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Influence of EFB-based biochar on complete removal of TSS and decolorization of palm-oil-mill-effluent (POME)

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ABSTRACT

Treatment of Palm Oil Mill Effluent (POME) after the anaerobic digestion process has been carried out using biochar as an adsorbent to reduce its initial color intensity, and the total suspended solids (TSS). Biochars derived from empty oil palm fruit bunches (EFBs) were produced through pyrolysis at 700°C. About 95% color reduction and 100% TSS removal were observed after 24 h of contact time with 5 g biochar/50 ml POME. It has been observed that the pH and the duration of treatment played an important role in the adsorption process. The equilibrium adsorption data were best represented by the Langmuir isotherm. The kinetics of adsorption of suspended solids and color on the biochars were found to correlate with the pseudo-second-order model, with a correlation coefficient of $R^2 > 0.99$. Considering the high efficiency of the adsorbent in decreasing the color and TSS concentration, the EFB-based biosorbent is an environmentally-friendly biomass material that may be encouraged for use in waste management for resource and reuse.

Keywords: Pyrolysis; POME; Biochar; EFB; Adsorption; Isotherms; Kinetics

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1. Introduction

The oil palm industry is growing rapidly and yields large amounts of poorly-utilized biomass waste [1]. Oil palm (mainly grown in tropical countries like Indonesia and Malaysia), is the highest yielding oil crop in the world. United states Department of Agriculture (USDA) has recently predicted worldwide production of 65.39 million metric tons of palm oil during 2016–2017 [2]. According to a report by Malaysian Palm Oil Board (MPOB) in 2016, Malaysia owns 5.74 million hectares of palm oil plantation. The industry has predicted a solid 5% annual growth on palm oil production worldwide, reaching 78 million tons in 2020 [3]. The two major byproducts of this industry are oil palm trunks (OPT) and oil palm fronds (OPF). Waste stream in such industries carry valuable biomass including empty fruit bunches (EFB), palm kernel cake (PKC), palm oil mill effluent (POME), palm press fiber (PPF), and shell [4,5]. In Malaysia, nearly 24 million tons of POME are being disposed every year, frequently polluting underground water [6]. The quantity of EFB generated was estimated at about 14.9 and 37.7 million tons in Malaysia and worldwide, respectively [7]. EFBs comprise a large resource of lignocellulosic biomass which has the potential to be used as fuel or be upgraded to higher value products. Today, many researchers attempt to transform EFBs into more valuable products which will be a solution to the problem of this excessive waste [8–10]. The applications include self-adhesive carbon grains (SACG), cushion and rubberized mattresses, briquettes as fuel, bioethanol

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production, fertilizer for plywood and pulp paper production [11]. POME, as an industrial wastewater is a problematic stream of all palm industries similar to other waste streams which contain paints, oils, metals, phosphate fertilizers, electronic components, wood, and sewage. Apparently, this complex stream containing POME is being discharged into fresh open waters without passing into any type of filtration system and this practice has raised many environmental concerns. The metal content in the drinking water requires appropriate attention to prevent any over dosage incidents. Thankfully in recent years the treatment of POME has gained more attention due to the rising human health concerns[12]. Also, the dark color of POME makes it less attractive for reuse applications and this unaesthetic, high BOD stream needs to be considered in treatment plants.

Meanwhile, different methods are intensively being employed to treat industrial effluents that include: biological treatment using anaerobic granular sludge [13], membrane technology applying various additives [14], ultrasound irradiation [15], electrochemical oxidation [16], photochemical treatment [17], natural and surfactant-modified natural zeolite [18], fuel oil fly ash [19], combined treatment methods and activated carbon obtained from different natural resources [20–22]. For the wastewater treatment, adsorption has been found to be a beneficial technique as it offers many advantages including cost effectiveness, ease of processing conditions, environmental friendliness, and less chances in the formation of harmful substances [23,24]. Zahangir et al. [25] employed activated carbon as an adsorbent derived from EFBs to remove phenolic compounds from the wastewater, where the adsorbents were prepared at 800°C. Recently the focus is also on the methods which will reduce the emission of greenhouse gases to the environment leading to the development of natural renewable adsorbents and biochar sorbents [26].

