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Agro-Based Wastewater Profile by Biological Treatment of Pond Treatment System in Kulai, Johor

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Abstract: Agro-based wastewater industries tremendously impact the environment when discharged into rivers. The oil palm industry is one such industry, and its daily operations to produce palm oil generate large amounts of wastewater, called palm oil mill effluent (POME). A high organic content of POME is continuously produced, and its production increases annually. The challenge of the POME treatment system is to meet the required effluent standards, and the color of the POME is difficult to remove. Due to several advantages, the ponding system is the preferred conventional wastewater treatment method for POME. Therefore, this study aimed to investigate the performance characteristics of the ponding system in relation to color-causing compounds. This study collected POME samples from cooling, anaerobic, facultative, and two algae (aerobic) ponds. The physicochemical characteristics of the samples were measured in the influent and effluent of each pond, including the pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (AN), total organic carbon (TOC), color, oil and grease (O&G), carotene, phenolics, and tannin-lignin. Pollutants in POME were statistically analyzed for their relationships. To evaluate the efficiency of the ponding system, pollutant removal was measured for each biological treatment pond. The results showed that the biological treatment system removed 70-90% of the pollutants, with the final effluent meeting the acceptable standards for TN and AN parameters. However, removing color-causing compounds in POME, particularly phenolics (0.955, P = 0.003) and tannin-lignin (0.969, P = 0.001), remains a challenge in the treatment process. These compounds had the strongest correlation with color, with low removal rates observed in the facultative ponds due to floating sludge formation. Further analysis of the POME samples showed that carotene, which had the lowest presence in POME, was not significantly correlated with color (0.649, P = 0.163). This study can be useful for tertiary treatment, and additional treatment methods may be necessary to improve the effluent quality by polishing biologically treated POME.

Keywords: treatment ponds; biological treatment; agro-based wastewater; POME; phenolic; tannin-lignin; carotene.

1. Introduction

Biological treatment has been introduced for the past few decades and has been continuously used in industrial wastewater treatment. Biological wastewater treatment is a popular choice among industries because of its effectiveness in eliminating contaminants and several other important considerations. It includes energy efficiency for valorizing excess nutrients in the wastewater to a certain extent [1]. In addition, it is cost-effective in removing nutrients and is flexible in the treatment process compared to others [2]. Interest in using biological wastewater treatment to remove toxic heavy metals from high-strength wastewater has increased [3]. Wastewater from palm oil processing is a substantial source of water pollution in Malaysian rivers. The wastewater produced from the extraction of palm fruit bunches for oil is called Palm Oil Mill Effluent (POME).

In this process, palm fruit bunches were stripped to separate the fruits and bunches. It was then sterilized by steam to yield crude palm oil (CPO). The pericarp was separated from the seeds by steaming the fruit in the digesters. The digested fruits were pressed to extract the oil and then refined by centrifugation and evaporation to eliminate water. Next, the kernels must be cleaned and dried after removing the remaining fibers and shells [4]. This agricultural industry is driven by tropical weather, which receives a large amount of sunlight and rainwater throughout the year. In December 2019, oil palm plantations accounted for 5.217 million hectares throughout the country. Another 0.683 million hectares are cultivated to expand the oil palm industry [5]. This industry produces over 20 million tonnes of crude palm oil annually, contributing 4% to Malaysia's gross domestic product.

POME has a high organic content, solids, and oil and grease (O&G) [6]. Besides, it has significant amounts of heavy metals [7, 8]. If discharged improperly, POME with acidic, thick, brownish viscous, and high colloidal suspension can disrupt the aquatic ecosystem and adversely affect nearby villages [9, 10]. In the direct discharge of POME, clogs and waterlogs may occur in the soil, destroying the flora [11]. However, direct release into the river results in water depletion and subsequent aquatic pollution, as microorganisms and organic compounds exist in POME [12]. Despite this, POME has been reported to contain nontoxic heavy metals that can be handled without posing a significant environmental risk [13]. POME production is expected to increase annually. Malaysian palm oil is the second largest contributor to palm oil worldwide, accounting for approximately 80% of its production [9]. Thus, ponding systems have become the preferred practice for treating high volumes of wastewater in palm oil mills. The geographical location of the mill makes this choice possible. The site provides a large area of land and a consistently warm climate, making it a suitable location for treating POME [14]. In addition, this treatment is widely used in Malaysia because of its relatively low initial investment, low requirement for labor skills, and affordable operating costs. CPO production produces 2.5–3.75 tonnes of POME, which requires 5–7.5 tonnes of water to process, 50% of which may end up as wastewater [15]. Davies *et al*. [16] estimated that 3 tonnes of POME are generated for every CPO production per tonne. According to the Malaysian Palm Oil Board (MPOB), Malaysia produced approximately 19.14 x 106 tonnes of CPO in 2020. However, due to the pandemic, production was slightly reduced in 2021 and 2022. Despite this, the trend for CPO production has been increasing, with production rising from 18.12 x 106 tonnes in 2021 to 18.45 x 106 tonnes in 2022. Therefore, it could be interpreted that the generation of POME in those years would be around 57.42 x 106 tonnes (2020), 54.35 x 106 tonnes (2021), and 55.36 x 106 tonnes (2021).

