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A Hybrid Ultrasonic Membrane Anaerobic System (UMAS) Development for Palm Oil Mill Effluent (POME) Treatment

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Abstract: The high chemical oxygen demand (COD) and biochemical oxygen demand (BOD) levels in palm oil mill effluent (POME) wastewater make it an environmental contaminant. Moreover, conventional POME wastewater treatment approaches pose economic and environmental risks. The present study employed an ultrasonic membrane anaerobic system (UMAS) to treat POME. Resultantly, six steady states were procured when a kinetic assessment involving 11,800–21,700 mg·L^{-1} of mixed liquor suspended solids (MLSS) and 9800–16,800 mg·L^{-1} of mixed liquor volatile suspended solids (MLVSS) was conducted. The POME treatment kinetics were explained with kinetic equations derived by Monod, Contois and Chen and Hashimoto for organic at loading rates within the 1–11 kg·COD·m^{-3}·d^{-1} range. The UMAS proposed successfully removed 96.6–98.4% COD with a 7.5 day hydraulic retention time. The Y value was 0.67 g·VSS/g·COD, while the specific micro-organism decay rate, b was 0.24 day^{-1}. Methane (CH_4) gas production ranged from 0.24 to 0.59 litres per gram of COD daily. Once the initial steady state was achieved, the incoming COD concentrations increased to 88,100 mg·L^{-1}. The three kinetic models recorded a minimum calculated solids retention time of 12.1 days with maximum substrate utilization rate, K values ranging from 0.340 to 0.527 COD·g^{-1}·VSS·d^{-1} and maximum specific growth rate, μ_{max} from 0.248 to 0.474 d^{-1}. Furthermore, the solids retention time (SRT) was reduced from 500 to 12.1 days, resulting in a 98.4% COD level reduction to 1400 mg·L^{-1}.

Keywords: ultrasonic; COD removal; POME; kinetics equations; membrane; anaerobic

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1. Introduction

The palm oil industry primarily contributes to the global economy, contributing significantly to vegetable oil manufacturing. Nevertheless, palm oil production produces a substantial amount of wastewater, palm oil mill effluent (POME) [1]. The POME comprises organic and inorganic compounds, including high fats, oils, and grease concentrations, which are challenging to treat with traditional treatment methods. Furthermore, improper POME handling and discharge could lead to severe environmental impacts, such as water pollution and the release of greenhouse gases [2].

Anaerobic digestion has been established as an effective POME treatment approach as it converts complex organic compounds into biogas, which could be utilised as an energy source [3]. Nonetheless, conventional anaerobic digestion processes possess limitations, including low organic removal efficiency, long hydraulic retention time, and toxic compound accumulation, which could hinder biogas production [4]. Consequently, researchers have been investigating the employment of advanced techniques, such as ultrasonic and membrane technologies, in combination with anaerobic digestion, to enhance the efficiency of POME treatment and overcome the limitations of conventional methods [5].

High-frequency sound waves are utilised in ultrasonic technology to disrupt micro-organism cell membranes, increasing the accessibility of the waves to the substrates in the micro-organisms, thus promoting biodegradation [6]. Conversely, membrane technology enhances biogas production rates by providing a physical barrier for separating solids and liquids, allowing a more concentrated and homogeneous feed to anaerobic reactors [7].

A hybrid ultrasonic membrane anaerobic system (UMAS) combines ultrasonic and membrane technologies with the anaerobic digestion process, yielding a promising alternative for POME treatment [8]. The ultrasonic waves aid in breaking down the complex organic compounds in POME, making them more accessible to anaerobic micro-organisms. Conversely, the membrane technology promotes process stability and efficiency by hindering solid and other impurities from aggregating in anaerobic reactors [9].

Developing a hybrid UMAS for POME treatment is still in its early stages despite its potential advantages. Consequently, further research on the optimal conditions and design parameters necessary for the efficient operation of a hybrid UMAS in treating POME is essential [10], including investigating the effects of integrating ultrasonic and membrane technologies, hydraulic retention time (HRT), organic loading rate (OLR), pH, and temperature [11]. Additionally, the long-term stability and maintenance requirements of the system necessitate exploration.

Developing UMAS to treat POME could significantly impact sustainable development goals (SDGs) in terms of environmental protection and economic growth. Treating POME with a hybrid UMAS could considerably reduce the environmental impacts of the palm oil industry [12]. The POME is a highly polluting wastewater stream of concentrated organic compounds and other pollutants, which could result in severe water pollution and contribute to greenhouse gas emissions if discharged untreated [13]. A hybrid UMAS converts the complex organic compounds in POME into biogas, a form of renewable energy that could be employed to offset fossil fuel usage, therefore offering a more sustainable approach to POME treatment [14]. Consequently, the approach could aid in promoting sustainable development and support global efforts to combat climate change.

Developing and implementing a hybrid UMAS could stimulate economic growth by providing an additional source of income for the palm oil industry [15]. Furthermore, the POME-produced biogas could be employed to generate electricity that could then be sold to the national grid or utilised to power palm oil mills, reducing their reliance on fossil fuels. Moreover, the technology offers diminished palm oil industry operating costs and creates new business opportunities in the renewable energy sector, promoting economic growth [16].

A hybrid UMAS could serve as a model for sustainable wastewater treatment in other industries [17]. The ultrasonic and membrane technologies with anaerobic digestion combination could potentially enhance the efficiency and sustainability of wastewater treatment for a wide range of industrial applications, reducing the environmental impact and improving economic sustainability. In summary, developing a hybrid ultrasonic membrane anaerobic system (UMAS) to treat palm oil mill effluent (POME) can significantly impact sustainable development, promoting environmental protection, economic growth, and technological innovations.

The purpose of this is study to develop and evaluate a hybrid UMAS to treat POME to address the research gap in the sector. The system was designed and optimised to achieve high biogas production rates and efficient organic pollutant removal. Moreover, the effects of various designs and operational parameters on the system performance were assessed, including the effects of ultrasonic power, membrane flux rate, and organic loading rate. The stability and maintenance requirements of the system over a long period of operation were also evaluated. Other than elucidating the performance of the proposed UMAS for POME treatment and methane (CH_4) production, the process kinetic variables based on the Monod, Contois, and Chen and Hashimoto models were also determined (see Table 1). The results would contribute to developing a sustainable and systematic POME treatment approach, which would reduce the environmental impacts of the palm oil industry and provide a potential renewable energy source.

Table 1. The mathematical equations of the kinetic models employed in this study.

Kinetic Model	Equation (1)	Equation (2)
Monod [18]	$U = \frac{kS}{k_s + S}$	$\frac{1}{U} = \frac{K_s}{K}\left(\frac{1}{S}\right) + \frac{1}{k}$
Contois [19]	$U = \frac{U_{\max} \times S}{Y(B \times X + S)}$	$\frac{1}{U} = \frac{a \times X}{\mu_{\max} \times S} + \frac{Y(1 + a)}{\mu_{\max}}$
Chen & Hashimoto [20]	$U = \frac{\mu_{\max} \times S}{YKS_o + (1 - K)SY}$	$\frac{1}{U} = \frac{YKS_o}{\mu_{\max} S} + \frac{Y(1 - K)}{\mu_{\max}}$

2. Materials and Procedures

The current study designed an ultrasonic membrane anaerobic system (UMAS) with six transducers, three on each side, to avoid and overcome membrane fouling. The UMAS employed a 60-L laboratory digester to process the POME according to the procedure outlined by Abdurahman et al. [21], with slight modifications. Figure 1 demonstrates a simplified version of the UMAS system proposed in this study. The system included a centrifugal pump, an anaerobic reactor, and a cross-flow ultra-filtration membrane (CUF) [21], all housed in a single unit. The UMAS used in this study had a power of 20 kHz and an effective volume of 45 litres.

