC) as the main feedstock for bioethanol production. One approach that has shown promise is the acidic pretreatment followed by enzymatic hydrolysis. The ideal process parameters were a solid-liquid ratio of 1:2, a pH of 7, and a temperature of 35 °C with a concentration of 3 g of T. viride. When BSS-10 was used at its ideal particle size, T. viride enzymes produced 76 g/L of reducing sugars. These sugars might subsequently be transformed through fermentation into bioethanol, producing 37.5 g L^{-1} of bioethanol [15]. The significant potential of food waste (FW) rich in carbohydrates for biohydrogen production has been acknowledged, providing a viable solution to waste management challenges. The dark fermentation process of FW, which contains a substantial amount of organic matter, is a highly effective substrate for biohydrogen production. Implementing a sustainable methodology that incorporates the manipulation of metabolic pathways makes it possible to optimize hydrogen generation and effectively convert waste materials. The process's sustainability and economic viability are improved when combining dark fermentation with microbial fuel cells and electrolysis cells in hybrid systems. Using novel microorganisms, genetically engineered strains, and mixed consortia has shown promising results in achieving an increased output of biohydrogen. Sadukha et al. [16] used four types of de-oiled cakes (DOCs) in their study: groundnut, sesame, mustard, and cottonseed (CDOC). The three pretreatment techniques of leachate, acidic hydrolysate, and basic hydrolysate were coupled with these. More biomass amounts were seen while using the CDOC basic hydrolysate. A notable 82% decrease in COD and a high utilization rate of 88–90% for phosphate and ammonium were also seen at the ideal amount of CDOC basic hydrolysate application. When providing a complete and economical nutritional solution for microalgal development, using DOCs made from agricultural waste offers a lot of promise. As a result, compounds, including lutein, phytol, and lipids, may be extracted. Alsharidi et al. [17] devised a sophisticated solution for a nonlinear dynamical system in anaerobic digestion, incorporating Monod-based kinetics and considering the impact of slowly changing model parameters due to environmental fluctuations. The model considers bacterial and substrate inflows, and the derived analytic approximations strongly agree with numerical solutions, which validates the proposed methodology. Because they produce a large amount of methane, lipids are well-recognized as advantageous substrates for anaerobic digestion. Nonetheless, there may be some difficulties when there are excessive lipid concentrations. To address this issue, the researchers experimented with pretreated and untreated sugarcane bagasse as fat adsorbents to reduce the harmful effects of fatty waste. These adsorbents were used in a dairy wastewater treatment facility to handle grease trap waste. Untreated sugarcane bagasse has shown potential for direct use without requiring pretreatment in anaerobic processes [18]. Chen et al. [19] analyzed the impact of bio-solids from municipal solid waste (MSW) on gas yields and anaerobic transformation efficiency at a wastewater treatment facility, which is the research goal. Several variables were considered, including pH, salt concentration, oil content, and particle size. According to the research, alkalinity and pH had a significant role in deciding how the transformation process turned out. According to the findings, anaerobic digestion of one kilogram of dry food residue required around 0.16–0.17 kg of alkalinity. By using MSW treatment, this need was reduced [20]. This research investigated the anaerobic digesting capabilities of D.

dichotoma, a plant with many rare earth elements (REEs). The research used cellulose, xylan, and glucose as model substrates to examine how La(III) affected the hydrolysis and methane generation in batch anaerobic digestion. The research showed that the methane produced from cellulose was reduced by 20% at a concentration of 500 mg/L of La(III). According to the microbial community study, the primary obstacle preventing methane synthesis may be the absence of cellulose-hydrolyzing bacteria, notably Clostridium III and Clostridium XlVa. Deepanraj et al. [21] researched how different degrees of solid concentration (10%, 15%, 20%, and 25% of total solids) affected the amount of biogas that could be produced from rapeseed oil cake. Laboratory-size batch reactors with a 2 L capacity and a 30-day retention time were used for the studies. According to the findings, a substrate concentration of 20% produced the best removal rates for total solids (TS), volatile solids (VS), and chemical oxygen demand (COD). This concentration also increased biogas generation compared to 25%, 15%, and 10%. Furthermore, the kinetic research showed that the modified Gompertz model provided a more accurate match to the experimental data than the Gompertz and Logistic models. Sharma et al. [22] investigated cow dung and Jatropha de-oiled cake co-digestion in a floating-type biogas digester for 60 days. According to the research, the average specific biogas production values for cow dung slurry and Jatropha de-oiled cake were 0.287 m^3/kg TS, 0.335 m^3/kg VS, and 0.216 m^3/kg TS and 0.252 m^3/kg VS, respectively. In comparison to psychrophilic temperature circumstances, it was discovered that mesophilic temperature conditions resulted in a 7% better removal efficiency of total volatile solids from the feeding material [23].

