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Enhancement of Electrochemical–Anaerobic Digested Palm Oil Mill Effluent Waste Activated Sludge in Solids Minimization and Biogas Production: Bench–Scale Verification

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Abstract: The development of the palm oil industry has induced the generation of palm oil mill effluent (POME) together with its waste activated sludge (WAS) in recent years. This study aims to discover new opportunities in treating POME WAS that has high organic content with low degradability but having potential in converting waste into energy. The optimized electrochemical oxidation (EO) of pre-treated WAS was applied prior to anaerobic digestion (AD) to improve the POME WAS digestibility (by assessing its solids minimization and biogas production) under mesophilic conditions at 30 ± 0.5 °C and solids retention time of 15 days. The enhancement in sludge minimization was verified, with 1.6-fold over the control at steady-state. Promising results were obtained with a total chemical oxygen demand (COD) removal of 68.8% with 11.47 mL CH_4/g COD_{added} in pre-treat digester, compared with 37.1% and 3.9 mL CH_4/g COD_{added} in control digester. It is also worth noting that the specific energy (SE) obtained for this EO pre-treated AD system is 2505 kJ/kg TS with about 94% increment in methane production. It is evident that this system was applicable on POME WAS in ameliorating solids minimization as well as enhancing biogas production.

Keywords: anaerobic digestion; biogas; electrochemical; palm oil mill effluent; solids minimization; specific energy; waste activated sludge

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1. Introduction

Anaerobic digestion (AD) had always been an effective biochemical treatment to treat waste or wastewater through the decomposition of complex organic wastes without the presence of oxygen [1]. AD has the ability of treating a variety of wastes such as activated sludge, manure, industrial, food waste, leachate, etc. [2]. Other than its high acceptability considering different types of waste, its popular traits are the stabilization of waste, reduction of the overall mass volume and the ability to produce a renewable energy source-biogas [3,4]. The entire AD treatment involves four main stages, which are hydrolysis, acidogenesis, acetogenesis and methanogenesis [5,6]. Hydrolysis serves the purpose of breaking down raw materials into susceptible simpler forms and preparing them to be further degraded into intermediary compounds through acidogenesis [7]. Volatile fatty acids are then further broken down in acetogenesis to form acetate, hydrogen and carbon dioxide [8]. Methanogens are responsible for converting acetate into biogas, redox between hydrogen and carbon dioxide [9]. Despite the attracting qualities shown, AD still holds on to some limitations. Hydrolysis is known to be the limiting step for AD as recalcitrant intercellular organic matters are protected by a layer of extracellular polymeric substances (EPS) that prevents decomposition from happening easily [3,10]. Therefore, the decomposition of AD in terms of volatile solids reduction has often been limited within 35–45% [11].

In order to overcome the rate limiting steps, which improves the efficiency of AD, various kinds of pre-treatment methods have been introduced in order to degrade high-molecular-weight organic compounds into simpler forms, to assist in ameliorating the hydrolysis rate of wastewater and boosting the biogas production yield at the same time [12,13]. In addition, it is important to understand that the pre-treatment methods used aim to grant more access for anaerobes to decompose organic matter without producing inhibitory substances [14]. There are a variety of pre-treatment methods available for improving hydrolysis and the reaction rates, thus enhancing solids minimization and biogas generation. Physical pre-treatment methods, for instance, thermal pre-treatment at a temperature higher than 80 °C causes the dissolution of the cell wall and helped to improve methane production by 44–46% [15]. Furthermore, chemical pre-treatment through the addition of acid or alkaline chemicals were able to improve COD solubilization by 15.7% and 28%, respectively [16]. Enzymatic pre-treatment, a biological pre-treatment involving enzymes, enhances the disintegration of biomass substrate that helps to boost the biogas production yield [14]. Combined pre-treatment such as electrical-alkali pre-treatment that uses electrolysis with the addition of sodium hydroxide showed a methane yield improvement of 20.3% when compared with non-pre-treated sludge [17]. Despite the different kinds of pre-treatment methods used to improve the performance of AD, the standard pre-treatment method has yet been determined due to the different nature and characteristics of waste. Therefore, considerations need to be taken in terms of the nature of the treated waste prior to selecting a suitable pre-treatment method.