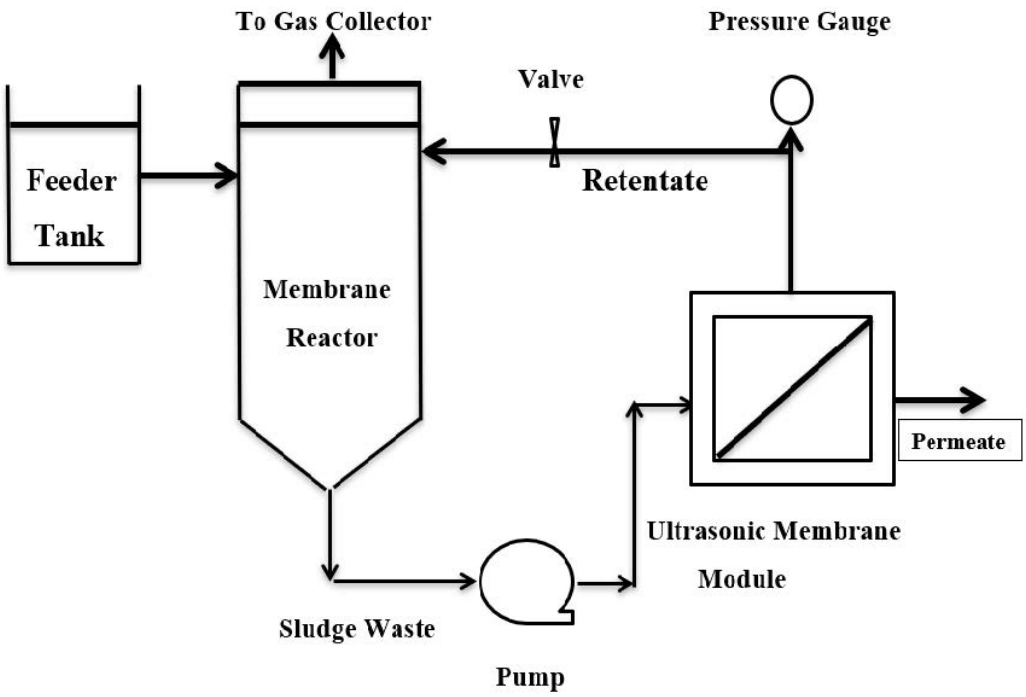

Figure 1. The experimental setup employed in the current study.

The CUF module possessed a 200,000 molecular weight cut-off (MWCO) with a 1.25 cm tube diameter and 0.1 µm average membrane pore size. Each tube in the current study was 30 cm long, producing a total effective area of 0.024 m^2 when two were employed together. The membranes could also resist a 55 bars maximum operating pressure at 70 °C within a 2–12 pH range, depending on the temperature.

The anaerobic reactor in this study was made of transparent PVC, 100 cm in height, and had an inside diameter of 15 cm. During specific experiments, the gate regulator on the retentive line placed after the CUF unit was adjusted to maintain a working pressure of 1.5–2 bars.

2.1. The POME

In this study, raw POME samples were collected from Lepar Hilir, located in the geographical coordinates: 3°43′0″ North, 103°6′0″ East in Kuantan, Malaysia, and subjected to various assessments to determine their pH levels, total suspended solids [21], chemical oxygen demand (COD), volatile suspended solids (VSS), substrate utilisation rates (SUR), and specific substrate utilisation rates (SSUR). For COD measurement, the closed reflux colorimetric method was used. Moreover, a cool room was employed in this study to maintain the temperature of the effluent samples at 4 °C.

The collected POME sample was placed in a 4 °C cold room to preserve the micro-organism's properties and avoid substrate degradation. The POME was stored under these conditions with no significant changes in its composition. The substrate was placed in a room temperature of 25 °C prior to the experimental procedures. The volume was kept constant at 60 L for each process. POME samples were sieved through a mesh of 90 µm to remove larger particles that could clog or damage the membrane while allowing smaller particles and dissolved components to pass through. Following the sieving of the sample, the reactor was covered with aluminium foil. This step was required to shield the sample from direct sunlight and prevent algae from growing inside the reactor.

2.2. The Bioreactor Operation

Bioreactor operation in a membrane anaerobic system involves the use of specialised bioreactors combined with membrane filtration technology to treat wastewater or organic waste. In this process, a hybrid ultrasonic assisted membrane anaerobic system, UMAS is used to treat POME.

The current study selected six steady-state scenarios to analyse the performance of the proposed system. The present study also employed 60,000–87,000 mg·L^{-1} influent COD, while the organic loading rates (OLRs) were 1–11 kg·COD·m^{-3}·d^{-1}. The system was assumed as being in a steady state when the operational and controlled parameters were within 10% of the average values. The threshold was determined by comparing the values to the average figure obtained from each condition evaluated. The daily gas volume in the present study was determined with a 20-L water displacement bottle. Considering that the biogas procured only consisted of CO_2 and CH_4, removing carbon dioxide (CO_2) gas with sodium hydroxide (NaOH) solution was sufficient to isolate CH_4 gas effectively.

2.3. Mechanisms of Ultrasonic Transducers

Ultrasonic transducers are devices that convert electrical energy into mechanical vibrations and vice versa, allowing the generation and detection of ultrasonic waves. These transducers rely on the principles of piezoelectricity or magnetostriction to function.

Ultrasonic transducers are critical in ultrasonic cleaning machines. The device produces ultrasonic vibrations, sounds over the human hearing range commonly starting at 20 kHz. Ultrasonic cleaning devices employ cavitation bubbles to agitate liquids prompted by high-frequency pressure (sound) waves [22]. The agitation results in significant forces on contaminants adhering to substrates, such as metals, plastics, glass, rubber, and ceramics, and penetrates blind holes, cracks, and recesses.

Ultrasonic transducers comprise active elements, mostly piezoelectric crystals, and backing and radiating plates. The piezoelectric crystals transform electrical energy to ultrasonic energy via the piezoelectric effect, changing their size and shape. A thick material is employed as the backing in ultrasonic transducers, which absorbs the energy radiating from the backs of the piezoelectric crystals. In contrast, the radiating plate in an ultrasonic transducer transforms the ultrasonic energy to mechanical (pressure) waves in the fluid, similar to a diaphragm [23]. Consequently, when the piezoelectric crystals in an ultrasonic transducer receive electrical energy pulses, the radiating plate alters them into ultrasonic vibrations in the cleaning solution.

2.4. Ultrasonic Cleaner Mechanics

Ultrasonic cleaner mechanics refer to the principles and components involved in the operation of an ultrasonic cleaning system. Ultrasonic cleaning is a process that uses high-frequency sound waves (ultrasonic waves) to remove dirt, contaminants, and debris from various objects.

Ultrasonic parts cleaners scrub surfaces through implosions of tiny bubbles [24]. Sonic energy forms voids (or cavities) trapped as bubbles in liquid solutions of water or solvents, resulting in cavitation "bubbles". Subsequently, the force from the microscopic bubbles imploding dislodges any contaminants adhering to the surfaces cleaned. Consequently, the type of contaminant primarily influences the instrument and cleansing media selected for ultrasonic scrubbing [22,24]. Contaminants are classified according to three basic criteria; withstanding micro impact loading action capabilities, bond strength with the surface to be cleaned, and the type of the chemical reaction with the detergent, since the mechanical destruction of contaminant films under the cavitation and acceleration of the chemical interactions between the washing liquids and contaminants from acoustic streaming actions co-occur in the sound field [23].

2.5. The Ultrasonic Generator

Ultrasonic cleaning uses high-frequency, high-intensity sound waves in a liquid to facilitate or enhance the removal of foreign contaminants from surfaces submerged in an ultrasonically activated liquid. Ultrasonic technology has more recently been used in a growing number of applications involving chemical processes and surface conditioning, which, although outside the classic definition of cleaning, use basically the same techniques. Demands for increased cleanliness have driven the development of increasingly sophisticated technology in the field, particularly within the past decade. Today it is possible to customise ultrasonic waves to optimise effects in a wide range of applications, as described by [23].

Electronic ultrasonic generators supply power. The device converts alternating current (AC) electrical energy from a power source, such as a wall outlet, to electrical energy suitable for powering transducers at ultrasonic frequencies. In principle, ultrasonic generators provide high electrical energy pulses to transducers [22–24], where the energy is transformed into mechanical (pressure) waves in the cleaning fluid for vibratory ultrasonic washing actions.