Deoiled cakes of groundnut, rapeseed, and neem oil cakes were considered for anaerobic digestion due to their high organic content and biodegradability, making them ideal substrates for biogas production. These cakes are rich in proteins, carbohydrates, and fats, broken down by anaerobic microbes, resulting in methane-rich biogas. Additionally, using deoiled cakes, abundant agro-industrial byproducts, promotes resource efficiency by turning waste materials into renewable energy, contributing to waste reduction and sustainability goals.

The literature review found limited work is performed on AD of DOCs obtained from agricultural farming, a residue whose disposal is challenging. Harvesting energy from the DOCs will be an ideal method to dispose of it effectively using the AD procedure, and the leftovers may be used as fertilizers. In this study, three different DOCs from groundnut (GC), neem (NC), and rapeseed (RC) were considered as potential energy recovery feedstock, which is the novelty of the present study. An experimental investigation is performed on a batch reactor on a lab scale, and the results obtained are verified with the outcomes of the numerical simulation modelled and executed via MATLAB Simulink.

2. Materials and Methods

2.1 De-oiled cakes

The de-oiled cakes derived from waste groundnut (GC), neem (NC), and rapeseed (RC) are the residual products obtained post-extraction of edible oil from the seeds through mechanical pressing. These cakes, highlighted for their protein and mineral content, exhibit varying compositions. For example, GCs consist of different proportions of protein, carbohydrate, crude fibre, and minerals. Furthermore, the proximate analysis indicates the following proportions: moisture content of 5.6%, volatile matter comprising 83%, ash content amounting to 4.8%, and fixed carbon content totalling 6.6% [24]. Salannin, nimbin, azadirachtin, meliantriol, and azadiradione are the primary constituents present in nanocarriers (NCs), functioning as an organic fertilizer, providing essential macronutrients (nitrogen, phosphorus, potassium) and micronutrients (magnesium, zinc, manganese, copper, iron, etc.). The study of NCs indicates that it comprises 73.2% volatile matter, 0.5% sulfur, and 4.8% ash [25]. RC contains essential amino acids, including methionine and cysteine, and a range of vitamins and minerals, including calcium, phosphorus, and magnesium. RC proximate analysis reveals moisture of 10.59%, volatile matter of 67.31%, fixed carbon of 15.8%, and ash of 6.3% [26]. The oil cakes are fragmented into tiny fragments using a mortar and pestle before being introduced into the laboratory-scale batch reactor. The contents of the de-oiled cakes under consideration are detailed in Table 1, while the methodology employed in this study to generate biogas is illustrated in Figure 1.

Table 1. Properties of groundnut, neem, and rapeseed oiled cakes

Feedstock	Dry matter	Crude protein	Crude fiber	Ash	Calcium	Phosphorous	Source
Groundnut DOC	92.6	49.5	5.3	4.5	0.11	0.74	[27]
Neem DOC	80.67	41.30	0.51	14	0.77	3.0	[28]
Rapeseed DOC	943	294	303	64	0.65	0.57	[29]