An innovative pre-treatment-electrochemical oxidation (EO), a form of advanced oxidation process, has been showing its positive traits as a pre-treatment, to improve the biodegradability of waste activated sludge (WAS) [18–21]. EO is a clean technology that involves electrons by generating strong oxidizing agents in breaking down the EPS protecting layer of organic matter, which subsequently helps in dewatering and degrading the organic matters into simpler forms to help with the subsequent AD process [3,10,22]. EO aims to prepare the organic matters in a degradable form that helps AD in the disintegration and stabilization of wastewater [23]. Palm oil mill effluent (POME) WAS has been increasing gradually due to the development of the palm oil sector. Limited studies have been performed upon the treatment of this low degradability waste, whereby it would jeopardize the safety of the environment and welfare in the near future [24,25].

EO as a pre-treatment for improving AD had been applied using different types of wastewaters for instance, sewage treatment plant WAS [19], yard waste [26], food waste [2], and landfill leachate [27]. Several studies have successfully showed the feasibility of EO as pre-treatment for different wastes. Pérez-Rodríguez and his co-researchers [24] were able to improve the solubilization of WAS by 1.78% using boron-doped diamond (BDD) electrodes with a current density of 19.3 mA/cm^2 for 30 min. Furthermore, a study by Heng et al. [19] showed a solid removal rate of 38% with Ti/RuO_2 electrodes considering the current density (6 mA/cm^2), electrolysis time (35 min) and sodium chloride (NaCl) electrolyte (1000 mg/L). Erkan et al. [20] also reported a disintegration degree of 23.93% on pre-treated WAS, conducted at pH 10 with 3 A for 100 min using Ti/RuO_2 electrodes. Another research on EO pre-treatment of food waste using Ti/RuO_2 electrodes conducted by Liyanage and Babel [2] with operating conditions of 20 V for 40 min improved the sCOD solubilization by 40%. To date, no attempt has been made using POME WAS as a subject of treatment in AD as this high organic content wastewater has potential in converting waste into energy. This paper is a bench-scale verification in proving EO pre-treatment for further degradation of POME WAS using AD, to compare its digestibility in terms of solids minimization, chemical oxygen demand (COD) removal and biogas production.

2. Materials and Methods

2.1. Sample Characterization

Raw POME WAS was collected from a local palm oil mill, located at Ayer Kuning, Perak, Malaysia. After the sample collection, the collected WAS was left to be settled, and excessive water had been removed prior to any test. Pre-treated POME WAS was prepared according to the previous optimized condition generated through a Design Expert Software [21]. Both raw and pre-treated samples once prepared were stored in the refrigerator (4 °C) for better preservation and to prevent contamination of the samples physiochemically [28]. The characterization of both raw WAS and pre-treated POME WAS were carried out and shown in Table 1.

Table 1. Characteristics of Raw and Pre-treated WAS.

Parameter	Raw WAS	Pre-Treated WAS
pH	8.0 ± 0.1	8.1 ± 0.1
Total Solids (mg/L)	44,702 ± 5142	41,573 ± 4846
Total Volatile Solids (mg/L)	27,190 ± 4583	21,500 ± 2404
Chemical Oxygen Demand, COD (mg/L)	14,224 ± 1720	15,385 ± 2467
Soluble Chemical Oxygen Demand, sCOD (mg/L)	7696 ± 1022	11,453 ± 1084
Suspended Solids, SS (mg/L)	34,700 ± 990	26,970 ± 381
Volatile Suspended Solids, VSS (mg/L)	26,250 ± 2616	20,839 ± 1077

2.2. Bench-Scale Electrochemical Oxidation Pre-Treatment and Anaerobic Digestion

2.2.1. Electrochemical Oxidation (EO) Pre-Treatment

The mechanism of EO is through direct and indirect oxidation, whereby direct oxidation happens directly at the surface of the electrode where organic matter is oxidized. As for indirect oxidation, the disintegration of organic matter happens through the presence of oxidizing agents such as hydroxyl radicals (•OH) and chloride (Cl^-)-related intermediate oxidants [29]. Figure 1 shows a schematic diagram of the EO pre-treatment system, where (1) is the DC power supply; (2), magnetic stirrer; (3), retort stand; (4), electric wires with clips; (5), electrodes; and (6), magnetic bar stirrer. In our previous study, EO pre-treatment on POME WAS had been optimized through a central composite design (CCD)-based response surface methodology (RSM) with the optimum conditions of 17–27 mA/cm^2 current density, 55–75 min of electrolysis time at a fixed electrolyte, sodium chloride (NaCl) concentration of 10 g/L, in achieving MLVSS removal (>20%), capillary suction time (CST) reduction (>43%), EPS increment (<19%) and sCOD increment (>25%) [21]. The pre-treatment process aims to break down high-molecular-weight substances and the EPS layer protecting organic matter from being decomposed by AD microbes. The outcome showed promising results on cell lysis, in terms of sCOD and EPS increment as well as improvement on dewaterability through CST reduction [21]. EO showed a certain percentage of sludge reduction too whereby 23.1% MLVSS was removed after the EO pre-treatment.