In treatment ponds, POME is channeled to a series of ponds, namely cooling, anaerobic, facultative, and algae ponds. The fresh POME discharged from the extraction process is at a high temperature and must be cooled in the cooling pond. Initially, POME was treated using an anaerobic pond, offering a cost-effective method for digesting large amounts of solids without aeration. In the literature, anaerobic effluents have been recorded at a low sludge concentration of 5-10% [17]. Anaerobic and facultative ponds can also degrade Biochemical Oxygen Demand (BOD) [18]. However, the treated POME has not yet been ready for discharge to the river because of the high levels of Chemical Oxygen Demand (COD) and BOD. The POME is further treated in the algae pond, which grows microbial cells by consuming phosphorus and nitrogen to break down carbonaceous contaminants. Other than conventional open ponding systems, various researchers have attempted to lower the POME concentrations to acceptable BOD levels of 100 ppm and 20 ppm for West and East Malaysia, respectively. Among the technologies considered are membrane filters, bioprocesses, physical processes, and a combination of physical and bioprocesses. Despite producing high-quality effluent, replacing the current ponding system treatment practice is not feasible. For instance, membrane filtration can remove approximately 90% of pollutants [19, 20]. Even so, the fouling problem caused by the cloudiness of POME makes it ineffective for treating raw POME. Besides that, owing to the solid and lipid contents in POME dissolved air flotation and grease traps have been used as treatment methods [21]. However, these systems are still distant when considering excess sludge, chemical usage, and energy consumption, which lead to high operational costs [21, 22]. POME has also been treated using Fenton oxidation, photocatalysis, adsorption, and coagulation [23]. However, organic pollutants can only migrate between forms using these methods [24]. Also, organic pollutants cannot be effectively mineralized.

The ponding system has previously been evaluated for its performance in treating POME; however, its performance characteristics with respect to the color of POME have never been investigated. Color removal during POME treatment remains a challenging problem. This paper presents a novel approach for removing color from POME using a ponding system. In this study, the biological treatment efficiency was evaluated using a conventional ponding system in relation to the color of POME for wastewater with high organic content. By studying how the ponding system removes POME, its advantages and disadvantages, and potential applications, this study could contribute to understanding POME removal patterns. Furthermore, it presents a basis for enhancing treatment processes to meet Malaysian effluent quality standards if used in conjunction with other technologies.

2. Materials and Methods

2.1. POME sampling physicochemical characterization.

POME samples were obtained from a ponding system at a local palm oil mill in Kulai, Johor. This pond system consisted of cooling, anaerobic, facultative, and two algae (aerobic) ponds, as shown in Figure 1. All samples were collected from the influent and effluent points of each pond. 3 L of samples were collected three times. POME samples were preserved in an icebox during transport to the Environmental Engineering Laboratory at the Universiti Teknologi Malaysia.

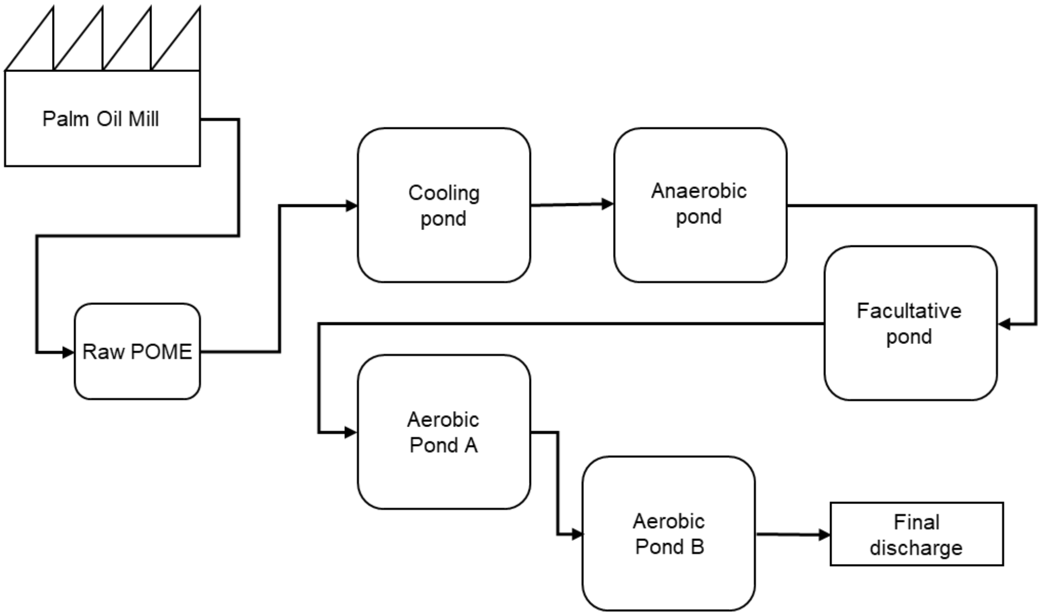

Figure 1. Schematic diagram of a pond treatment system.