During the investigation, a precise proportion of de-oiled cakes and water is blended with inoculum slurries from anaerobic digesters containing pathogenic bacteria that contribute to increased biogas volume and methane fraction production. A substrate was prepared by diluting cow dung with water in a 1:1 proportion. The slurry obtained was then subjected to anaerobic fermentation for the inoculum [30]. Cow dung is an ideal choice for preparing the inoculum slurry in anaerobic digesters due to its rich microbial community, as it has a balanced carbon-to-nitrogen (C-N) ratio, which includes a wide variety of anaerobic bacteria necessary for efficient digestion. These microbes, such as methanogens, hydrolytic, and acidogenic bacteria, play a critical role in breaking down organic matter and facilitating biogas production. Cow dung is also readily available and inexpensive, preventing process imbalances, such as acid buildup or ammonia inhibition. Additionally, cow dung provides essential buffering capacity, stabilizing the pH in the digester and creating favourable conditions for anaerobic microbes to thrive. Its proven effectiveness in enhancing biogas yield and promoting stable and consistent digestion performance justifies its selection as a critical component for inoculum slurry in anaerobic digestion processes. The cow dung used in the research had a composition of TS (mg/L) -159 and VS (mg/L)-34.5, with a moisture content of 42.6% and a pH range between 6.8 and 7.6. Subsequently, the inoculum was introduced into the digester to begin the fermentation process.

Figure 1. Methodology of this study

2.2 Anaerobic Digestion Process

Anaerobic digestion (AD) is an inherent biological mechanism that naturally decomposes organic substances without oxygen. Microorganisms in an enclosed vessel break down the waste plant and animal matter, producing a gas with a high methane content. AD produces biogas, liquid digestate, and solid digestate. The methane in biogas can be captured and burned to produce heat electricity [31]. This study uses GC, NC, and RC in de-oiled conditions as the organic matter to produce biogas. There is a discernible correlation between the rate of development of methanogenic bacteria and the biogas produced under batch circumstances, as shown by the observation period's beginning and end, which show a slow rate of biogas generation. The findings unequivocally indicate that the solid's concentration strongly influences biogas generation [32]. The degradation process is categorized into four phases: including acidogenesis, acetogenesis, methanogenesis, and hydrolysis. Various categories of facultative or obligatory anaerobic microorganisms are involved in each phase [33].

A 0.5 m^3 digester and a 300-litre gas-holding floating dome made of fibre material were part of the anaerobic floating drum-type biogas plant used for the experiment. A floating drum digester in the AD process provides a simple, reliable, and efficient biogas collection and storage method. The gas holder in the floating drum moves up and down based on the volume of gas produced, providing a direct visual indication of biogas generation, ensuring consistent pressure and easy gas retrieval, and making it user-friendly for small-scale and rural applications. The sealed, movable gas drum minimizes gas leakage and allows for safer storage, enhancing efficiency. Its ability to maintain consistent gas pressure regardless of the amount of biogas produced makes it an ideal choice for AD use. Using a batch procedure, the digester was kept at a constant temperature between 28 and 38°C for a predetermined time. They were weighed throughout the inquiry to ascertain each raw material's unique weight [34]. The temperature indicator was used to monitor the temperature in the slurry, while the redox pH meter was utilized to test the pH in the combination. The digester was filled with the feed material and agitated to attain a uniform mixture and to decompose any surface film. The biogas production was quantified using the SH Alborg gas flow meter, while the APHA standard methods adhered to determine total solids and volatile solids [35].

The cakes stripped of fat were fragmented into particles to enhance the surface area conducive to microbial activity. Subsequently, water was introduced to the waste material to form the substrate with the desired solid concentration. A $NaHCO_3$ solution was added to achieve a suitable pH level [36]. Glass laboratory-scale anaerobic batch reactors were used in the experimental setting, as shown in Figure 2. These reactors had an adequate working capacity of 1.8 litres and a total volume of 2 litres. An inverted measuring glass cylinder submerged in water was used to calculate the daily output of biogas. The flowchart showing the working procedure of the AD process is presented in Figure 3.