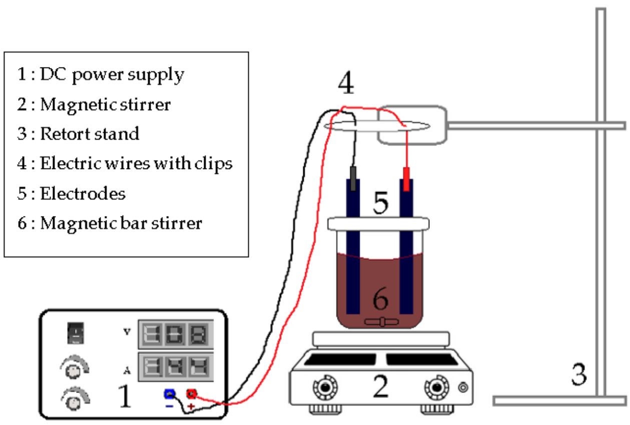

Figure 1. Electrochemical oxidation pre-treatment set-up.

2.2.2. Anaerobic Digestion (AD)

Two identical batch-fed digesters were fabricated using a 1 L Buncher Flask with a working volume of 800 mL. The opening of the Buncher Flasks was sealed with a rubber cork, each connected with two rubber pipes as depicted in Figure 2. Each pipe served different functions, i.e., the shorter pipe was for the flowing in of nitrogen gas (NG), whilst the longer pipe was for feed in-discharge (FD). At the shoulder of the buncher flask, the opening was connected with another pipe for recording the volume of daily biogas (BG) production through a water displacement method. Tedlar bags were used for biogas collection. All openings were sealed with epoxy and white thread pipe tapes to reduce chances of leakage.

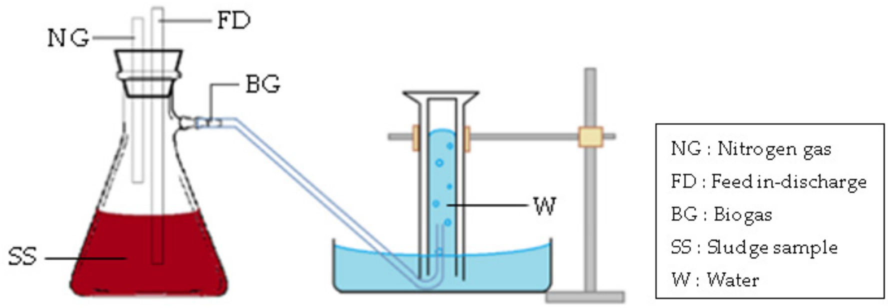

Figure 2. Anaerobic digester set-up.

The inoculum sludge used was collected from existing anaerobic digesters for the treatment of POME. The start-up seed volume was according to the United States Environmental Protection Agency (USEPA), which is 20 times the raw volatile solid of raw WAS [22]. Both inocula of raw and pre-treated WAS were inserted into the digesters through the FD pipe, and nitrogen gas was purged through the NG pipe, to ensure that existing oxygen was completely removed from the digesters, creating an anaerobic condition. The outcome of the digesters was compared considering solids minimization, COD removal and biogas production. The treated sludge from both digesters were collected and analyzed five days per week until it reached steady-state. The steady-state in both the digesters was confirmed considering the stability of some state variables, such as pH, VSS reduction, COD removal, biogas production, and methane and carbon dioxide content in biogas with a variation of less than 10%.