2.2. Sample preservation.

The POME samples were preserved at 4°C to prevent the biodegradation of microbes in wastewater. Prior to analysis, the samples were removed from the cold room and allowed to reach room temperature.

2.3. Sample analysis.

The physicochemical characteristics of the POME samples were analyzed in accordance with the standards of the American Public Health Association (APHA) [25]. The samples analysis included pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (AN), total organic carbon (TOC), color, oil and grease (O&G), carotene, phenolic, and tannin-lignin.

2.4. Statistical analysis.

The rate of association between two variables was calculated using the Pearson correlation coefficient (r) (Eq. (1)). A significant association between these variables was measured by hypothesizing that they were normally distributed. A correlation coefficient of -1, 0, or +1 indicates a negative linear correlation, no linear correlation, or a positive linear correlation [26].

$$r = \left(\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})\right) \Big/ \left(\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sum_{i=1}^{n}(y_i - \bar{y})^2\right) \quad (1)$$

3. Results and Discussion

3.1. Physicochemical properties of POME.

Raw POME is biologically treated in anaerobic, facultative, algae A, and algae B ponds. An overview of the series of treatment ponds for removing pollutants from POME is presented in Table 1. POME was continuously treated, and the retention times for each pond were as follows: cooling (1 day), anaerobic (45 days), facultative (20 days), and both aerobic ponds (7 days). POME concentration varies widely according to a number of factors, including the mill's discharge standards, the effectiveness of the extraction process, variations in processing techniques, time, geographical region, harvest season, climate, and grade of palm oil produced [27, 28]. Since the palm oil mill operates intermittently, it is possible that fresh fruit bunches need to be stored before they can be processed. As a result, oil extraction may be affected. Due to the decaying fruit lets of the oil palms, POME has a substantially higher solid content. Therefore, there is a significant likelihood that fresh POME could be mixed with the old one, resulting in an increase in the organic and inorganic content [29, 30]. The table shows that the raw POME concentration decreased significantly in the final effluents before discharge into the local stream.

The table below shows a few parameters with standard effluent limits for the Malaysian oil palm industry according to the Department of Environment (DOE) [31, 32]. POME concentrations demonstrated large degradations over a series of treatment ponds, especially at the initial stage [28]. Despite the high level of pollutant removal from treated POME, the concentration of some parameters is insufficient to meet the allowable discharge limits. This observation is expected for open ponding systems because of their reliance on weather conditions [9, 10], especially during heavy rainy weather when effluent overflows and short hydraulic retention time. Moreover, the POME properties are also different [10, 14]. The insufficient biological treatment of POME is attributed to the high BOD loading, acidic pH, and colloidal nature of suspended solids in wastewater [15-17].

Table 1. Biological treatment efficiencies of POME in a series of ponding systems.

Parameter	Raw POME	Cooling	Anaerobic	Facultative	Algae A	Algae B	Discharge Standard
pH	4.7	4.7	7.4	7.9	8.4	8.0	5.0 – 9.0
BOD5 [1] (mg/L)	108817	88783	911	1012	430	261	100 [2]
COD (mg/L)	165071	144078	4714	8801	4980	1798	-
TOC (mg/L)	17208	11442	1018	817	698	716	
TSS (mg/L)	24463	21880	5660	13940	1647	6220	400
VSS (mg/L)	21597	20090	4260	9860	1320	4353	
TP (mg/L)	597	428	160	144	159	147	
TN (mg/L)	4400	2817	290	251	185	169	200
AN (mg/L)	421	342	221	148	133	94	150
O&G (mg/L)	14647	11508	4006	2794	2386	1255	50
Carotene (mg/L)	1.914	4.574	0.322	0.233	0.177	0.165	
Phenolic (mg/L GA)	3185	2852	446	288	191	207	
Tannin-Lignin (mg/L)	822	681	133	94	76	61	
Color (ADMI)	14130	9371	5203	4093	3393	3960	

[1] 5-day BOD.[2] 3-day BOD.

3.2. Organic contents in POME.

Figure 2 depicts the biological treatment efficiency of the organic content in POME at the initial concentration. According to the figure, the final effluent contained 261 mg/L of BOD and 1798 mg/L of COD. It appeared that 99.7% of the BOD and 98.9% of the COD were removed. However, their concentrations failed to meet the final effluent standards. In this study, the BOD:COD ratios for untreated POME were 0.65, on average, indicating that the wastewater can be treated biologically. Based on the average BOD:COD ratio calculated for the final effluent, the ratio was 0.14, considered a safe value within the acceptable range. All treatment ponds, except facultative ponds, had declining BOD levels on the bar graph. Similar results were observed for COD levels in the facultative pond. There was a slight increase in BOD and COD concentrations in the facultative pond compared to the anaerobic pond, resulting in negative pollutant removal.