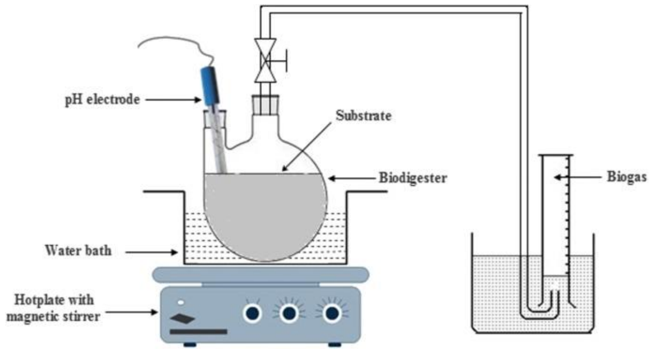

Figure 2. Laboratory scale AD setup

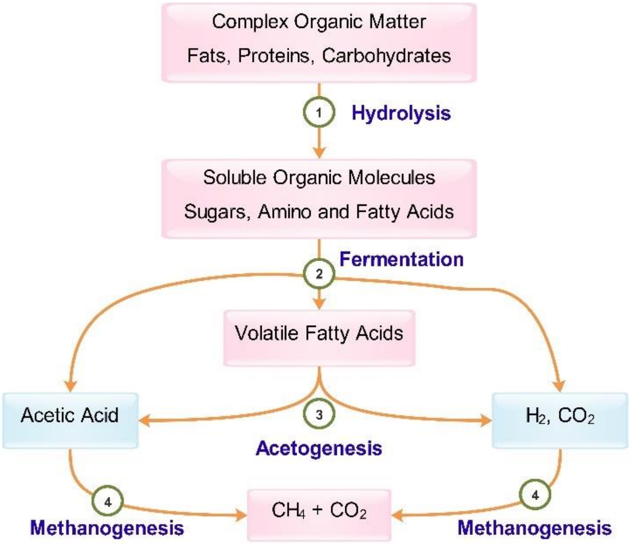

Figure 3. Flowchart of the AD process

2.3 Numerical Modeling of the AD process

Experiments may be costly and time-consuming, and the findings are sometimes unreliable. Simulations are thus often favoured. Process simulations, however, might provide inaccurate results for real-world applications if the wrong tools and assumptions are used [37]. Nevertheless, microscopic studies have been done on AD models. Published studies have reported using the Anaerobic Digestion Model No. 1 (ADM1) by several researchers to replicate the AcoD process [38]. Software programs, including Aspen Plus [39], SuperPro Designer [40], AQUASIM [41], SIMBA [42], BioWin [43], CFD [44], and MATLAB Simulink [45], are often used to simulate AD processes. MATLAB Simulink is an excellent choice for simulating anaerobic digestion processes due to its powerful computational capabilities, flexibility, and ease of use for dynamic modelling. It allows users to create highly accurate, customized models of complex AD processes by offering a wide range of built-in mathematical functions and control tools [46,47]. Simulink's graphical interface facilitates the design of block-based simulations, making it easy to visualize and adjust parameters for various stages of the digestion process, such as hydrolysis, acidogenesis, and methanogenesis. MATLAB's extensive library, combined with its ability to integrate with other toolboxes for statistical analysis, data visualization, and optimization, makes it ideal for simulating dynamic and nonlinear systems like anaerobic digesters.

The organic loading rate (OLR), system volume, retention duration, pH levels, inhibitions, rate kinetics, reactor volume, operating temperature, and retention time were among the parameters that were considered for the simulation. Figure 4 illustrates the mesophilic conditions in which the AD system in MATLAB Simulink will work. Temperatures between 20 and 45°C are ideal for mesophilic digestion, with 30-38°C being the most conducive. This process is influenced by two controlled inputs: the specific heat addition rate, Gu, and the influent feed rate, Q. A temperature controller (TC), which adds heat to maintain the required temperature, is coupled to a temperature sensor (TT) that is put on the process to assure temperature management. A flow controller (QC), which regulates the input of influent material into the process, is also coupled to a total organic carbon analysis (TOCA), which is placed on the effluent stream, changes in the concentration of organic substrate (Si) and the temperature of the input (Ti) cause problems in the process. A feedback control loop identifies deviations from the desired process temperature and provides the required heat. The influent flow rate is also modified via feedback control to compensate for any incoming steady-state substrate concentration variations [48]. A feedforward control method is used with feedback control to improve responsiveness to variations in substrate concentration [49].