Digesters were carried out at a sludge retention time (SRT) of 15 days with the mesophilic temperature of 30 $\pm$ 0.5 °C. SRT is important for the anaerobic digestion of POME WAS as it serves the purpose of ensuring that sufficient time was given for hydrolysis to take place [30]. A typical mesophilic digester requires a SRT range of 15 to 30 days for better solids minimization [31]. However, it is important to take into account that a prolonged SRT would lead to the bulking of inert compounds that would slow down the microbial activity, while a short SRT would cause the washing out of methanogens [32]. Moreover, studies showed that a SRT of less than 15 days provides a suitable condition for methanogens to grow, while a SRT of more than 15 days would contribute to the competition of microbes for nutrients [33]. Various studies showed that the thermophilic condition (50 $\pm$ 1 °C) was able to achieve better solubility of organic matter [34]. However, a higher temperature of 45 °C was able to reduce the activation energy at the same time, achieving a higher activity of microbes [35]. Despite that, the mesophilic condition of AD was better at ensuring the stability of the entire AD process. Furthermore, the pre-treatment process prior to AD was able to reduce the activation energy as well. A study done by Isa et al. showed that AD at 30 °C for pre-treated POME achieved a better specific growth rate of microbes than that obtained at a higher temperature [35].

2.3. Analytical Methods

The measurement of the VSS concentrations was based on the Standard Method 2540E to keep track of the solids minimization while the Standard Method 5220D was applied to obtain the COD concentrations to monitor the digestibility of the treated sludges. A UV-vis spectrophotometer (model: JASCO V-730, Japan) was used throughout the experiment for the detection of COD concentrations at a wavelength of 600 nm. Biogas volumes were recorded based on the water displacement method, and Tedlar bags were connected to the digesters for biogas collection. Gas chromatography (Model: Perkin Elmer Clarus 580 NGA & SCD & Simdist, United States) equipped with a CARBOXEN-1010 column and thermal conductivity detector (TCD) was used to evaluate the composition of the biogas. The measurement was conducted using the ASTM D1945-14 Standard Test Method.

The specific energy (*SE*) for EO pre-treatment is calculated in terms of the energy usage per unit mass, to identify the energy consumption of the overall pre-treatment system. Equation (1) showed the calculation for *SE* [36]:

$$SE = \frac{(P \times t)}{(V \times TS)} \quad (1)$$

where,

P = electrical power used (kW)
t = electrolysis time (s)
V = volume of pre-treated sludge (L)
TS = total solids concentration (kg/L)

3. Results and Discussion

3.1. pH Monitoring

pH can be considered as an indicator on monitoring the stability of both pre-treated and control digesters [37]. The reason is because most of the microorganisms within the digesters are pH dependent. pH values lesser than 5 or higher than 9 would limit the AD process due to the toxicity effect of methanogens [38]. Figure 3 shows the pH variation of control and pre-treated digesters. At times, just after starting feeding, the pH of the AD system varied and fluctuated in the first four cycles. This is a common phenomenon where a higher percentage of sludge hydrolysis takes place and could be due to the adaptation period of sludge digestion [37]. Starting at the fifth cycle, the pH fluctuated less with a relatively narrower range of 7.8–8.15 and 8.05–8.28, for the control and pre-treated WAS, respectively. The consistency in pH between the control and pre-treated POME WAS represented the stability of the AD system throughout the entire treatment process [39]. In addition, the slight fluctuation of pH might be due to a balanced condition being achieved between methanogenic bacteria with the conversion of organic substances to organic acids [37]. A higher biogas production yield for an AD system to achieve stability falls in the pH range of 7.0–8.5 [40].