3. Results and Discussion

3.1. The Performance of the Semi-Continuous UMAS

Table 2 summarises the performance of the UMAS proposed in the current study at six steady-state parameters. In the first week the reactor was fed with an influent COD of 65,000 $mg \cdot L^{-1}$ (OLR = 1 $kg \cdot COD \cdot m^{-3} \cdot d^{-1}$) and the COD removal efficiency was enhanced from 97 to 98%. The influent COD concentration was then increased to 88,100 $mg \cdot L^{-1}$ for the six steady states of the experiment. It is clear that increases in influent COD from 65,000 to 88,100 $mg \cdot L^{-1}$ and effluent COD from 1000 $mg \cdot L^{-1}$ to 1500 $mg \cdot L^{-1}$ caused reduction in the methane gas product, CH_4, from 73% to 68.8%, implying that the system was put under stress. This is also reflected by the increase in the concentration of volatile fatty acids (VFAs) during these periods.

The criteria were established by varying the HRT and COD influent concentrations. The UMAS performed well under the steady-state conditions. Moreover, the pH in the reactor was sustained at 6.7–7.8, which was the acceptable range for anaerobic digesters despite the COD level range employed (65,000–88,100 $mg \cdot L^{-1}$).

A linear connection determined from Equation (2) (see Table 1) was utilised to determine the kinetic coefficients in the current study, which are listed in Table 3. During the initial steady state, the MLSS was around 11,800 $mg \cdot L^{-1}$, while MLVSS recorded 9800 $mg \cdot L^{-1}$, 73% of the MLSS. The low MLVSS/MLSS ratio was attributable to the significant suspended solid levels in the POME.

Table 2. Scenarios of bioreactor operation.

Steady-State (SS)	1	2	3	4	5	6
COD feed, mg·L^{-1}	65,000	74,500	76,500	79,400	83,000	88,100
COD permeate, mg·L^{-1}	1000	1980	1500	1350	1450	1500
Gas production, L·d^{-1}	248.8	320	360	385	440	460
Total gas yield, L·g^{-1}·COD·d^{-1}	0.26	0.35	0.58	0.73	0.75	0.87
CH_4, %	73	72.5	68.8	72.5	70.4	68.8
CH_4 yield, L·g^{-1}·COD·d^{-1}	0.19	0.25	0.40	0.53	0.53	0.60
MLSS, mg·L^{-1}	11,800	12,950	15,379	15,900	18,400	21,700
MLVSS, mg·L^{-1}	8614	10,800	11,400	12,600	14,832	18,662
VSS, %	77.40	78.60	79.50	80.80	83.00	87.00
HRT, d	100.4	73.5	23.8	10.6	9.80	7.50
Solid retention time (SRT), d	500	350	140	44.6	18.8	12.1
OLR, kg·COD·m^{-3}·d^{-1}	1	3	5	7	9	11
SSUR, kg·COD·kg^{-1}·VSS·d^{-1}	0.200	0.264	0.274	0.284	0.289	0.340
SUR, kg·COD·m^{-3}·d^{-1}	0.0430	0.9353	4.4540	6.7501	7.8850	9.7000

Table 3. The results of the three substrate utilisation models.

Model	Equation	R^2
Monod	$U^{-1} = 2025S^{-1} + 3.61$ (kg·COD·kg^{-1}·VSS·d^{-1}) Ks = 498 (mg·COD·L^{-1}) K = 0.350 (g·COD·g^{-1}·VSS·d^{-1}) $\mu_{max} = 0.259$ (d^{-1})	99.4%
Contois	$U^{-1} = 0.306XS^{-1} + 2.78$ (kg·COD·kg^{-1}·VSS·d^{-1}) B = 0.111 (-) $U_{max} = 0.344$ (d^{-1}) α = 0.115 (-) $\mu_{max} = 0.384$ (day^{-1}) K = 0.519 (g·COD·g^{-1}·VSS·d^{-1})	99.7%
Chen & Hashimoto	$U^{-1} = 0.0190S_oS^{-1} + 3.77$ (kg·COD·kg^{-1}·VSS·d^{-1}) K = 0.006 (g·COD·g^{-1}·VSS·d^{-1}) α = 0.006 (-) $\mu_{max} = 0.277$ (d^{-1}) k = 0.374 (g·COD·g^{-1}·VSS·d^{-1})	99.5%

The proposed UMAS documented an even higher VSS proportion at the sixth steady state, comprising 86% of the total MLSS. The observation suggested that the UMAS effectively broke down the suspended particles and converted them into CH_4 with increased solid retention time (SRT), In this study, the organic loading rate (OLR) and hydraulic retention time (HRT) were used to control the solid retention time (SRT). The rate at which organic matter is introduced into the system has an effect on the SRT. To control the SRT, the OLR was varied from 1 to 11. SRT increases when the OLR is reduced, while SRT decreases when the OLR is increased. SRT is also indirectly controlled by HRT, which determines how long wastewater remains in the system. Increasing the HRT generally increases the SRT, allowing for a longer solids retention time in the system, consistent with the findings reported in [5]. The observations demonstrated that an extended SRT was beneficial to the system.

At the sixth steady state, the highest influent COD concentration observed was 88,100 mg·L^{-1}, in accordance with the 11 kg·COD·m^{-3}·d^{-1} OLR. The data suggested that the UMAS could process high levels of organic matter while maintaining stable performance. At an 11 kg·COD·m^{-3}·d^{-1} OLR, the UMAS could remove 98.4% of the COD while maintaining a constant 1400 mg/L COD concentration in the effluent. The performance observed in this study was superior to that in [9,10], where the anaerobic digestion of POME was investigated.

Figures 2–4 demonstrate that the three membrane anaerobic system kinetic models for POME treatments were correlated considerably (R^2 values over 98%). The findings suggested the reliability and consistency of the models in predicting the UMAS performance under varying operating conditions. Nonetheless, the Contois and Chen and Hashimoto models performed better than the others, suggesting that OLRs were a vital consideration for the proposed UMAS [3,21]. Considering the effects of OLRs on the system is critical to optimise the performance of the anaerobic digester. High OLRs could negatively impact the stability and efficiency of a digester, therefore requiring careful monitoring and control.

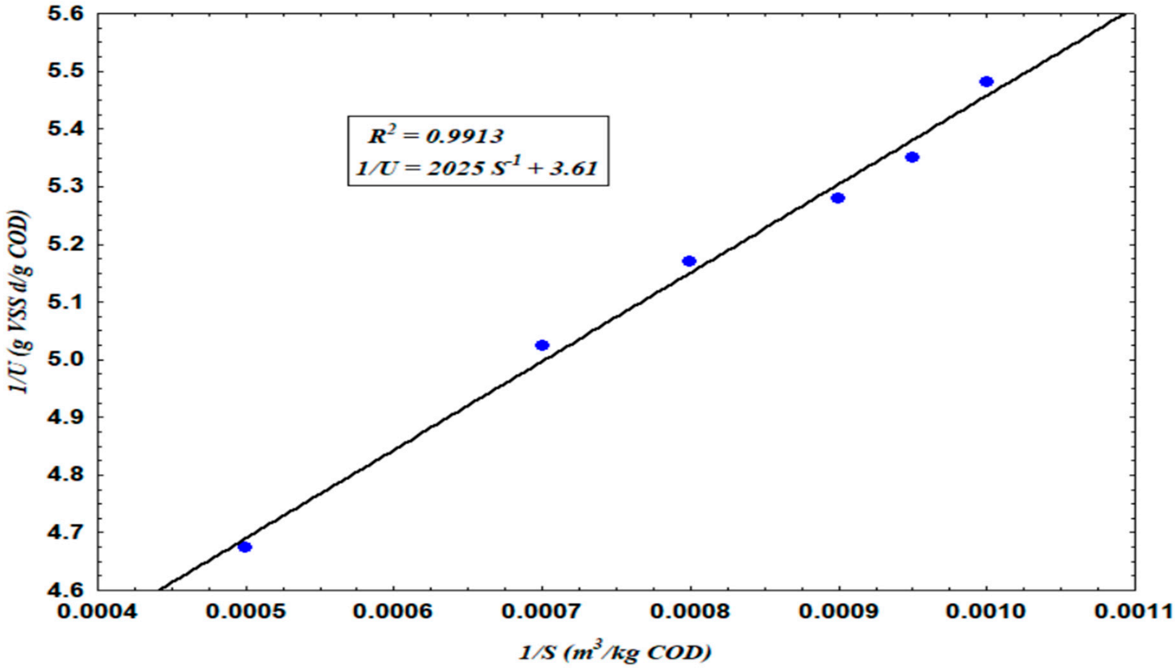

Figure 2. The Monod model.