It was observed that biochars obtained both from EFBs and rice husks have the ability to adsorb Zn, Cu and Pb from aqueous solutions. Meanwhile a higher adsorption capacity was achieved using EFBs as compared to rice husk biochars [27,28]. One of the issues affecting the adsorption capacity is the occurrence of saturating the biochars. During this, the pores of biochar are eventually blocked and the adsorption effectiveness is affected both in terms of quality and quantity. A smaller surface area is recommended as the biochars have less available surface to interact with each other. Less interaction within the biochars results in more efficient dispersion, decrease chances of agglomeration, and prevent pore overlapping. In addition, varying the pH can enhance the removal of pollutants in water by about 50% suggesting the role of pH in the treatment process should be investigated [29].

Biochars have a porous structure which is ideal for efficient adsorption. Biochars produced at 700°C contain up to about 70% of carbon depending on the source of feedstock. This temperature was found to be optimum to yield a quality adsorbent biochar [26,30]. In comparison to other natural renewables resources such as rice husk, EFBs are able to yield higher amounts of biochar [31,32].

Anaerobic digestion is now widely used directly for POME treatment with large emphasis placed on capturing the methane gas released as a product of this biodegradation treatment method. The anaerobic digestion method is recognized as a clean development mechanism (CDM) under the Kyoto protocol. Certified emission reduction (CER) can be obtained by using methane gas as a renewable energy. Consequently, the water treatment process stage is now being deferred to the treatment of the wastewater after the anaerobic digestion stage. This investigation reports on the novel application of EFB biochars for the treatment of POME for both TSS and color removal.

2. Experimental

2.1. Materials and preparation of samples

2.1.1. Drying and grinding the EFBs

The EFBs were collected from The University of Nottingham Malaysia campus, and were air-dried in open air to extend their half-life. The drying of EFBs is important in the long-term usage of this material; it becomes much more important when the materials are used in a humid area as it gradually increases the moisture content of the EFBs. To follow an economically viable method, the EFBs were only ground using a Retsch Cutting Mill SM 100, with a mesh size of 0.2.

2.1.2. Pyrolysis

The pyrolysis was carried out using a vertical furnace (Kanzen-Tetsu fluidized bed reactor, designed following ASTM A312 standards). To displace the excess air inside the reactor, nitrogen as an inert gas with the flow rate of 10 cm^3/min was used. The furnace was programmed to raise the temperature by 5°C/min up to a maximum of 700°C, which was then maintained at 700°C for 3 h. The average maximum temperature (700°C) was chosen following other similar work [32–35]. The resultant material was then cooled to room temperature after 12 h. Due to the flammability of biochar, the nitrogen flow was continued until the completion of cooling.

2.1.3. Grinding and sieving of biochars

The biochars were ground using a Retsch Ultra Centrifugal Mill ZM 200 with a mesh size of 0.2 mm, and were sieved using an ELE international laboratory sieve with a size of 125 micron. The powders of the biochars were kept in sealed plastic bags to prevent any adsorption of moisture.

2.1.4. Preparation of POME

The POME was collected from the effluent of final anaerobic pond of a palm oil mill in Dengkil, Selangor, Malaysia. Containers used for storage were carefully washed, rinsed, and dried to avoid any contamination or dilution. The filled containers of POME were stored in a refrigerator until testing and analysis.

Table 1 shows the characteristics of the collected untreated post-anaerobic digested POME wastewater. According to the Department of Environment (DoE), Malaysia, this untreated wastewater exceeds the standard

Table 1
Characteristics of untreated POME obtained from a local palm oil mill before any treatment

Property	Values	Limits
pH	8.4	5–9
Color, PtCo/l	9900	–
TSS, mg/l	1800	400
COD, mg/l	4700	50
BOD, mg/l	1350	100
Tannin and lignin, mg/l	215	–

discharge limits, which illustrates the high concentration of COD, color, BOD and total suspended solids [24,36].