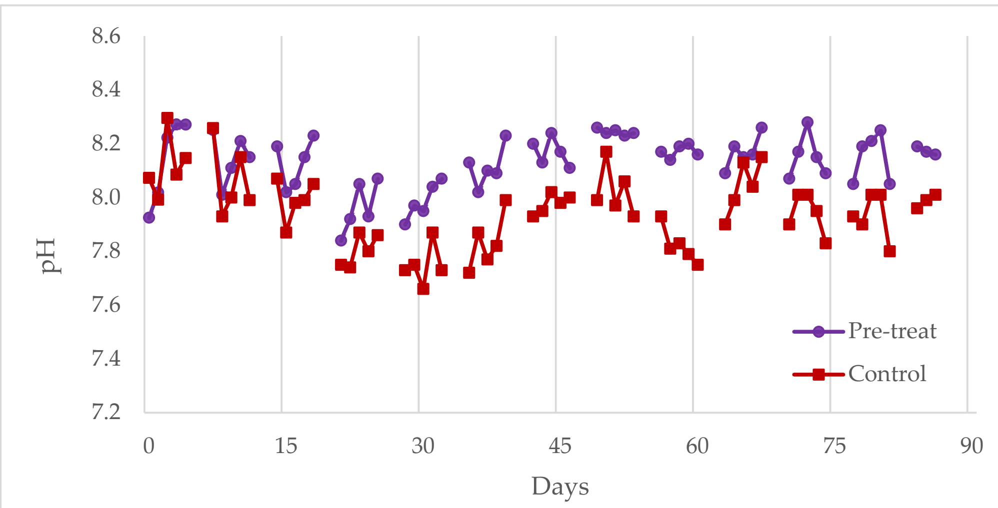

Figure 3. pH variation of control and pre-treated digesters.

3.2. Volatile Suspended Solids (VSS) Concentration

Solids concentration has always been one of the important aspects in determining the efficiency of the digesters, which is reflected in biogas production. The course of VSS concentration is presented in Figure 4. Following both trends (control and pre-treated digesters), both digesters had successfully shown VSS concentration reduction as well as much lesser fluctuations approaching steady-state. However, when comparing both the digesters, it can be clearly seen that the pre-treated digester had achieved better VSS reduction, thus proving the minimization of total sludge volume.

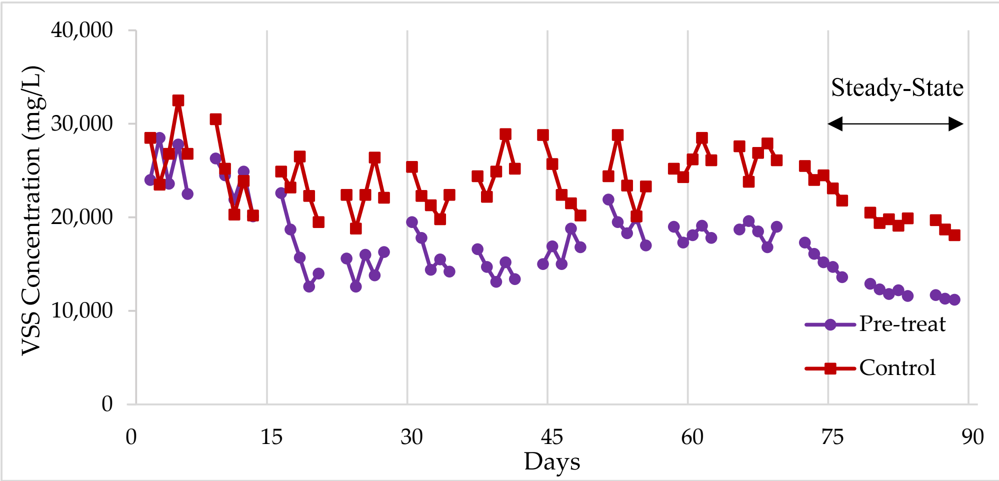

Figure 4. Concentration of VSS between control and pre-treated digesters.

The VSS concentration evinces the organic matter that existed within POME WAS [41]. Other than organic matter, the VSS represents active microbes in WAS. The VSS/SS ratio is often used to estimate the sludge activity [42]. It is important to ensure that microbes are sufficient in the digesters even with the reduction of VSS. The typical VSS/SS ratio of 0.65–0.90 suggested the stability of an AD system [30]. The VSS/SS ratio for control and pre-treated digesters was similar in this study (0.79 $\pm$ 0.03). In terms of solids minimization, a total of 60.8% of VSS reduction was obtained from the pre-treated digester, whilst the control digester achieved a removal efficiency of 48.4%. POME WAS when being treated via AD alone makes solids minimization more difficult due to the EPS and cell walls that makes it difficult for the microbes to reach the organic substances within, which explains the lower VSS reduction for the control digester [43]. According to the results from this study, better solids minimization was achieved after EO pre-treatment and in well agreement with the results obtained by Ye et al. [36] where 41.84% of solid removal was achieved with EO pre-treated AD of STP WAS. In addition, 47.2% of solids minimization in terms of VS was achieved by Heng et al. [19] as well on the WAS that had undergone EO pre-treatment. The results indicated that the EO pre-treatment had successfully improved the digestibility of the POME WAS whereby high-molecular-weight substances were broken down into simpler forms that enables hydrolysis of AD to be carried out more easily, hence the improvement of solids minimization [16]. It was believed that with the improvement in the rate of disintegration, organic acids were easily generated from organic matter during the acid formation stage [36].