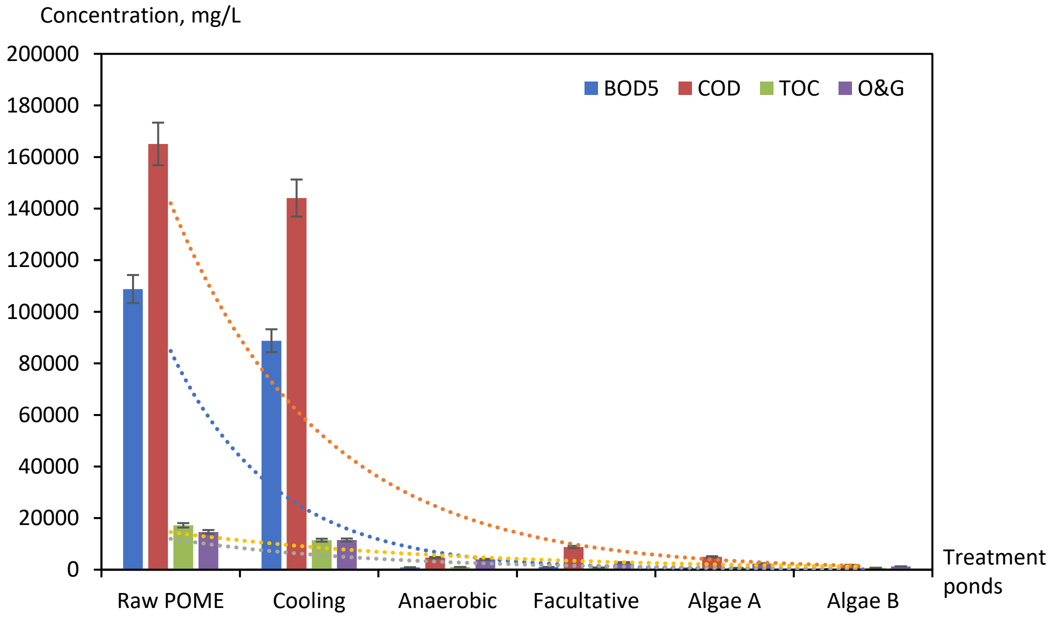

Figure 2. Biological treatment efficiencies of BOD, COD, TOC, and O&G in a series of ponding systems.

In our study, the COD:BOD ratio of the anaerobic effluents approached 5:1, which is considerably higher than the acceptable biodegradability ratio of 2:1 [33-35]. Therefore, it is likely that the influent of a facultative pond contains organic materials that are slow to degrade or not biodegradable, which could explain the low removal rate in the pond. In addition, the formation of floating sludge on the surface of the pond has made its condition even worse [36]. An increase in sludge age decreases the efficiency of the pond [37]. The sludge becomes inert after an extended period of endogenous respiration, resulting in a low specific substrate utilization rate [38]. According to the literature [39], high BOD levels have been reported in the biological solids formed in treated effluents. This may be due to inadequate maintenance of treatment facilities and an increased load rate during the harvest season [40].

In algae A effluent, the TOC concentration dropped from 17208 mg/L to 698 mg/L and rose to 716 mg/L in algae B effluent. Overall, 95.8% of the TOC was removed during the treatment process. A possible reason for the TOC reduction is the gas aeration of POME, which causes an atmospheric release of volatile organic compounds (VOCs) [41, 42]. Nevertheless, the increase in TOC could be explained by the sludge present in the final pond. Sludge samples with TOC ranging from 7.05% to 45.0% have been reported in the literature [43]. Organics dissolved in sludge can be transported to effluent [44, 45]. In raw POME, the TOC:COD ratio was 0.1, which indicates a high degree of biodegradability. However, the biological process may collapse if the ratio exceeds 0.4 [46]. It is apparent that the treated POME in the final effluent had a TOC:COD ratio of 0.4, indicating that the POME was not biodegradable.

A positive reduction in the O&G concentration was observed in the treated POME at 91.4%, where 14647 mg/L of raw POME was removed to 1255 mg/L in the final effluent. Despite the high level of O&G removal observed, the concentration achieved did not conform to the discharge standard. This observation is likely due to the high level of O&G in raw POME, which is ineffectively removed during the pretreatment process. It has been speculated that the presence of O&G in treatment ponds can lead to the proliferation of filamentous microorganisms and a decrease in microbiological activity [15, 47]. As a result, there may be floating and poorly sedimented sludge, as well as a decline in sludge biomass.