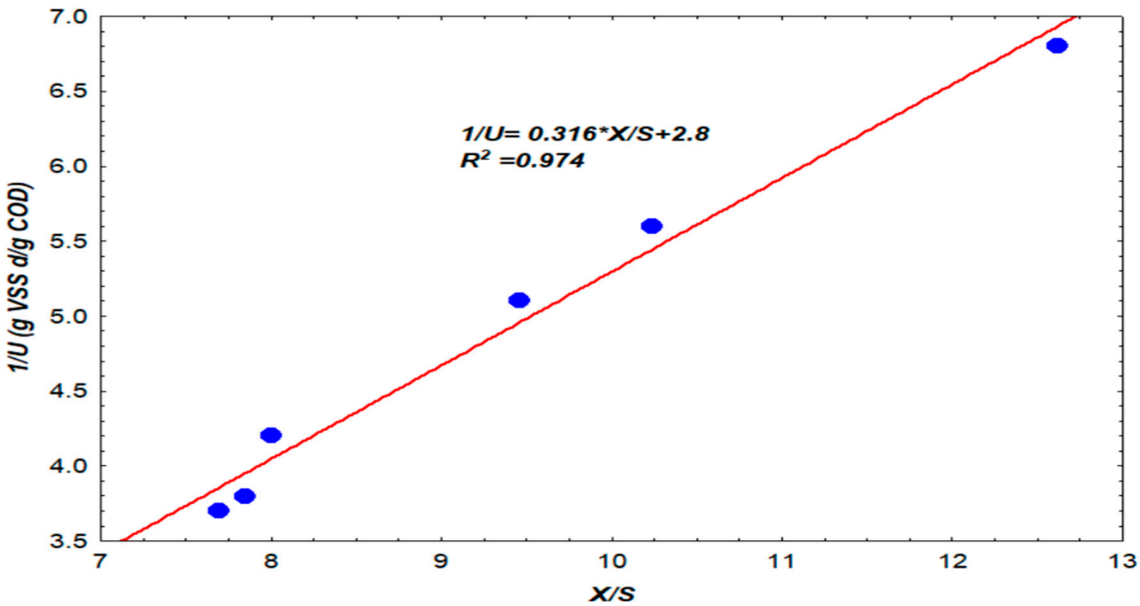

Figure 3. The Contois model.

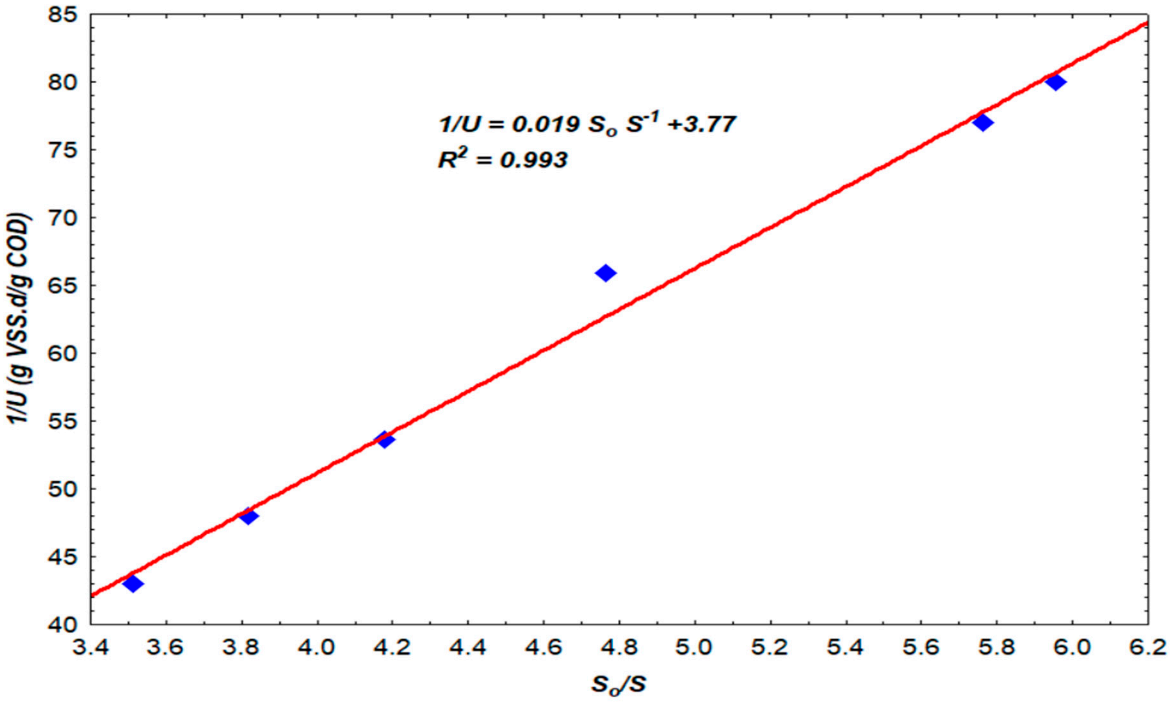

Figure 4. The Chen and Hashimoto model.

In the models, the expected COD concentration in the permeate was a function of the COD influent (So) concentration. The observations were consistent with the Monod model, where the effluent substrate concentration (mg·L^{-1}) (S) and So were treated as distinct entities. The strong correlation (R^2 values of over 97%) exhibited by the models indicated that the UMAS could be subjected to sustained organic loads within the 1–11 kg·COD·m^{-3}·d^{-1} range [3,21], revealing the robustness and adaptability of the system in treating high-strength wastewaters such as POME. Nonetheless, careful monitoring and control of the OLRs are necessary to ensure optimal system performance and prevent potential operational issues.

Figure 5 demonstrates the COD removal figures by the UMAS at different HRTs. The results indicated that the system proposed in the current study could achieve a high COD removal rate. The removal rates rose from 7.5 to 100.4 days of HRT and were maintained between 96 and 98% during the period. The performance of the system was significantly better than reported in previous studies that recorded 91.7–94.2% COD removal by MAS [11] and 85% in anaerobic fluidised bed reactors [12]. The proposed UMAS could achieve significant COD removal rates due to its ability to maintain a high biomass concentration and a long SRT [21], allowing effective anaerobic digestion and biodegradation of organic matter in the POME.

Figure 5 shows the percentages of COD removal by UMAS at various HRTs. COD removal efficiency increased as HRT increased from 7.5 to 100.4 days and it was in the range of 97–98.3%. The improved biomass concentration during the washout phase (see Table 2) might have contributed to the ability of the proposed system to obtain high COD removal rates at longer HRT, but the results also suggested that shorter HRT are equally effective [5,11,21]. Nevertheless, a reduced COD removal efficiency could arise as a shorter HRT might not provide sufficient time for effective anaerobic digestion and biodegradation of the organic matter in the POME. Conclusively, while the UMAS could achieve efficient COD removal in both periods, longer HRT was more desirable for optimal performance.