2.2. Isotherm adsorption experiments for color removal

The biosorbent was prepared to study its adsorption abilities on the untreated POME. Through this investigation, the influence of three main variables was observed: treatment time, dosage of biosorbent and pH. Hydrochloric acid (HCl) and sodium hydroxide (NaOH) solutions were used to adjust the initial pH of the solutions. The isotherm adsorption experiments were carried out in sixteen, 250 ml capped conical flasks. Each of the flasks contained 50 ml of the digested untreated POME wastewater, with varying amounts of biosorbent (2.5, 5, 7.5 and 10 g) at different pH values (2,5,7 and 8.4). The flasks were shaken at 300 rpm and at room temperature on a rotary orbital shaker (Lab Companion SK-300 Benchtop Shaker, GMI, United States of America (USA)), for 2 to 24 h. After the adsorption period, the solutions were centrifuged (Neofuge 18R Laboratory Centrifuge, China) for 30 min at 3000 rpm and then subjected to the determination of their residual color and TSS concentrations.

The percentage of pollutant removal (R (%)) and the quantity of adsorption were calculated using Eqs. (1) and (2).

$$R\ (\%) = [(C_o - C_t)/C_o] \times 100 \quad (1)$$

$$q_t = (C_o - C_t)V/M \quad (2)$$

where C_t is the concentration of the solution at any time (mg/L) and C_o is the initial concentration (mg/L), q_t is the adsorbed amount of pollutant at any time (mg/g), V is the sample volume (L), and M is the biosorbent mass (g).

The samples were given name tags for their easy identification, as shown in Table 2. Analytical grade chemicals (Aldrich Chemicals) were used in all the experiments. All the solutions used in this study were diluted with distilled water as required, and were made in triplicate. Results of the average readings were then considered.

2.3. Analytical methods

TSS and color concentration values were obtained using a spectrophotometer (DR 2800, HACH, USA). A Hach Sens ION 1 pH meter with a combined glass electrode was used to measure the pH of solutions.

Table 2
Samples: Name tags and specifications

Samples name	Amount of biochar (g)	pH
A-PH2	2.5	2
A-PH5	2.5	5
A-PH7	2.5	7
A-PH8.4	2.5	8.9
B-PH2	5	2
B-PH5	5	5
B-PH7	5	7
B-PH8.4	5	8.9
C-PH2	7.5	2
C-PH5	7.5	5
C-PH7	7.5	7
C-PH8.4	7.5	8.9
D-PH2	10	2
D-PH5	10	5
D-PH7	10	7
D-PH8.4	10	8.9

3. Results and discussion

3.1. Influence of dose, contact time and pH on the color and TSS concentration

Throughout this investigation, the three observed variables (contact time, pH, and adsorbent dosage) had a considerable impact on the treatment of the digested POME wastewater. It can be deduced that the biochar has a high impact in enhancing the color reduction as well as reducing the TSS concentration. Fig. 1 shows the influence of biosorbent dosage on the treatment of digested POME (at a fixed volume of 0.1 L). By comparing the results of A-PH2 and B-PH2 at equal treatment durations, the high efficiency of the biosorbent in reducing the color is evident. It clearly shows that an increase in the biosorbent dosage from 2.5 to 5 g biochar/50 ml POME increased the adsorption capacity, and increased the color removal from 91 to 94.94% (residual color decreased from 840 to 500 PtCo/l) at a pH of 2 and within 24 h of contact time.

It is apparent that with an increase in the biosorbent dosage from 2.5 to 5 g biochar/50 ml POME, an increase in the number of sorption sites available for sorbent–solute interaction and as a result a decrease in the residual color of the solution. Chin et al. [37], presented 71% of color removal using fungus at pH 5.7, 35°C, and 0.57% w/v glucose with 2.5% v/v inoculum. 71.26% of color removal was obtained with 0.20 g palm kernel shell-based activated carbon/1 L POME after 36 min of treatment [38]. Very recently, Sherlynna et al. [39], reported an average of 70% of color removal after 48 h using coconut shell based activated carbon to treat POME. Igwe et al. [29] obtained nearly the same level of color reduction in this study (~580 PtCo/l), using 40 g of boiler fly ash