3.3. Particulate solids in POME.

Figure 3 shows the average removal of suspended solids using the ponding system. In the final effluent, there was a reduction in the TSS concentration from 24463 mg/L to 6220 mg/L. TSS degradation was completed at a rate of 74.5% removal; however, its concentrations fluctuated in the pond effluent and were not within acceptable limits. It is anticipated that by forming floating sludge, the rate of TSS removal would decrease because it was flushed out with effluent. Furthermore, inadequate settling ability in wastewater is expected to result in flocculent sludge loss [48]. A high level of TSS removal may result from the flocculation of biomass and the removal of organic matter from the effluent [38]. As reported in the literature, settling time can also affect TSS removal [49]. Based on the results of Chan *et al*. [50], the TSS removal rate increased from 84.8% to 92.5% when the settling time was increased from 1 hour to 24 hours. The removal of TSS is also reflected in the VSS removal performance. A total of 79.8% of the VSS was removed from the raw POME, from 21597 mg/L to 4353 mg/L in the final effluent. The removal of VSS fluctuated similarly to that of TSS. Alternatively, using an aerator can provide bacterial cells with sufficient oxygen to break down organic matter, as reported by Yap *et al*. [29].

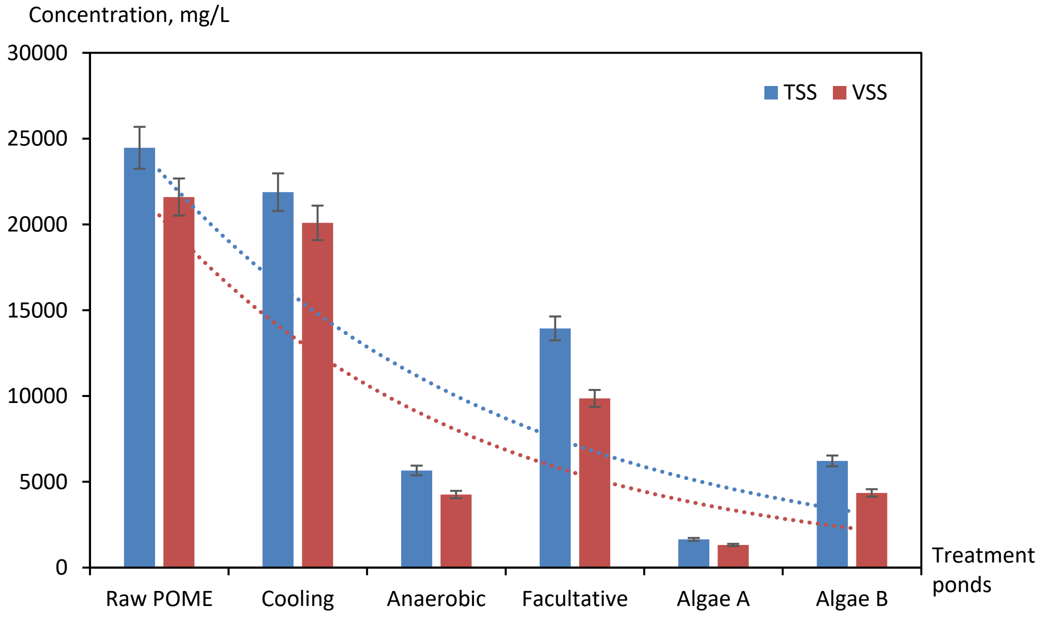

Figure 3. Biological treatment efficiencies of TSS and VSS in a series of ponding systems.

3.4. Nutrients in POME.

Figure 4 illustrates the average amount of nutrients removed from the POME using a ponding system. The AN concentration in raw POME decreased from 421 mg/L to 93 mg/L in the final effluent. A consistent trend was observed in the treated POME when 4400 mg/L TN was reduced to 169 mg/L. A total of 77.6% and 96.1% of AN and TN, respectively, were removed from raw POME through a series of treatment ponds. As can be seen from the table, the discharged effluents met effluent standards because their concentrations were less than 150 mg/L (AN) and 200 mg/L (TN). The biological processes of nitrification and denitrification facilitate the degradation of AN and TN in treatment ponds by converting AN into other intermediate compounds that are easily degraded [51]. Ammonia is oxidized to nitrite and then to nitrate during nitrification. During denitrification, nitrate is converted to nitrite and released as gaseous nitrogen. Another cause of AN reduction is ammonia volatilization, in which volatile ammonia is released into the atmosphere, especially at alkaline pH levels [52, 53]. In this study, POME had an alkaline pH value of up to 8.4, possibly contributing to the volatilization of the substance. Moreover, the presence of organic carbon dissolved in the POME indicates ammonia consumption by heterotrophic bacteria. Heterotrophic bacteria have been reported to consume ammonia at a dissolved COD-to-nitrogen ratio of more than 3.0 [54].