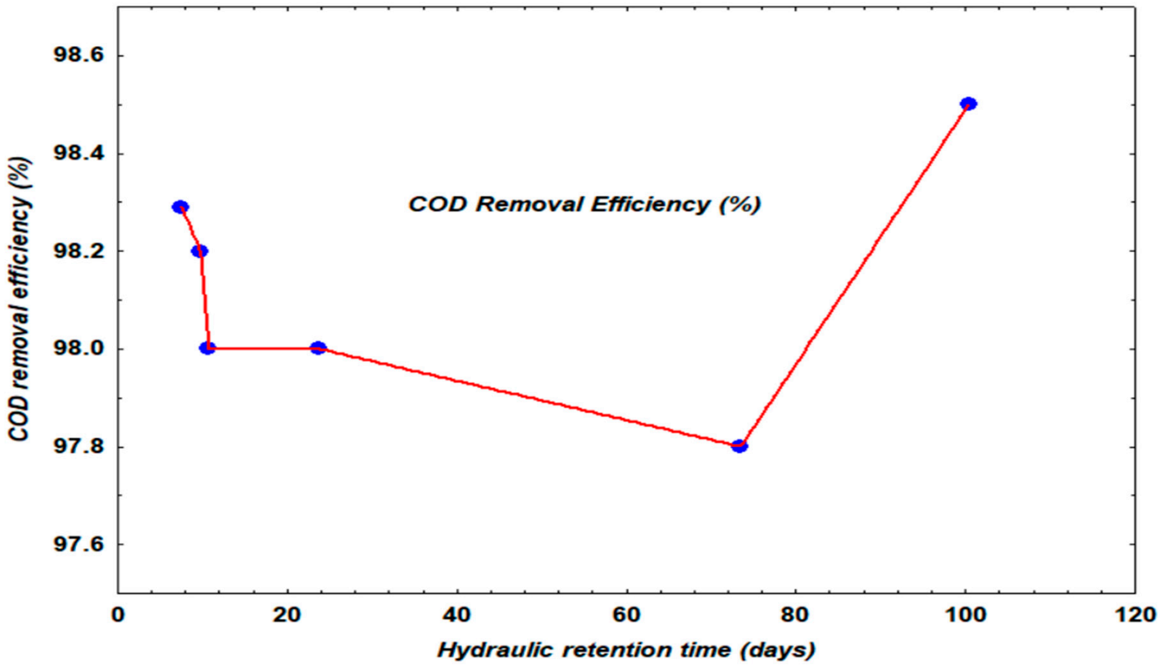

Figure 5. The UMAS COD removal efficiency under steady-state conditions at differing HRT.

3.2. Bio-Kinetic Coefficients Determination

This study plotted the OLR (kg·COD·m^{-3}·d^{-1}) and HRT (day) data obtained against SUR (kg·COD·m^{-3}·d^{-1}) and SSUR (kg·COD·kg^{-1}·VSS·d) to analyse the behaviour of the proposed UMAS system. Figure 6 illustrates the SSUR figures for COD under steady-state parameters. The HRT employed in the present study ranged from 7.5 to 100.4 days. Although the COD SSURs increased proportionately, the HRT decreased, indicating an increased bacterial population in the UMAS.

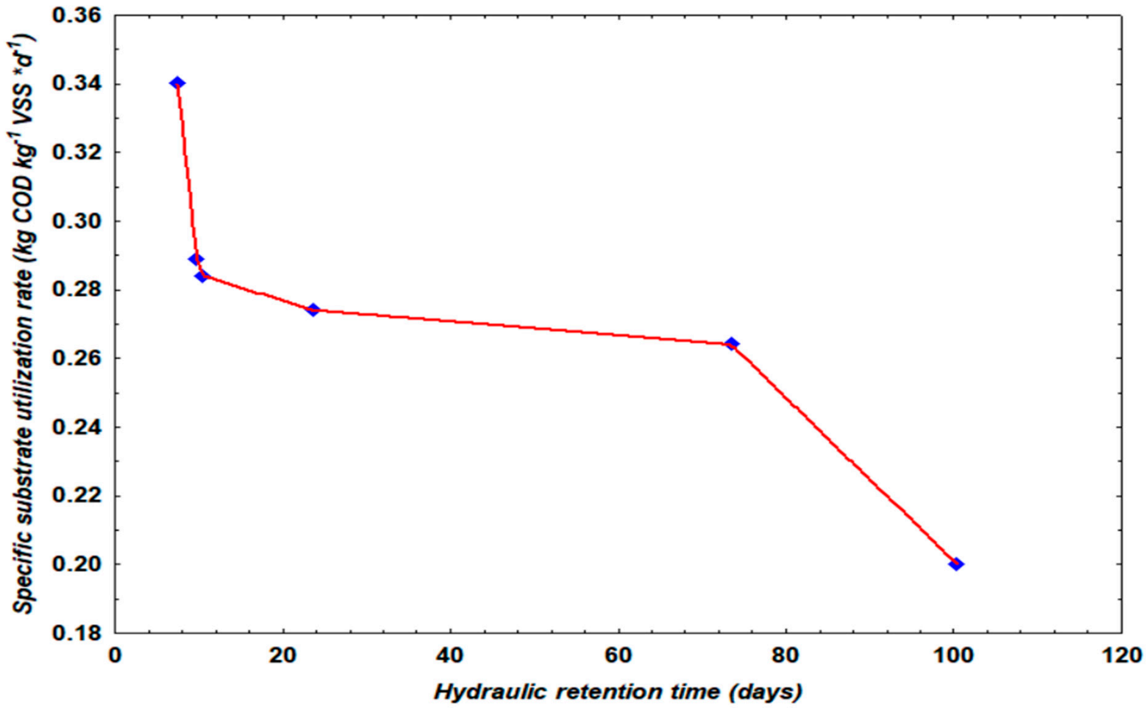

Figure 6. The specific substrate utilisation rates for COD under steady-state environment at different HRTs.

The study employed slopes and intercepts to determine the bio-kinetic growth yield coefficients [5] and specific micro-organic decay rates, demonstrated in Figures 7 and 8, respectively. The most considerable specific biomass growth rates (μ_{max}) procured in the study varied from 0.248 to 0.474 days^{-1}. Table 3 lists the kinetic coefficients obtained from the models. The low max values suggested significant biomass in the UMAS [13]. The findings supported the reports by [3,14], which stated that the parameters max and K values depended on the organisms and substrates under investigation. Cultivating the same organism under similar conditions on different substrates would result in significant max and K value variations. The phenomenon applies to laboratory and natural settings. Consequently, understanding the context-dependent nature of max and K values is crucial, and the potential influence of organism and substrate factors should be considered to interpret better and generalise the observations recorded.

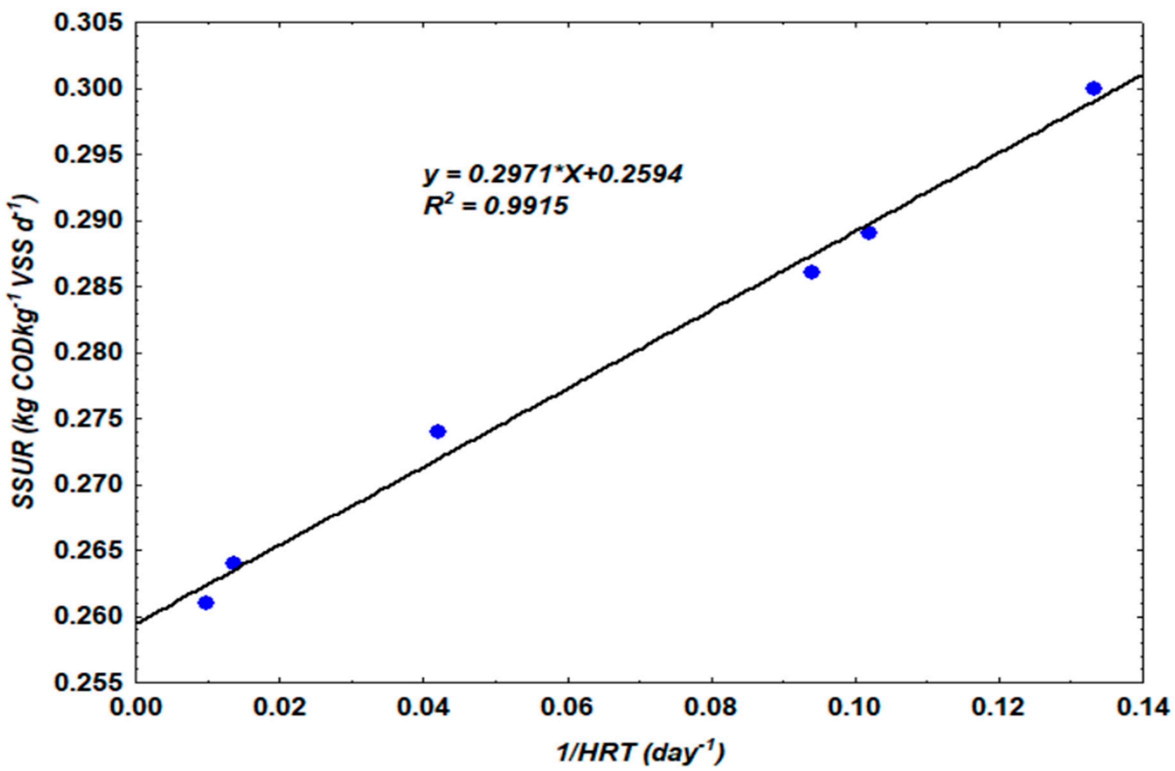

Figure 7. The specific biomass decay rate, b, and growth yield, Y, determination.