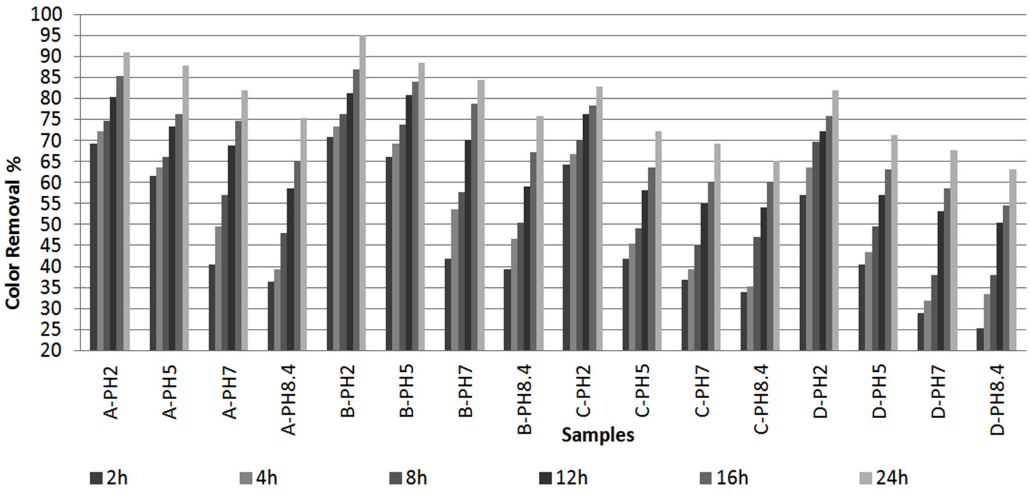

Fig. 1. Influence of treatment on color removal (%) from anaerobic digested POME using EFB-based biochar.

per 300 ml of POME. Whereas, in the current investigation, 94.94% of color reduction (500 PtCo/l) was achieved using only 5 g biochar/50 ml POME. As shown in Fig. 1, 5 g biochar/50 ml POME of biosorbent (starting with the letter "B") presents an optimum level of color reduction in comparison to other samples. It is also noted that with the addition of 7.5 and 10 g biochar/50 ml digested POME wastewater, the removal efficiency decreased significantly as compared to the samples carrying 2.5 and 5 g biochar/50 ml digested POME. It was confirmed that the addition of more than 5 g biochar/50 ml digested POME is not effective in significantly enhancing the removal of pollutants.

In addition, altering the pH and providing a longer treatment time also enhanced the color removal. Chang et al. [40] found that the rate of adsorption became insensitive to pH values in the range of 7.0–9.5. A decrease in the pH was noticeably effective in the adsorption and hence on the removals (especially in more acidic suspensions: A-PH2, B-PH2, C-PH2, and D-PH2). For instance, by comparing the two samples after 2 h of treatment, with notably at different pH levels, lower pH doubled the color removal (D-PH8.4 = 25% while D-PH2 = 57%).This improvement in color removal efficiency was observed through all samples accordingly.

The duration of treatment affected the adsorption significantly (Fig. 1); thereby giving more time for the adsorption process, more suspended solids on the surface of biochar which results in the reduction in the concentration of color. The color removal percentage was determined using Eq. (1). As shown in Fig. 1, adding 2.5 g biochar/50 ml digested POME after 2 h (A-PH8.4) resulted into 36% color removal (the maximum contact time did not exceed 24 h). By comparing the results of A-PH8.4 with A-PH2 after 2 h, the difference in color removal of about 30% could be noted. Whereas, after 24 h, a decrease in the rate of adsorption was noted (a difference of only 15% in the color removal). Following an increase in the treatment time, a gradual reduction in the adsorption capacity is expected which is due to the reduction in the available micropores on the biosorbent surface as the pollutants and the adsorbents are given more time to interact.

Eq. (1) was used to estimate the TSS removal, and the obtained results have been presented in Fig. 2. The influence of adsorbent dose on total suspended solids (TSS) removal is evident from Fig. 2. The TSS for the digested POME wastewater was 1800 mg/l which reduced to 0 mg/l after 12 h of treatment for both pH 2 and 5 (containing 2.5 and 5 g biochar/50 ml POME respectively). Meanwhile, even better TSS removal was achieved with the addition of 5 g biochar/50 ml digested POME.

By comparing the samples with the pH of 7 after 2 h, it is observed that the samples of 5 g biochar/50 ml digested POME (B-PH7) reached 57% of TSS removal, while under the same conditions D-PH7 containing 10 g biochar/50 ml POME reached 44% TSS removal. This could be related to the accumulation of excess biosorbent blocking the micropores and resulting in the overlapping. This decline in TSS removal with the addition of more than 5 g biochar/50 ml digested POME as observed previously has been linked to the aggregation of adsorption sites [41–43]. Furthermore, through the studies of the effect of pH on TSS removal, it is observed that decreasing the pH from 8.4 to 2 efficiently decreased the TSS by about 30% after 2 h.