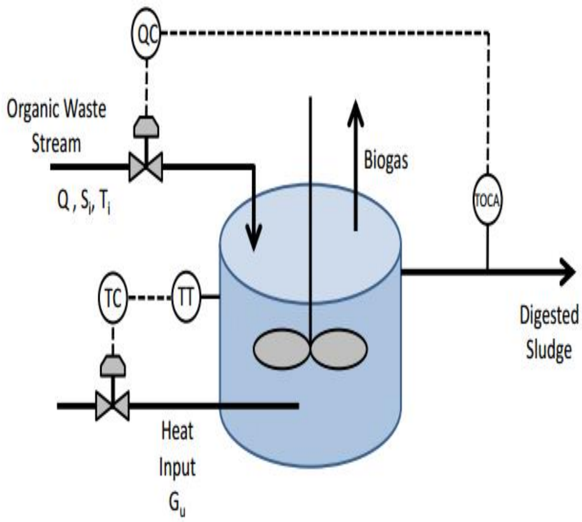

Figure 4. Basic process diagram for an AD in MATLAB Simulink

3. Results and Discussion

The current study examines the feasibility of three different types of cakes, namely GC, NC, and RC, for biogas production. Lab-scale bio-digesters were utilized to produce biogas from various samples, each with different oil cakes and water ratios. The execution of the AD process simulation using the Simulink tool is presented in Figure 5.

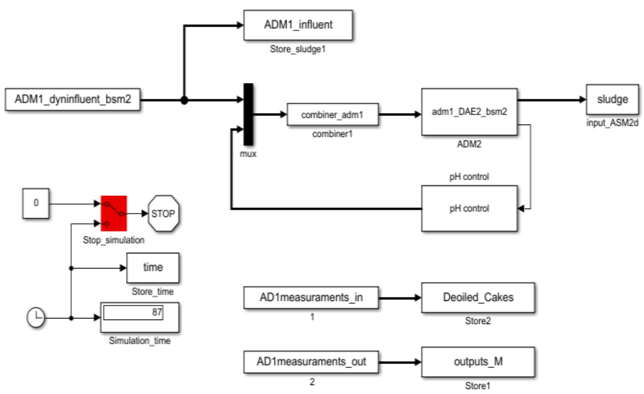

Figure 5. Execution of AD process in Simulink

The study also investigated the impact of hydraulic retention time (HRT) on biogas production and other aspects of anaerobic digestion (AD). Figure 6 illustrates the observation of biogas within the digester throughout the batch process, which encompasses the entire biodegradation process. Groundnut, neem, and rapeseed de-oiled cake produced the most biogas on the fifteenth day of retention, generating around 4 litres per day (up). On the third or fourth day of the digestive process, biogas generation started in both situations. This is because the digestive process is sped up using cow dung as a column. After a slow rise throughout the second week, the rate of biogas outputs peaked between the sixteenth and eighteenth day of digestion. Then, since there was less available substrate and less methanogen activity in the slurry, the methane generation rate started to drop [50]. Extending the hydraulic retention time (HRT) results in enhanced decomposition of organic matter and increased biogas generation per unit of volatile solid (VS) input. This is due to the extended contact time that enables the microbial population to break down the substrate efficiently [51]. In a concise hormone replacement therapy (HRT) exhibition, it becomes evident that the microbial population lacks sufficient time for growth, leading to a decline in their numbers [52]. A notable correlation exists between experimental observations and numerical simulations concerning biogas production, with experimental studies indicating a higher level of biogas production than the predicted values from simulations. Long Hydraulic Retention Times (HRT) might cause components of biogas to be used inefficiently, which would reduce the amount of biogas produced [53].