In addition, by integrating these results with those from previous studies, additional solids minimization from EO needs to be included in the overall solids minimization for pre-treated digesters, which was a total of 79.4% with the final concentration of 11,200 mg/L. The pre-treated digester removed 38.1% more VSS concentration at the end of the AD process compared with the control digester (18,100 mg/L). The better solids minimization of VSS was 1.6-fold for the pre-treated digester compared with the control digester, proving that EO as a pre-treatment was able to enhance solids minimization of POME WAS.

3.3. Chemical Oxygen Demand (COD) Concentration

COD was one of the organic pollutant indicators for wastewater that was measured as manifestations to prove the effectiveness of the AD process, as illustrated in Figure 5. Positive outcomes were attained from both digesters. Three different patterns can be identified at different cycles of AD. At the starting of the first and second cycles (first 30 days) of the digestion process, both COD concentrations portrayed a wider fluctuation, which then gradually decreased during the third and fourth cycles (31–60 days) of treatment. Vast fluctuations at the early stage of treatment may be an indication of microbes acclimatizing to the newly introduced environment. Although the inoculum used was previously equipped for treating POME, microbes would still require a period of time to adapt into the POME WAS environment. New cells will multiply after the acclimatizing stage, which explains the lower fluctuation at the third and fourth cycles [44]. Both the COD concentrations reached the steady-state at the fifth and sixth cycles.

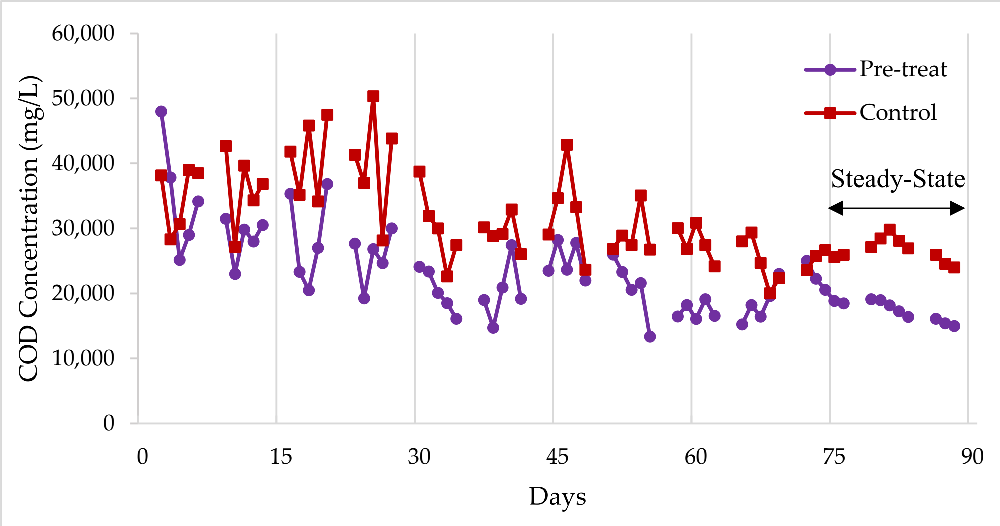

Figure 5. Concentration of COD between the control and pre-treated digesters.

It is distinctive that the pre-treated digester achieved better COD removal when compared with the control digester by the end of the digestion process. The EO pre-treated digester achieved almost two times better COD removal when used with the control digester, with removal of 68.8 and 37.1%, respectively. The outcome of this study tallied with the results obtained from other research where AD with electrochemically pre-treated sewage WAS achieved 61.5% of COD removal [19]. Results obtained from this research even surpassed the performance shown by Feki et al. [45], that achieved total COD removal of 28.3% for EO pre-treated STP WAS. The higher removal efficiency achieved mainly due to the EO process whereby •OH and other oxidizing agents were able to oxidize the recalcitrant cell wall of the organic matter, thus leading to solubilization and releasing the soluble COD. With the increase in sCOD, it grants more access for the microbes in AD to disintegrate POME WAS, which resulted in the consequences of removal in the concentration of COD [3]. Moreover, the final COD concentration for control and pre-treated digesters were 23,999 mg/L and 14,976 mg/L, respectively. Digester that had undergone pre-treatment showed the difference of 37.6% in comparison with the control in terms of COD concentration. The improvement in eliminating COD concentration proved that EO was an effective pre-treatment for AD of POME WAS, also making it practical [45].