TSS level for all the samples with pH 2 reached 0 mg/l (100% removal) after 24 h of treatment. Also through the conditions of A-PH5, A-PH7,B-PH5,B-PH7, after 24 h, 100% TSS removal was achieved. Moreover, for A-PH2, B-PH2 and B-PH5, the same results were obtained. However, a higher rate of adsorption was observed only after 2 h of treatment. This may be because of the dose of adsorbent in addition to the pH level as compared to the digested POME wastewater.

The concentrations and removals of 16 fragrance materials (EMs) were measured in 17 U.S. and European wastewater treatment plants between 1997 and 2000; where higher TSS removals were achieved with the long duration of treatment (5 d). The best results obtained for the wastewater collected from Loveland in U.S. were 99% TSS removal. Moreover, POME was recently treated through a combined mechanism (using activated carbon while applying ultrasound cavitation) and 98.33% of TSS removal was achieved using 50 g biosorbent/L of effluent under 15 min of ultrasound cavi-

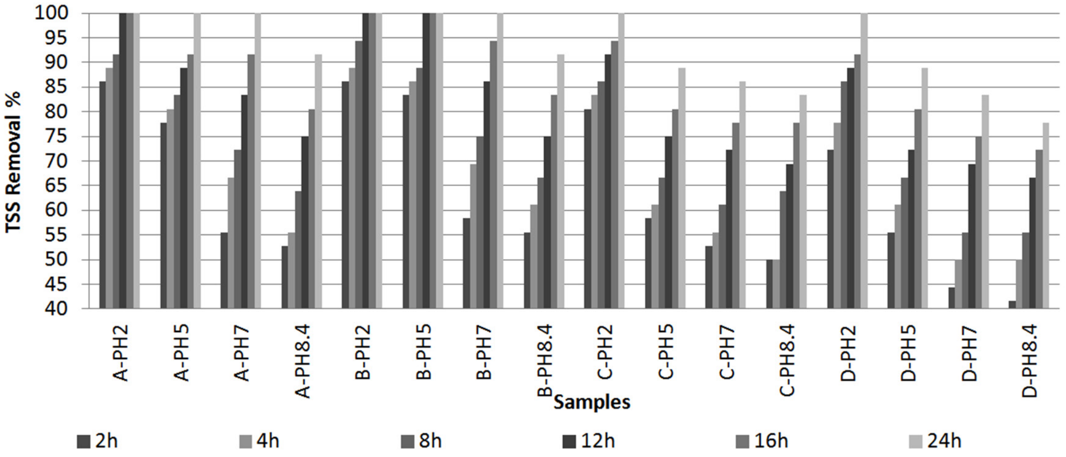

Fig. 2. Influence of treatment on total suspended solids removal (%) from anaerobic digested POME using EFB-based biochar.

tation [15]. Very recently, 87% removal of TSS from POME was reported using cationic plant-based seed gum derived from Cassia obtusifolia over 5 h [44]. In the current investigation after 12 h and using an acidic solution, the biosorbent achieved 100% removal of TSS. This indicates that the current method could be introduced as a replacement to wastewater treatment plants, especially to the development of anaerobic digested POME wastewater treatment.

Further to this type of treatment, the waste biochar could be used in agricultural applications as an economic fertilizer. Biochar increases nitrogen retention, lowers greenhouse gas emissions, and nutrient retention [45,46]. Furthermore, the use of EFB biochar has two major advantages, (i) millions of tonnes of EFBs are produced each year and are classified as a biomass waste, (ii) the spent EFB biochar is also a biomass waste fuel and instead of undertaking expensive regeneration studies this residue can be combusted or gasified directly producing fuel gas to produce electricity or syngas.