3.3. The Permeate Appearance

After the treatment, the permeate appeared significantly different from the raw POME. In comparison to the raw POME, which was black and muddy, the colour was transformed to clear light brown, as shown in Figure 9b while Figure 9a shows the original raw POME. The suspended and dissolved particles in the sample contribute colour to the POME [25]. Following the treatment, the particles in the POME were captured by the membrane, giving the permeate a clearer colour.

3.4. The Production and Compositions of Natural Gas

Ensuring the effective operation of anaerobic digesters and preventing malfunction in POME treatments involve managing several criteria, such as pH and mixing levels, temperature, nutrient availability, and OLR (kg·COD·m^{-3}·d^{-1}). Throughout this study, the microbial population in the anaerobic digester was sensitive to pH alterations. Consequently, the present study retained the pH within the optimal range of 6.8–7.0 to minimise the environmental impacts of methanogens and prevent biogas formation [21,26]. Moreover, deviations from the optimal range could substantially reduce methanogenic activities.

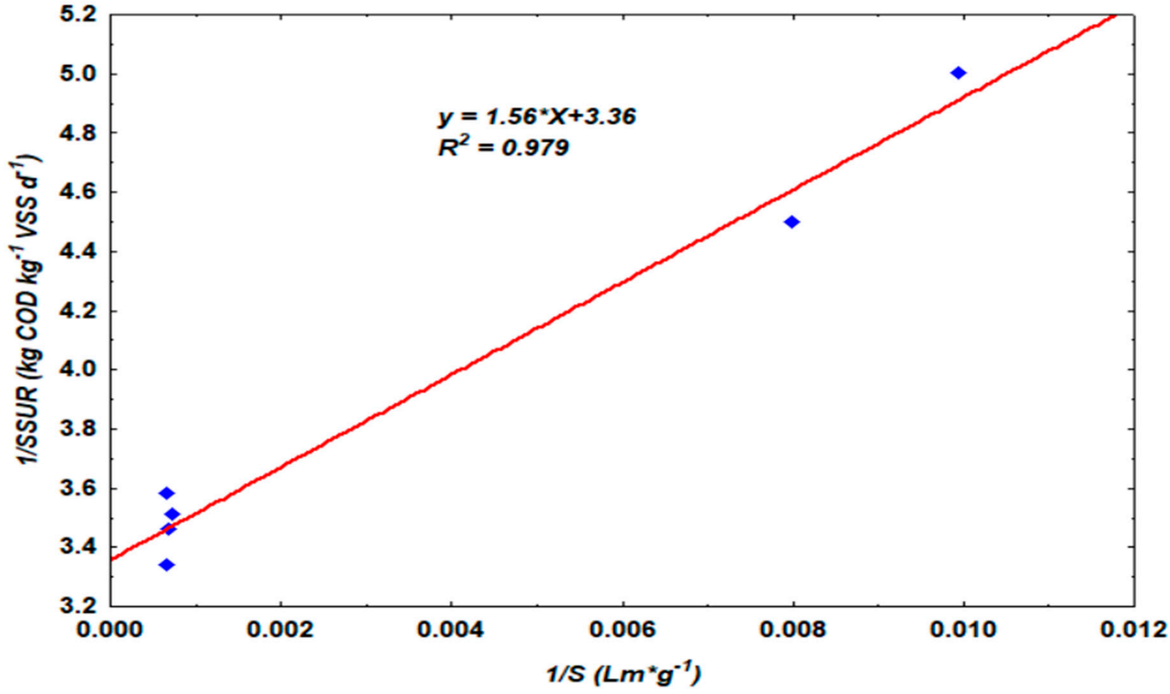

Figure 8. Determination of the maximum specific substrate utilization and saturation constant, K.

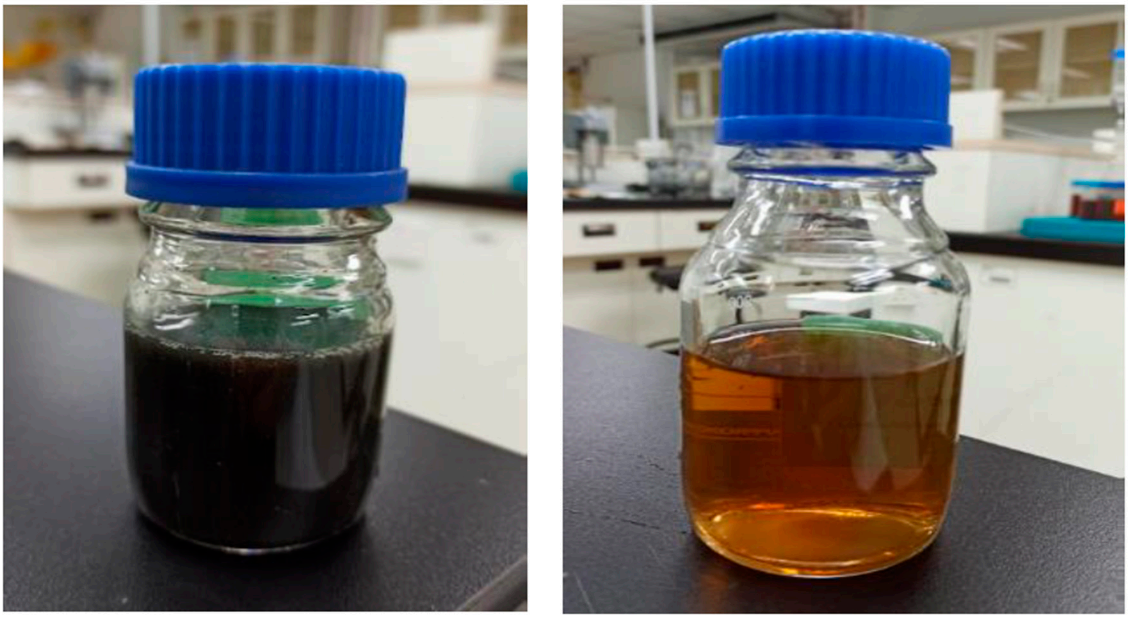

Figure 9. (**a**) Raw POMR, (**b**) Treated POME (permeate).

Mixing is critical for improving microbe–substrate interactions, reducing resistance to mass transfer and formations of inhibitory intermediates, and stabilising environmental conditions. It continuously monitors the pH levels using pH sensors for pH control. Temperature sensors (30–40 °C) were used to continuously monitor the temperature within the anaerobic digestor. Agitators were installed inside the anaerobic digestor to control mixing levels in the UMAS. The current study employed mechanical mixing and the recirculation of biogas [21]. Figure 10 illustrates the amount of CH_4 in the biogas utilised and its production rate. The CH_4 was diminished as the OLRs improved. The percentages of CH_4 gas produced ranged from 68.8 to 73%, with a corresponding CH_4 yield of 0.24 to 0.59% $L \cdot g^{-1} \cdot COD \cdot d^{-1}$.