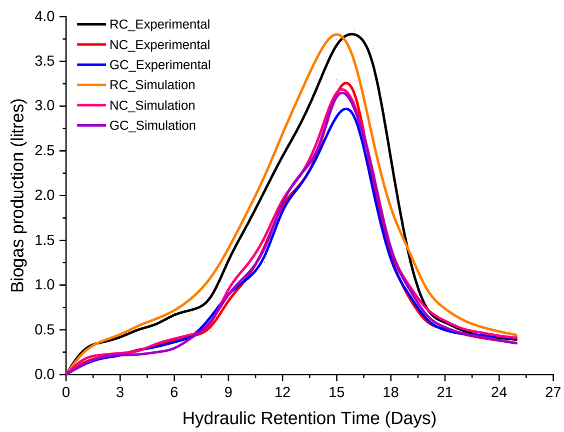

Figure 6. Variation of biogas production for the HRT period

Biogas production in an AD process is susceptible to changes in both pH and temperature, as these factors directly influence microbial activity. Optimal pH levels for biogas production typically range between 6.5 and 7.5, where methanogenic bacteria thrive. A decrease in pH (acidic conditions) can inhibit methanogenesis, leading to reduced biogas output, while a pH above 8.0 (alkaline conditions) can also disrupt microbial activity by causing ammonia toxicity [54]. Similarly, temperature plays a critical role: mesophilic conditions (around 30°C to 40°C) are generally ideal for stable microbial growth and gas production. In comparison, thermophilic conditions (around 50°C to 60°C) can increase biogas yield due to faster microbial metabolism but may also lead to system instability. Large temperature fluctuations can stress or kill anaerobic bacteria, producing lower biogas. Maintaining stable pH and temperature within optimal ranges is crucial for maximizing biogas yield and ensuring a consistent digestion process [55].

Figure 7 depicts the pace at which the anaerobic digestion of dissolved organic compounds produces biogas. The initial production of biogas is slight but gradually increases as the hydraulic retention time (HRT) progresses. There is a significant rise in biogas production during ten days of retention. However, the curve somewhat settles as the HRT approaches 20 days. This stability is ascribed to the reduction in biogas production brought about by the feedstock's severe fouling and the reactor rate dropping [56].

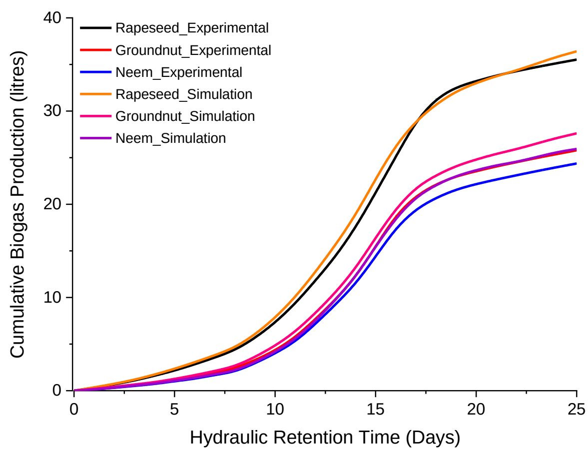

Figure 7. Cumulative biogas production for the considered HRT period

The anaerobic digestion process comprises four critical phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Higher pH conditions are usually used for the last phase, whereas lower pH values are typically used for the earlier stages [57]. Usually, the pH should remain between 6.8 and 7.2 for the process to work efficiently [58]. The variation of pH during the AD of DOCs is presented in Figure 8. The digester's pH decreases due to volatile fatty acid buildup. The formation of volatile acid is reduced during the acid regression phase, leading to the formation of acetate and ammonia molecules, which raise pH levels. In this study, the pH tends to vary between 6.9 and 7.2. During the HRT, pH fluctuates, as observed in both simulation and experimental methods. The pH variation is higher during simulation than in the experimental conditions. The optimal pH range for anaerobic microorganisms is generally around neutral. Nevertheless, a pH below five can challenge the metabolic processes of methanogenic bacteria within the community [59].