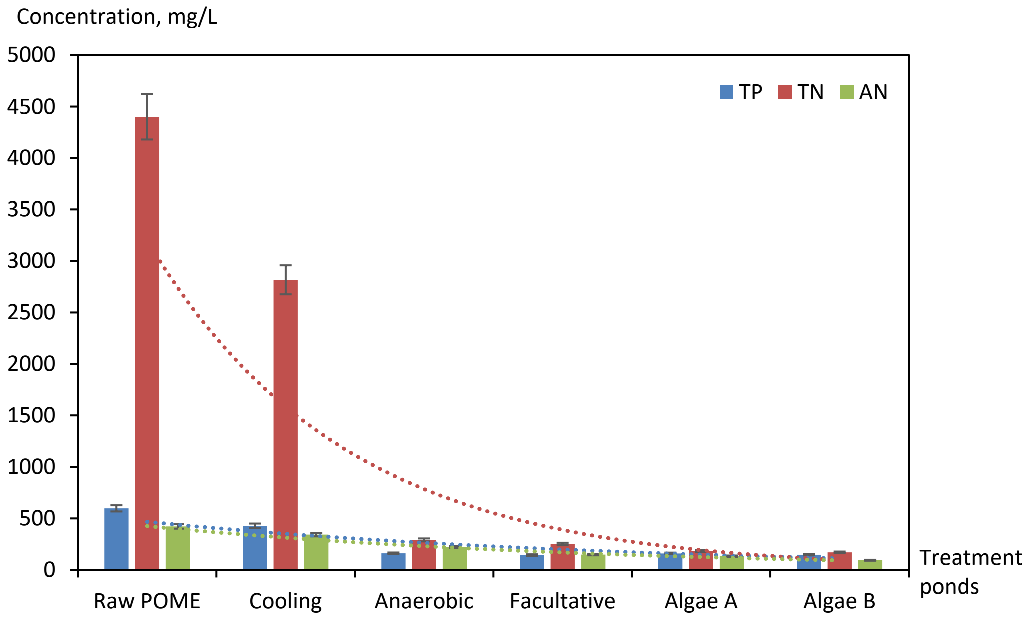

Figure 4. Biological treatment efficiencies of TP, TN, and AN in a series of ponding systems.

The TP reduction was recorded at 75.3% removal, as the initial 597 mg/L concentration was reduced to 147 mg/L in the final effluent. However, there was no continuous reduction in its concentration in any of the ponds. The TP concentrations in algae A increased slightly, resulting in the lowest efficiency level among all ponds. According to Fernando *et al*. [13], the poor phosphorus content of POME renders microalgae incapable of removing TP. The percentage removal in this study was observed to decrease due to a low phosphorus concentration, with most TP removal (62.6%) occurring under anaerobic conditions. Furthermore, microalgal cell death and the production of extracellular organic compounds may contribute to the accumulation of COD and nutrients in POME [13].

3.5. Physical Properties in POME.

Figure 5 illustrates the results of average color removal and other organic removal processes. In the affluent, the POME remained colored after being treated in a series of ponds. This observation has become one of the most challenging aspects of POME treatment. The raw POME color was tested at 14130 ADMI, and was reduced by 71.9% to 3960 ADMI in the final effluent. It was recorded that in every pond, the color value decreased until the last pond showed a slight increase. It is possible that the color reduction could be caused by microbes consuming organic matter in these ponds for growth and cell division [55]. In this study, the same pattern of color removal was observed for TOC removal. The Pearson correlation coefficient test for the results of color and TOC indicated an R-value of 0.986 (P = 0.0003). Therefore, organic carbon appears to be significantly related to color, with a high correlation observed in the effluent [56, 57]. According to Ujang *et al.* [58], the remaining color in the effluent is caused by non-degradable organic material.

The organic materials investigated in this study include phenolic, carotene, and tannin-lignin. In raw POME, the phenolic content is high because of the sterilization process of the fresh fruit bunches [59]. It was determined that the concentration of phenolics decreased from 3185 mg/L to 206 mg/L. A removal rate of 93.5% was achieved. The presence of phenolics in POME causes the apparent color in wastewater [60]. Carotene was formed at the lowest concentration of 1.91 mg/L in raw POME. Carotene was removed from the raw POME to the extent of 91.3% with 0.16 mg/L remaining. Although carotene was present at a low concentration, it remained in the final effluent because of the pigment's functional group, which is difficult to remove [61]. In wastewater, carotene contributes to the dark brown color of POME [62]. There was a consistent decrease in tannin-lignin concentration throughout all treatment ponds. The tannin-lignin content of the initial effluent decreased from 822 mg/L to 61 mg/L in the final effluent. In most cases, tannin-lignin is responsible for the brown and yellow color and gives it a musty smell [63].