3.2. Adsorption isotherms correlation

To perform the design of sorption systems to treat the digested POME wastewater, a suitable correlation for the equilibrium curve is required. The amount of solute adsorbed per unit mass of adsorbent as a function of the equilibrium concentration in bulk solution at constant temperature, is known as an adsorption equilibrium isotherm. In this investigation, the isotherms were calculated using the Langmuir [42] and Freundlich [43] isotherm equations. It should be stated that the data used for calculations in both the models are based on the optimum results obtained from samples containing 5 g biochar/50 ml digested POME wastewater (samples shown with an alphabet letter "B"), where the dots in Fig. 3 represent the experimental results and the linear line is the theoretical correlation obtained.

Initially, the Freundlich isotherm model was used to correlate the experimental observations (Freundlich 1906)[47]. The Freundlich isotherm is represented by Eq. (3), where C_e is the equilibrium concentration (mg/L), and K_F and n are constants incorporating the factors affecting the adsorption, such as adsorption capacity and intensity.

$$q_e = K_F C_e^{1/n} \tag{3}$$

Linear plots of the Freundlich isotherm model as shown in Eq. (4), (log q_e vs. log C_e) were drawn. K_F and n values were calculated from the intercept and slope of the plots and are represented in Table 3. The Freundlich model generates a correlation factor R^2 which is used to assess the fit of the model. The transfer of molecules between the liquid and the solid phases are related to different isotherm studies that can identify whether the distribution processes are homogeneous or heterogeneous. The values of n from 1 to 10 represent a good adsorbent. In this study, the Langmuir mode showed to obtain a more suitable isotherm bio-sorption model by achieving values below 1.

$$\text{Log } q_e = \log K_f + (1/n) \log C_e \tag{4}$$

According to the Langmuir model, adsorption occurs uniformly on the active sites of the adsorbent and once a particle occupies a site no further adsorption can take place at the same site. The Langmuir model is specified by Eq. (5), where C_e is the equilibrium concentration (mg/L), q_e is the amount of adsorption at equilibrium (mg/g), and q_m and b are Langmuir constants related to adsorption capacity and energy of adsorption respectively. The adsorption followed the Langmuir isotherm model as shown by the linear plot of C_e/q_e vs. C_e, in Eq. (6) and shown in Fig. 3. The values for q_m and b were calculated from the intercept and slope of the plots, as presented in Fig. 3 and depicted in Table 3. It should be mentioned that in Fig. 3, the points refer to the experimental data, while the linear format of the Langmuir model is represented by Eq. (6).

$$q_e = (q_m b\, C_e)/\ (1 + b\, C_e) \tag{5}$$

$$C_e/q_e = 1/\ (q_m\, b) + C_e/q_m \tag{6}$$

The applicability of each isotherm was evaluated by the value of correlation coefficient, R^2. Fig. 3 and Table 3 summarize the values of constants for the Langmuir and Freundlich isotherms, which were calculated from the best-fit lines. It can be concluded that the removal of color and TSS

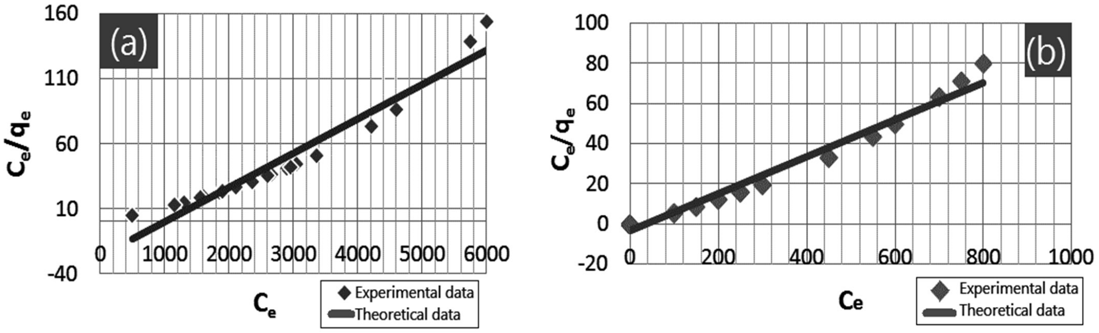

Fig. 3. Langmuir model isotherm linear plot using theoretical data for treatment of anaerobic digested POME using EFB-based biochar ((a) Based on color reduction, (b) Based on TSS removal).