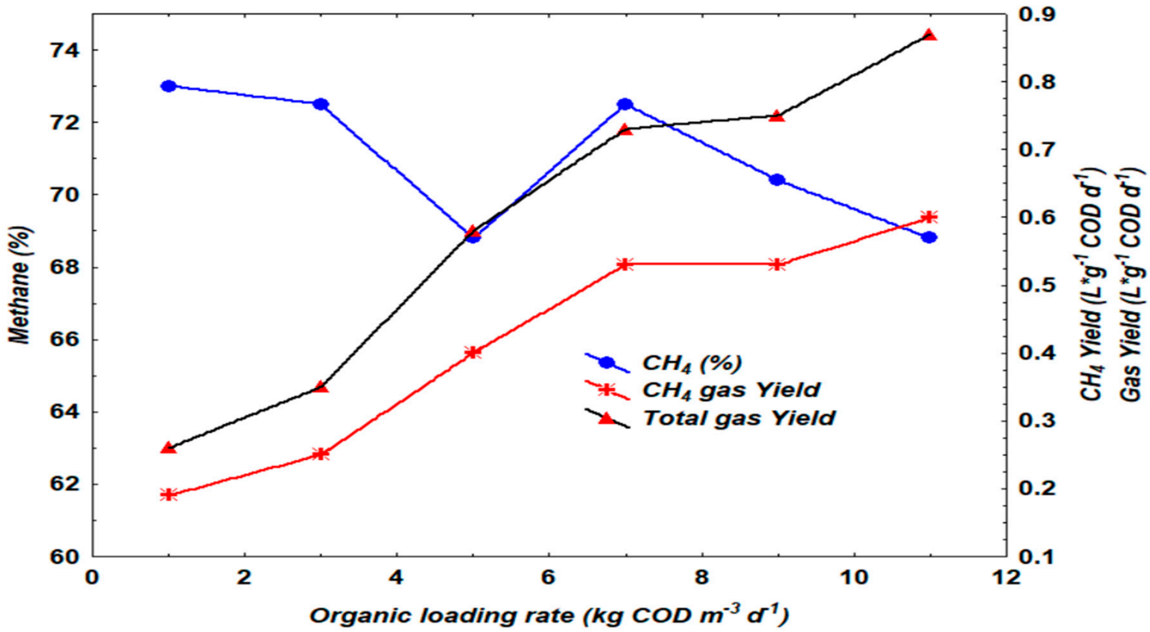

Figure 10. The CH_4 content and gas production.

The biogas production in the current study increased from 0.26 to 0.87 Lg^{-1} COD/d when the OLR was raised to 1 $kg \cdot COD \cdot m^{-3} \cdot d^{-1}$, suggesting that the declining CH_4 gas level might be attributable to the increased OLR that favoured acid-forming bacteria growth over methanogenic bacteria [11,12,21]. Methanogens produce CH_4 through metabolic processes. Nonetheless, the rate of CO_2 production is higher in this study, which led to reduced CH_4 in the biogas. In Figure 10, the curve of CH_4 (%) has a strange bump, which might be attributed to the microbial activity and adaptation. As the OLR is increased from 5 $kg \cdot COD \cdot m^{-3} \cdot d^{-1}$ to 7 $kg \cdot COD \cdot m^{-3} \cdot d^{-1}$, the system experiences an influx of organic matter, which initially overwhelms the existing microbial community. This can lead to a shift in the microbial population and a temporary decrease in methane production efficiency, causing the CH_4 (%) to drop.

Figure 11 demonstrates the relationship between the normalised concentration of COD in the effluent and the SRT at different HRT at an 87,000 $mg \cdot L^{-1}$ influent COD concentration. The normalised effluent COD decreased with rising SRT, and the trend was consistent across all HRT [21,26].

3.5. The Production and Compositions of Natural Gas Analysis

Fourier Transform Infrared Spectroscopy (FTIR) is a technique for obtaining the infrared spectrum of solid, liquid, and gas absorption, emission, and photoconductivity [27]. It is used in this study to identify the different functional groups in both untreated and treated POME samples. The POME bands are depicted in Figures 12 and 13. The main absorption bands are in the regions of 3300–3500 cm^{-1}, 1500–1700 cm^{-1}, and 500–700 cm^{-1}, which represent, respectively, the O-H, C=C, and C-Br stretching. The C-Br peaks might be from the KBr pellet for FTIR, and were strongly similar in both figures [28]. Furthermore, there are weak absorption bands ranging between 2000–2300 cm^{-1} that represent C=C stretching. Some of the treated POME peaks disappeared in Figure 13, indicating that the functional group had been removed by the organic material and particles were captured by the membrane and digested during the 5 h treatment process [29,30].

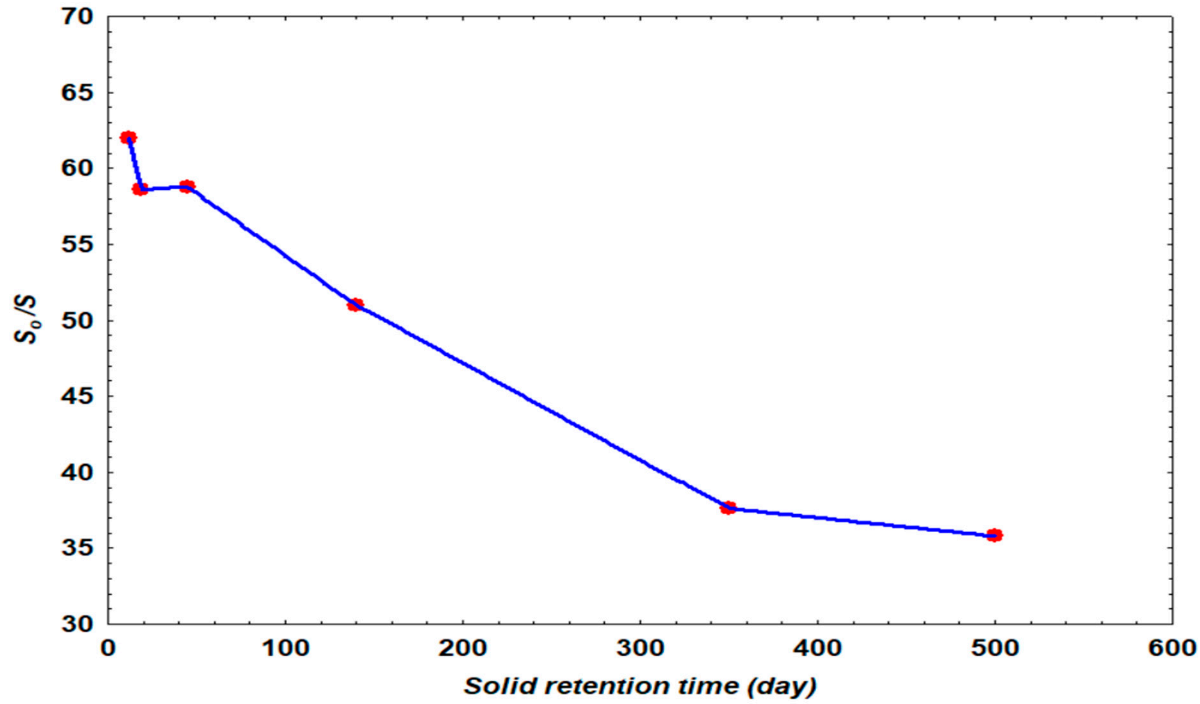

Figure 11. The normalised COD concentration as a function of SRT.