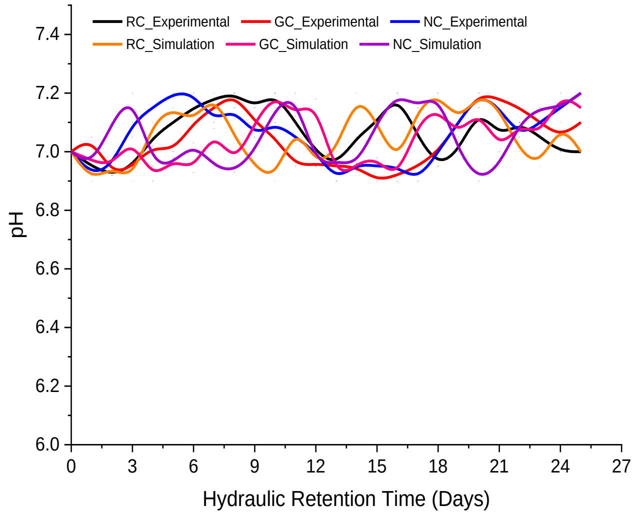

Figure 8. pH variation during AD of de-oiled cakes

The change in temperature inside the AD reactor for the period of HRT is presented in Figure 9, where the temperature is maintained between 48 to 52°C to improve the digestion process. Temperature affects the organic matter removal rate constants, leading to changes in biological oxygen demand (BOD) removal. The removal rate constant will increase as temperature increases, but this will happen until a temperature is reached. After this limit, the removal will decrease because the microorganisms will die. Due to the favourable temperature ranges for methanogen activity, anaerobic digestion is frequently conducted at either the thermophilic temperature range (50–60°C) or the mesophilic temperature range (30–40°C) [60].

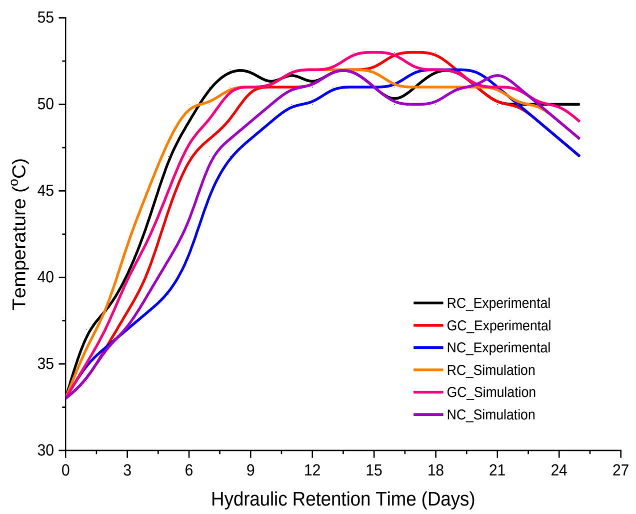

Figure 9. Temperature variation during AD of de-oiled cakes

The amount of oxygen that oxidizing agents may use in a sludge sample is determined by measuring the chemical oxygen demand (COD) [61]. The concentration of organic compounds within the sludge can be determined by assessing the COD during anaerobic digestion [62]. During the initial stages of AD of organic compounds, the concentration of COD within the digester increases with time [63]. However, after the peak biogas production, there is a significant reduction in COD levels observed at an accelerated rate, as evidenced by Figure 10.

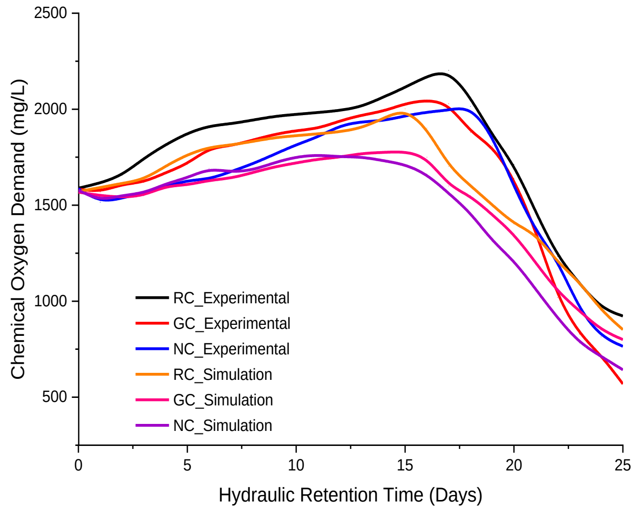

Figure 10. COD variation during AD of de-oiled cakes

Figure 11 displays the total suspended solids (TSS) variation accessible throughout the AD of DOCs. Methanogens are protected from the inhibitory action of total suspended solids (TSS) by increasing their digestibility in the early stages of the process [64]. The TSS concentration significantly influences the efficacy of anaerobic digestion in DOCs. This impact is most apparent in the efficiency of biogas and methane production and the quantity of volatile fatty acids (VFA) [65–67]. Interestingly, an increase in the total solids (TS) content is associated with a rise in the concentration of VFA [68–70]. TSS and biogas production follow a similar path, with a fall in TSS levels in the digestor causing a subsequent drop in the amount of biogas generated [71–73].