Table 3
Langmuir and Freundlich isotherm models constants

Langmuir isotherm			
	q_m (mg/g)	b (L/mg)	R^2
Color reduction	38.02	–0.001	0.9383
TSS removal	10.86	–0.028	0.9732
Freundlich isotherm			
	K_F	n	R^2
Color reduction	2.15	–0.36	0.7845
TSS removal	3.50	–3.00	0.8851

was best explained by the Langmuir model, as the R^2 values for both parameters were 0.9383 and 0.9732 respectively. The model implies that the removal of color and TSS were based on monolayer adsorption onto a surface with a finite number of identical sites.

Similar results were observed by Alam et al. [35], where the Langmuir isotherm model was found to fit better than the Freundlich isotherm for the removal of 2,4-dichlorophenol by activated carbon generated from EFBs. In addition, Rebitanim et al. [48] noted similar results when determining the adsorption capacity of raw EFB as an adsorbent. This reveals that the equilibrium adsorption data matches well with the Langmuir isotherm and indicates that the EFB adsorption is homogeneous and monolayer.

3.3. Adsorption kinetics correlation

The kinetics of biochar adsorption was modeled using the Lagergren pseudo-first-order, the Ho–McKay pseudo-second-order, and second-order rate equations, as presented in Eqs. (7)–(9), respectively [49, 50]:

$$\ln(1-(q_t/q_e)) = -k_1 t \tag{7}$$

$$t/q_t = 1/(k_2 q_e^2) + 1/q_e \tag{8}$$

$$1/(q_e - q_t) = 1/q_e + kt \tag{9}$$

where q_e and q_t are the amount of adsorption capacity at equilibrium and at time t (h) respectively, k_1 is the pseudo-first-order rate constant (h^{-1}), and k_2 is the rate constant of pseudo second-order adsorption (g mg^{-1} min^{-1}).

The values of kinetic parameters of rate equations both for color reduction and TSS removal have been shown in Table 4. Regarding the adsorption capacity, a Lagergren's pseudo-first-order rate equation was applied to determine the adsorption of liquid/solid system [50]. One adsorbate species reacts with one active site on the surface as indicated in this model. This equation was applied to the kinetic behavior of color removal and suspended solids adsorption on the biochars. Lagergren's equation is known to be suitable for homogeneous adsorption rates. The surface of biochar was assumed to have homogeneous micropores. To find an accurate kinetic equation Ho and McKay's pseudo-second-order rate equation was applied for the adsorption of lead ions from aqueous solution onto peat [51,52]. While using Ho and McKay's pseudo-second-order rate equation, two surface sites were assumed to be occupied by one divalent adsorbent ion. It must be noted that the figures and calculations are based on the optimum results obtained from samples containing 5 g biochar/50 ml POME (samples shown with an alphabet letter "B"), where the dots in Fig. 4 represent the experimental data, and the linear line signifies the theoretical data obtained through the treatment.

Following the results obtained using Eq. (9) (Table 4), the highest value for the correlation coefficient (R^2) can be observed. The correlation coefficients for the second-order rate equation [Eq. (9)] are close to that of the pseudo-first-order, but still lower than the pseudo-second-order rate equation. As a result, in this investigation the pseudo-second-order model was found to be the most suitable for the kinetics of color reduction. It should also be noted that by using the second-order kinetic model, the calculated q_e values found to be consistent with the experimental values.

To obtain more accurate correlations on the adsorption kinetics, the results of TSS removal were also tested through three models following Eqs. (7)–(9) as shown in Figs. 4a–c. The highest value correlation for the adsorption kinetics was achieved ($R^2 > 0.9981$) using the pseudo-second-order kinetics model.

Moreover, the correlation coefficient for the color removal showed that the pseudo-second-order kinetic model with $R^2 = 0.997$ was better-suited than the pseudo-first-order and second order models. The pseudo-second-order model also proved successful for methylene blue dye on raw empty fruit bunch biomass adsorption [48]. For

Table 4
Kinetic parameters of rate equations for the treatment of POME by biochar (a. Based on Color reduction, b. Based on TSS removal)

(a) Color reduction				
Rate equations for adsorption	R^2	Experimental, q_t	Theoretical, q_e	k
Pseudo first-order model	0.989	99	106	–0.0111
Pseudo second-order model	0.997	99	90.9	0.0056
Second-order model	0.986	99	45.5	0.0026
(b) TSS removal				
Rate equations for adsorption	R^2	Experimental, q_t	*Theoretical*, q_e	k
Pseudo first-order model	0.665	15	205	–0.0274
Pseudo second-order model	0.998	15	18.8	0.056
Second-order model	0.596	15	2.24	–0.0219