3.4. Biogas Production and Its Composition

The digestibility of sludge can be determined based on the volume of biogas (methane) generated from AD. The reason is because organic matter within the WAS is protected by recalcitrant matters that restrict the anaerobes to degrade them during hydrolysis, which tends to affect the subsequent methanogenesis to take place in generating biogas. The cumulative biogas volumes for both the control and pre-treated digesters are depicted in Figure 6. From the trend, it can be seen that the pre-treated digester was able to achieve a total of 1490 mL of biogas (11.47 mL CH_4/g COD_{added}) whilst 781 mL was collected from the control digester (3.90 mL CH_4/g COD_{added}) towards the end of the AD. Furthermore, from the trend of the biogas production volume, the time required for pre-treated AD to achieve the same amount of biogas in the control digester (steadily at about 760 mL) was 45 days. Therefore, pre-treated digester took about 25 days lesser than the digestion process to achieve the same results as the control digester.

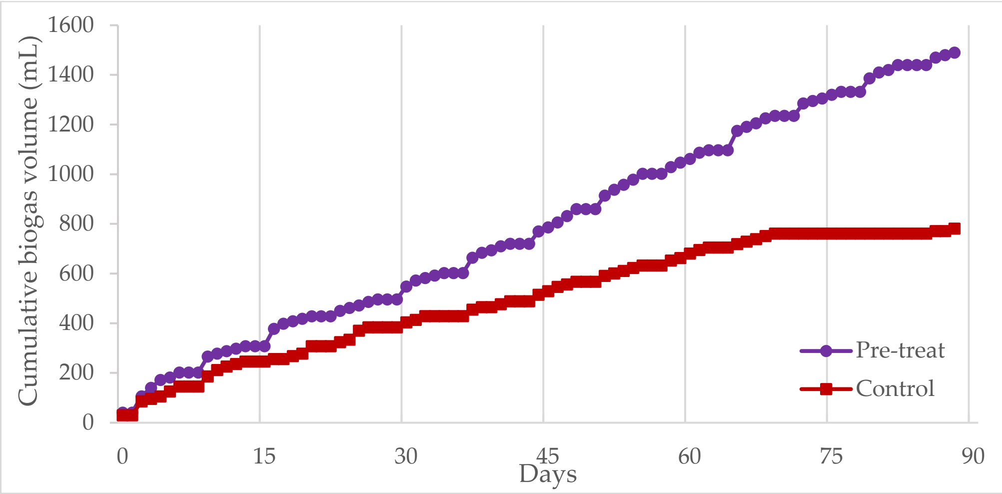

Figure 6. Cumulative biogas production of control and pre-treated digesters.

From the cumulative biogas collected, it proved that EO had effectively shortened the digestion time in terms of providing degradable organics for the subsequent anaerobic treatment of POME WAS. Furthermore, the increment in sCOD and EPS concentrations during EO made organic substances more attainable by microbes during the AD process [45]. VSS reduction and COD removal with biogas production were actually complementary in assessing the AD performance [46]. As discussed, the minimization of VSS volume and COD removal proved the disintegration of organic matter. The increase in mineralization of organic matter meant the improvement of the limiting hydrolysis step. Lastly, through the enhancement of hydrolysis, the subsequent step especially methanogenesis was able to be carried out more smoothly, thus producing more biogas. This corroborates that POME WAS that had undergone EO pre-treatment was able to improve the degradation of organic compounds through the demolition of recalcitrant cell walls of large molecules, thus improving the biogas production [26].