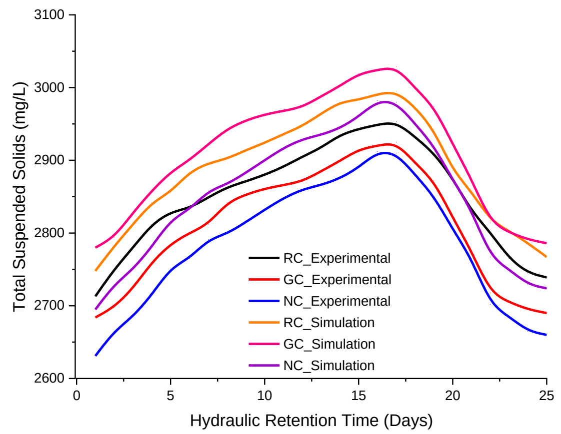

Figure 11. TSS variation during AD of de-oiled cakes

4. Conclusion

The generation of biogas from DOCs of RC, GC, and NC was investigated in this research. The results obtained from the experiments were further validated through numerical simulations performed with the Simulink tool. The research findings indicate that,

- The peak biogas production from DOCs occurs between the 16th and 18th digestion day. However, after that, the output steadily declines since less substrate is available and the slurry's methanogen activities decrease. The breakdown of organic matter and the amount of biogas produced per unit of VS are positively impacted by increased HRT.
- After 20 days of HRT, the total biogas output gradually rises, then rises sharply before stabilizing. Throughout the HRT, the pH of the feedstock slurry stays between 6.9 and 7.2, which is neutral and conducive to microbial activity.
- There is an increasing tendency for the COD inside the digester to increase during the early AD phases of DOCs. However, after the peak biogas production, COD significantly reduced faster. The effectiveness of anaerobic digestion is impacted substantially by the TSS content of digesting organic waste (DOCs), especially when creating biogas and methane.
- The maximum biogas production was obtained experimentally with RC (1.366 litres), followed by NC (0.992 litres) and GC (0.938 litres). Similarly, the average pH and temperature maintained inside the digestor for RC is 7.06 and 48.35°C, 7.02 47.46°C for GC, and 7.05 and 46°C for NC. The average COD obtained for RC is 93767.69 mg/L, GC is 93547.92 mg/L, and NC is 93394.27 mg/L.
- The difference among the experimental and simulation results for biogas production, pH, temperature in digestor, and COD is 7.04%, 0.64%, 1.76%, and 0.53% for NC, 6.39%, 0.39%, 2.03%, and 0.48% for GC and 2.51%, 0.14%, 0.16%, and 0.42% for RC. It is observed that a closer correlation exists between the experimental and simulation results.

5. Future Scope of Work

In continuation with this present study, hybrid DOCs of RC, GC, and NC can be used in the AD process for improved biogas production. When hybrid DOCs of groundnut, rapeseed, and neem oil cakes are considered feedstock rather than a single DOC, the resulting mixture offers a more balanced and enhanced nutrient profile, improving its overall value. Each cake brings unique characteristics: GC is rich in protein and minerals like phosphorus and calcium, RC contributes additional protein and specific nutrients like sulfur, while NC adds moderate nitrogen and bioactive compounds like azadirachtin, which provide natural pest-repellent properties. Additionally, using a hybrid mixture can reduce the dependency on a single source, making the feedstock more sustainable and cost-effective by leveraging multiple raw material streams.

Author contributions

N. Senthilkumar: Conceptualization, Methodology, Writing-Original draft preparation, Software, Validation. **M. Yuvaperiyasamy:** Visualization, Investigation, Writing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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