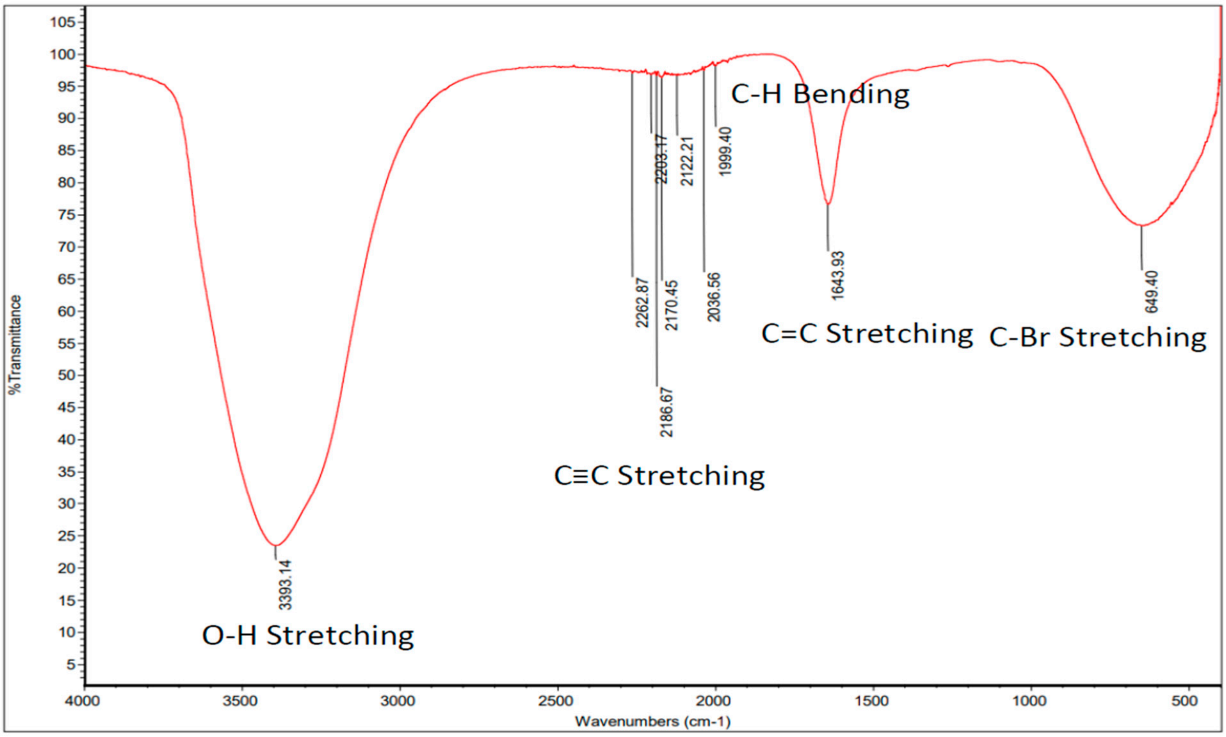

Figure 12. FTIR analysis for untreated POME.

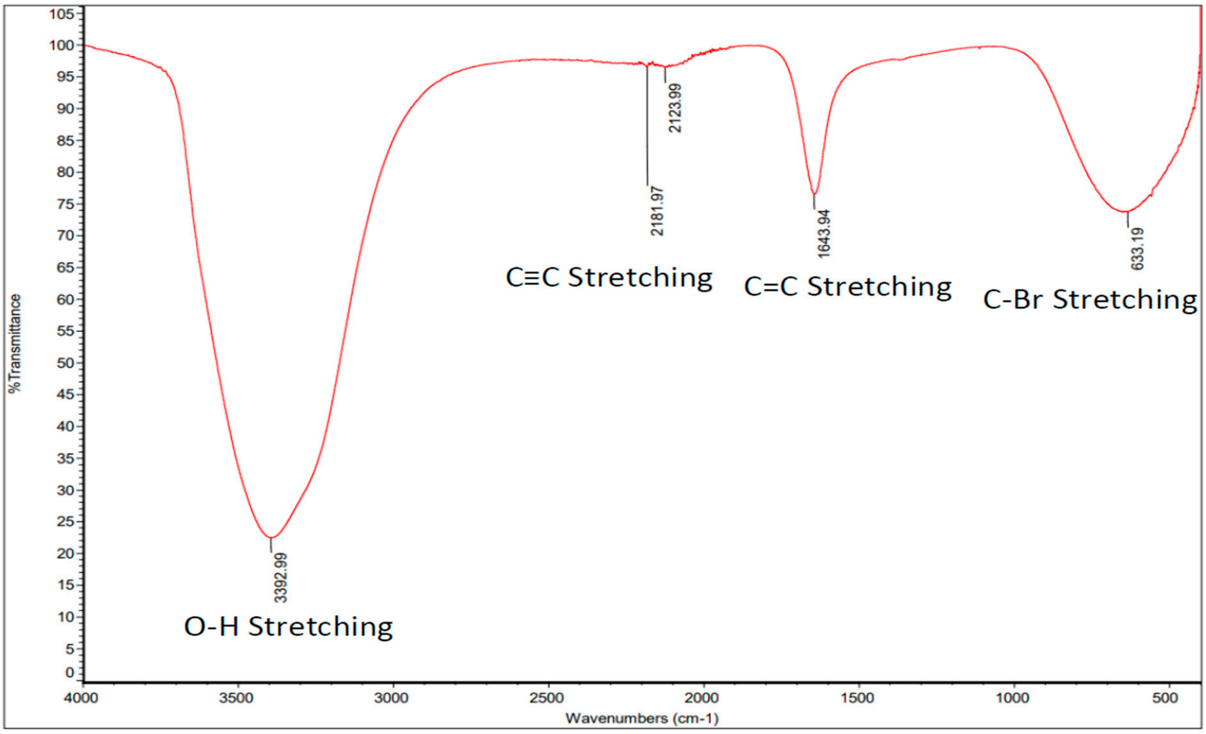

Figure 13. FTIR analysis for treated POME.

4. Conclusions

The ultrasonic membrane anaerobic system (UMAS) is a wastewater treatment system that combines anaerobic digestion principles with ultrasonic treatment and membrane filtration. UMAS enhanced biogas production, improved solids reduction, and enhanced membrane performance. Integrating membrane filtration in the UMAS system helps in the separation of suspended solids, pathogens, and other contaminants from the treated POME.

The concentration of CH_4 in the air decreased with higher organic loading rates, OLRs. The CH_4 yield procured in the current study ranged from 0.24 to 0.59 per gram of COD per day, while its percentage in the biogas was within the 68.8–73% range. The amount of biogas procured improved to 0.87 $L{\cdot}g^{-1}{\cdot}COD/d$ after raising the OLR to 11 $kg{\cdot}COD{\cdot}m^{-3}{\cdot}d^{-1}$. The increased OLR might have reduced CH_4 gas concentration, considering that higher OLRs stimulate the growth of acid-forming bacteria rather than methanogenic bacteria. Methanogenic bacteria produce CH_4, and the higher rate of CO_2 production associated with the growth of acid-forming bacteria reduces the amount of CH_4 in the biogas. The normalised concentration of COD in the effluent and the SRT for different HRT remained consistent across various HRT at 87,000 $mg{\cdot}L^{-1}$ influential COD concentration.

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Nomenclature

COD	Chemical oxygen demand ($mg{\cdot}L^{-1}$)
OLR	Organic loading rate ($kg{\cdot}m^{-3}{\cdot}d^{-1}$)
CUF	Cross-flow ultra-filtration membrane
SS	Steady state
SUR	Substrate utilisation rate ($kg{\cdot}m^{-3}{\cdot}d^{-1}$)
TSS	Total suspended solid ($mg{\cdot}L^{-1}$)
MLSS	Mixed liquid suspended solid ($mg{\cdot}L^{-1}$)
HRT	Hydraulic retention time (day)
SRT	Solids retention time (day)
SSUR	Specific substrate utilisation rate ($kg{\cdot}COD{\cdot}kg^{-1}{\cdot}VSS{\cdot}d^{-1}$)
MAS	Membrane Anaerobic System
MLVSS	Mixed liquid volatile suspended Solid ($mg{\cdot}L^{-1}$)
VSS	Volatile suspended solids ($mg{\cdot}L^{-1}$)
MWCO	Molecular weight Cut-Off
BLR	Biological loading rate
U	Specific substrate utilisation rate (SSUR) ($g{\cdot}CODg^{-1}{\cdot}VSS{\cdot}d^{-1}$)
U_{max}	Specific substrate utilisation rate (SSUR) ($g{\cdot}CODg^{-1}{\cdot}VSS{\cdot}d^{-1}$)
S	Effluent substrate concentration ($mg{\cdot}L^{-1}$)
S_o	Influent substrate concentration ($mg{\cdot}L^{-1}$)
X	Micro-organism concentration ($mg{\cdot}L^{-1}$)
μ_{max}	Maximum specific growth rate (day^{-1})
k	Maximum substrate utilisation rate ($COD{\cdot}g^{-1}{\cdot}VSS{\cdot}day^{-1}$)
k_s	Half velocity coefficient ($mg{\cdot}CODL^{-1}$)
X	Micro-organism concentration ($mg{\cdot}L^{-1}$)
b	Specific micro-organism decay rate (day^{-1})
Y	growth yield coefficient ($gm{\cdot}VSS{\cdot}gm^{-1}{\cdot}COD$)
T	time
a	Proportionality constant (dimensionless)
B	Proportionality constant in Contois model (dimensionless)

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