Conventionally, biogas composition consists of 50–75% of methane gas with 25–50% of carbon dioxide [47]. A better composition of methane within the biogas proves the low production of syntrophic acetogen where they tend to induce the conversion of hydrogen and carbon dioxide during digestion into acetic acid, thereby affecting the digestion process [18]. The biogas composition for both control and pre-treated digesters, together with the methane production rate, is shown in Table 2. A slightly higher methane percentage was achieved by the pre-treated digester (74.3%) when compared with the control digester (72.9%). Hydrogen sulfide was not detected in both digesters, proving that no over-acidification or process upset occurred in the ADs. It is worth noting that a high percentage of methane content would be able to convert to a higher amount of electricity. A higher methane content represents a lower percentage of impurities within the biogas produced. Moreover, the calorific value of the produced biogas can be prohibited by the higher percentage of carbon dioxide formed [48]. An improvement of 1.2-fold for the methane production rate was achieved when municipal WAS underwent electrical-alkali pre-treatment (at 5 V; pH 9.2) using Ti/RuO_2 electrodes [17]. In this study, the outcome was better whereby the methane production rate of the pre-treated digester improved by a factor of 2.9-fold when compared with the control digester.

Table 2. Biogas composition and methane production rate of control and pre-treated digesters.

	Control Digester	Pre-Treated Digester
Methane, CH_4 (%)	72.9	74.3
Carbon Dioxide, CO_2 (%)	27.1	25.7
Methane production rate (mL CH_4/g COD_{added})	3.90	11.47

3.5. Energy Consumption

The pre-treatment of POME WAS can improve its biodegradability and increase biogas production during AD. However, the process also consumes energy simultaneously. Hence, it is important to consider both the energy consumption and the effectiveness of the selected pre-treatment method in improving the biodegradability and biogas production when evaluating its sustainability and technoeconomic feasibility during decision making for process scale-up considering the industrial applications.

In this study, the calculated specific energy (SE) obtained for this EO pre-treated AD system is 2505 kJ/kg TS, with a 94% increment in methane production. A study of a similar pre-treatment but a different type of WAS obtained a lower SE (1811 kJ/kg TS), with only a 20% increment in methane production [32]. Although energy consumed via EO pre-treatment in this study was slightly higher, the enhanced AD performance could potentially contribute to more attractive economic advantages via the increment in methane/biogas production for sale and the reduction in disposal expenses for solid waste management. The way in which EO worked was by releasing organic matters present in the POME WAS, which enhanced their degradation and kinetics for biogas generation. The promising result demonstrated the potential of the EO pre-treated AD system for biogas production with the proper selection and application of WAS. In addition, the EO pre-treated AD system was found to surpass other pre-treatment methods, such as ultrasound, thermal and ozone processes, which had SE of more than 4000 kJ/kg TS with less than 20% of methane production enhancement [36]. This again highlighted the tremendous breakthrough in the utilization of EO to achieve substantial improvements for biogas production with effective energy utilization as compared with the other pre-treatment methodologies.

Moreover, energy consumption in EO can be potentially optimized via a combination of intensive process design, heat integration and incorporation of renewable energy sources within the system. This can be further explored via process simulation, design and technoeconomic assessment to optimize the EO-based pre-treatment technologies for the AD of biomass waste prior to large-scale application.

4. Conclusions

The generation of palm oil mill effluent (POME) waste activated sludge (WAS) has been gradually increasing annually and is still increasing due to the rapid development of the palm oil industry. The treatment of POME WAS is an unavoidable stage; while anaerobic digestion (AD) is the conventional treatment process, it can only do so much. Hence, it has been proven that pre-treatment is an essential step to enhance the digestibility of the AD through this study. The outcomes of this study showed an improvement in the EO pre-treated AD system compared with the control digester. A total of 60.8% of solids minimization was obtained from the pre-treated digester, whilst 48.4% from the control digester. In terms of COD removal and biogas production, promising results were shown, i.e., 68.8% of total COD removal with 11.47 mL CH_4/g COD_{added} of the methane production rate was obtained with the pre-treat digester, while 37.1% of total COD removal with 3.9 mL CH_4/g COD_{added} was obtained with the control digester. It was improved by a factor of 2.9-fold in the methane production rate when compared with the control digester. The specific energy obtained for this EO pre-treated AD system was 2505 kJ/kg TS with about a 94% increment in methane production. Therefore, it is evident that EO as a pre-treatment for AD of POME WAS was able to improve the biodegradability and biogas production when evaluating its sustainability and technoeconomic feasibility during decision making for process scale-up with industrial applications. Waste treatments are carried out in the hope of reducing the residue waste and relieve the threats it brings; the fact that it is able to convert matter into energy is an additional advantage of the treatment system. Future studies should be performed to evaluate the combination of waste management with the technology of possibly generating renewable energy.

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