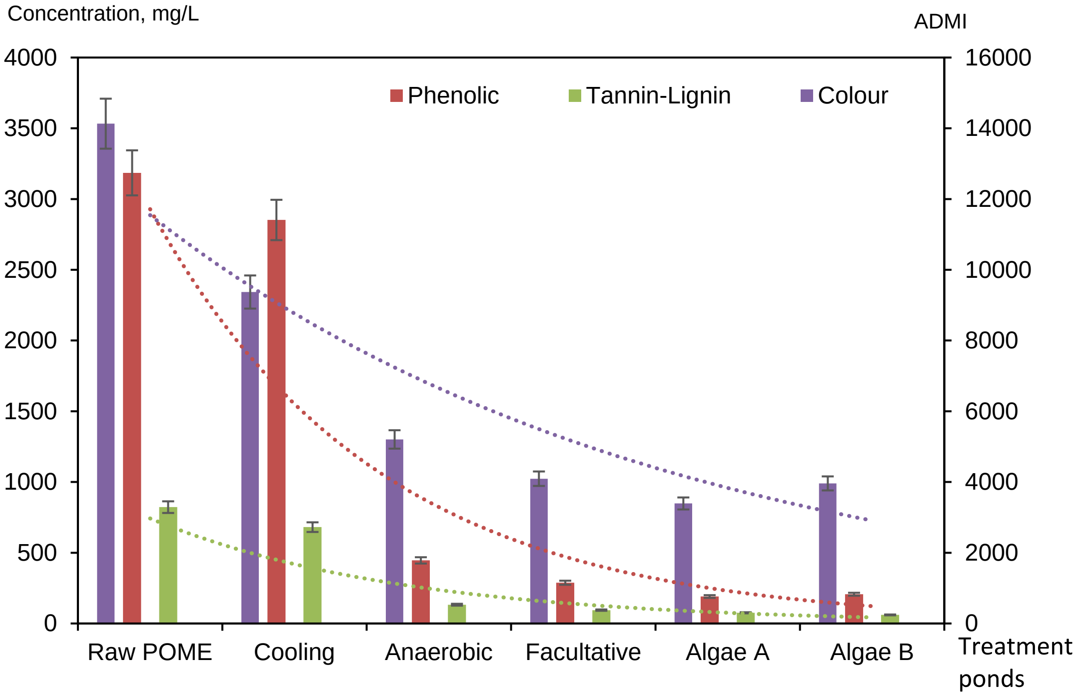

Figure 5. Biological treatment efficiencies of phenolic, tannin-lignin, and color in a series of ponding systems.

Degradation of organic materials occurs by the microbial digestion of lignocellulosic biomass from POME [64, 65]. However, the POME constituents may have contributed to the decline in their performance. It is possible that the reduction is due to the toxicity of phenolic compounds, which may interfere with the degradation activities of microbes [66]. Among these, only phenolic compounds shared the same color pattern. Moreover, using a biological approach may present a greater challenge for the degradation of phenolics [67].

3.6. Relationship of pollutant contaminants in POME.

The anaerobic, facultative, and algae ponds showed similar trends in removing BOD and TSS. Increases in TSS removal led to an increase in BOD removal, and vice versa, when TSS removal decreased. Therefore, it can be concluded that BOD removal depends on TSS removal. Moreover, the suspension of organic solids may affect COD removal. This contributed to a similar pattern of COD and TSS removal. In an anaerobic pond, high COD removal is achieved by acting as a settling basin for suspended solids, thus improving water quality [68]. Zeng *et al*. [69] found that the effectiveness of COD removal decreased as suspended solid loading increased. COD removal increased from 43% to 63% in algae ponds A and B because of partially degraded organics that are more readily metabolized by aerobic organisms [70]. Pearson correlation indicated that BOD and COD removal efficiencies were related to TSS at 0.906 (P = 0.012) and 0.912 (P = 0.011), respectively.

A reduction in TSS removal leads to an increase in TOC removal and vice versa when TSS removal is increased. This occurred because of organic carbon in the sedimentation of suspended particulates [71]. The TOC and O&G removal followed a similar pattern. Anaerobic, facultative, and algae pond A showed an increase in TOC reduction with the removal of O&G. Since O&G acts as a carbon source [72], the removal of TOC depends on the removal of O&G, which affects the ability of the ponding system to remove TOC. However, in algae pond B, the TOC removal was inversely proportional to the O&G removal. Suspended solids appear to reduce the effectiveness of biological treatments in reducing the TOC levels. O&G removal has increased due to adsorption and biodegradation, which absorb hydrocarbons from POME [73-75]. Pearson correlation indicated that TOC removal efficiencies were related to TSS and O&G at 0.895 (P = 0.016) and 0.987 (P = 0.0003), respectively.

In the facultative pond, a reduction in TSS removal also resulted in a reduction in the O&G removal. It is possible that O&G is suspended in suspended solids, which affects removal quality. It was estimated that 74% of the TSS was removed from the anaerobic pond, which increased the O&G removal to 66%. In the facultative pond, O&G removal decreased by 30%, owing to an increase in TSS concentration of 146%. These results are in accordance with those of Ahmad *et al*. [76], where the O&G content in wastewater and its removal may be affected by suspended solids. Pearson correlation indicated that the O&G removal efficiencies were related to TSS at 0.897 (P = 0.015).