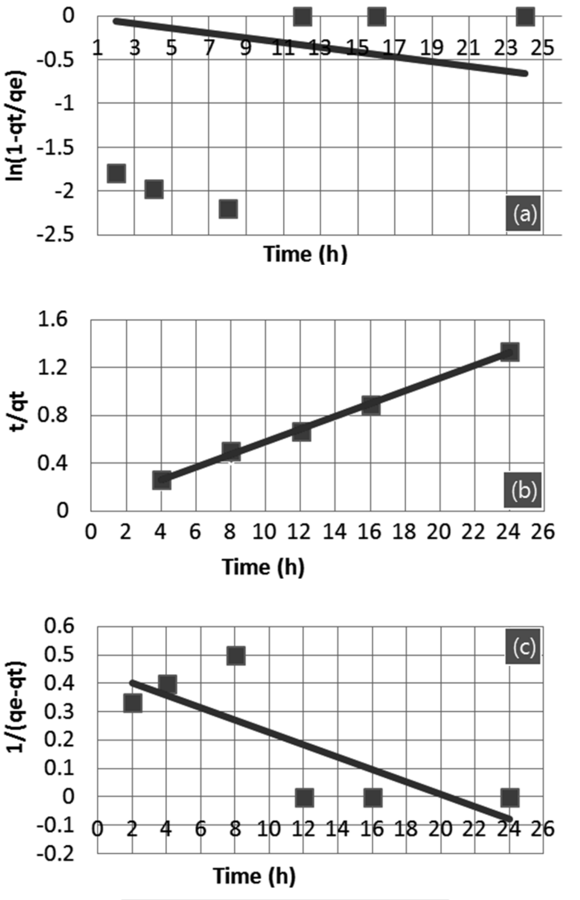

Fig. 4. Linear plot of adsorption isotherm correlations (based on the TSS removal from anaerobic digested POME using EFB-based biochar): (a) Pseudo first-order kinetics, (b) Pseudo second-order kinetics, (c) Second-order kinetics.

instance, through a greywater treatment, 88% TSS removal was achieved using aerobic digestion and hydrogen peroxide disinfection [53]. It could be feasible that the grey water treatment could be done more efficiently using biochars derived from EFBs in the future.

4. Conclusions

The biochar produced from empty fruit bunches (EFBs) at 700°C showed good capability for the complete removal of suspended solids and 95% color removal of anaerobic digested POME using 5 g biochar/50 ml digested POME, agitated at 300 rpm over 24 h in an acidic solution. The pH had a clear effect on the color and TSS removals. A decrease in the solution pH led to a significant increase in the adsorption capacities of color and TSS on the biochar; the maximum adsorption was achieved in a highly acidic environment. At the same time, a reduction in adsorption rate was observed during longer periods of treatment which was due to gradually decreasing available sites and pores on the biochar surface. Similarly, the adsorbate dosage was found to have a limitation; addition of biochar more than 5 g biochar/50 ml digested POME decreased the removal efficiency. The equilibrium adsorption data was best correlated by the Langmuir isotherm, indicating monolayer adsorption on a homogenous surface. At 30°C, the adsorption was 38.02 mg/g for the color reduction and 10.86 mg/g for TSS removal. The adsorption kinetics were studied using three kinetic models for comparison and the adsorption kinetics were best described by the pseudo-second-order model with a correlation coefficient of $R^2 > 0.997$ for color reduction and $R^2 > 0.9981$ for TSS removal. Overall, through this investigation the EFB-based biochar has been identified as an efficient adsorbent for color and TSS removal from anaerobic digested industrial POME and thus shows a promising application and is encouraged in the use of waste management for resource recovery and reuse. For further work, other pyrolysis conditions e.g. temperature and residence time, should be investigated to obtain a more effective biochar and even activation chemicals could be used to produce activated carbons. But since there are several uses for the spent biochar, such as a soil nutrient/fertilizer or waste energy resource for biogas/syngas generation the optimization study should be performed over the integrated process.

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