The TN removal was less effective in the presence of suspended solids. As observed in the anaerobic pond, although TSS was removed at 74%, there was a 90% increase in TN removal. Similarly, algae pond A eliminated 88% TSS and 26% TN. However, biological removal of TN is not as efficient as in an anaerobic pond because of the large amount of suspended solids in the influent. The organic content became more difficult to degrade as the amounts of suspended solids in the effluent increased. In the effluents of the facultative pond and algae pond B, the TSS content increased to 146% and 278%, respectively, resulting in the removal of 14% and 8% of TN. Pearson correlation indicated that TN removal efficiencies were related to TSS at 0.894 (P = 0.016). As TSS concentrations decreased, Avnimelech [77] reported that the rates of carbon and nitrogen contents decreased, which is consistent with our findings.

A reduction in the amount of TP may have resulted from the removal of O&G from the POME. It is likely that TP and O&G removal followed the same pattern. As observed in the anaerobic pond, the high O&G removal rate of 65% increased TP removal by 63%. In the presence of O&G, the ponding system may be unable to effectively remove TP [78]. Pearson correlation indicated that TP removal efficiencies were related to O&G at 0.985 (P = 0.0003). It is also possible that suspended solids affect the removal efficiency. In the anaerobic pond, 74% of TSS and 63% of TP were removed. In the facultative pond, however, only 10% of the TP was removed when the TSS content increased to 146%. It has also been reported that suspended solids may decrease TP removal [79, 80]. Another study found that the removal of TP increased from 92% to 95% when the removal of TSS reached 99% [81]. Pearson correlation indicated that TP removal efficiencies were related to TSS at 0.878 (P = 0.021).

The results of this study showed that all parameters had a strong relationship with color-causing compounds (P < 0.05). Similar to carotene removal, Table 1 shows that color removal decreased uniformly in most ponds. Compared to the anaerobic pond, which eliminated 44% of the color and 92% of the carotene, algae pond B increased the color concentration by 16% and removed 6% of the carotene. The removal pattern appears similar for both, with the amount of carotene likely to be a determining factor in color removal. Nevertheless, the Pearson correlation indicated that the carotene removal efficiency at 0.649 (P = 0.163) was significantly unrelated to the color, which could be attributed to POME containing less carotene.

The results indicated that the phenolic and color values exhibited the same removal trend. Other studies have also reported similar findings [82, 83]. The anaerobic pond achieved the highest color removal rate, followed by the facultative pond, algae pond A, and algae pond B, comparable to the phenolic removal rate. Similar findings have been reported by Abdullah *et al*. [84]. In their study, they observed that the color of POME was removed by 66% owing to the oxidation of phenolic compounds. Pearson correlation indicated that phenolic removal efficiencies were related to color at 0.955 (P = 0.003).

As with tannin-lignin removal, the anaerobic pond achieved the most effective color removal rates of 44%, whereas the facultative pond and algae pond A achieved 21% and 17%, respectively. In contrast, the effluent from algae pond B contained 3960 ADMI of color concentration, over 16% higher than that from algae pond A (3393 ADMI). The relationship between color and tannin-lignin found in this study is similar to that reported by Mohammed and Chong [85]. The increase in the color of POME may be caused by the low molecular weight of lignin polymerization [86, 87] as well as the accumulation of compounds such as carotene and phenolic compounds. Pearson correlation indicated that tannin-lignin removal efficiencies were related to color at 0.969 (P = 0.001).

These results showed that the removal of color was inhibited by organic materials, which increased the color of POME owing to tannin-lignin, phenolics [54], and suspended solids [81]. These findings are consistent with those in the literature [87], in which it was reported that tannin-lignin and phenolics were directly proportional to the removal of color from POME. Consequently, residual substances in POME become a limiting factor in biological treatment, leading to the formation of colored wastewater.

4. Conclusions

This study examined POME degradation using a ponding system under various biological conditions. The results showed that untreated POME could be biologically treated, as indicated by an average BOD:COD ratio of 0.65. Although the final effluent concentrations of BOD and COD failed to meet the final effluent standards, the average BOD:COD ratio of 0.14 was considered safe within an acceptable range. The removal rates of O&G, AN, TN, and TP were also promising, with removal rates of 91.4, 77.6, 96.1, and 75.3%, respectively. This study found that the reduction of pollutants was highly correlated with the removal of color-causing compounds. The removal rates of phenolic and tannin-lignin compounds were also significant, with removal rates of 93.5% and 92.6%, respectively. The color of treated POME achieved 71.9% removal, with a strong correlation with tannin-lignin (0.969, P = 0.001) and phenolics (0.955, P = 0.003). However, the decrease in performance may have been due to reductions in microbial digestion caused by the toxicity of the phenolic compounds. Additionally, the formation of floating sludge and lack of maintenance compromised the performance of the ponding system. Therefore, additional treatment methods may be necessary to improve the effluent quality by polishing biologically treated POME.

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Conflicts of Interest

The authors declare no conflict of interest.

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