In this study, the potential of an improved empty fruit bunch-based powdered activated carbon (PAC) with high surface area was employed in removing suspended solids and turbidity from a high-strength wastewater. Also, the effects of operating parameters, such as PAC dosage, contact time and mixing speed on sorption trends of the two pollutants from the wastewater—biotreated palm oil mill effluent using a full factorial experimental design was investigated. Adsorption efficiency of 89.1 and 91.4% were observed for suspended solids and turbidity, respectively, at the operating condition of 3.5 g PAC dosage, 45 min contact time and 150 rpm mixing speed. The analysis of variance also revealed that the actual and model predicted values were in agreement with $R^2$ values of 0.9949 and 0.9991.
for suspended solids and turbidity, respectively. The three operating factors had similar significance on the sorption of both pollutants with an increasing sequence of significance: contact time < mixing speed < PAC dosage. This is indicative of their similar mechanistic pathway and response trends to the adsorption process. The Freundlich and pseudo-second-order models also predicted the experimental data in describing the adsorption behaviour with \( R^2 \) values of 0.9057 and 0.9998.

**Subjects: Adsorption Science; Environmental; Pollution; Separation Processing; Water Engineering**

**Keywords: turbidity; suspended solids; pollution; factorial design; BPOME**

1. **Introduction**

The enormous quantity of wastewater generated by the palm oil mills and discharged into the water environment has become a noteworthy environmental peril. Suspended solids for instance are a key water quality parameter since they impact such activities as the design of wastewater treatments, turbidity removal in drinking water, sediment control in streams and disinfection. The concentration of other water quality parameters is related to suspended solids, since the solid structure may contain biochemical and chemical oxygen demand materials, trace metals, nutrients, pesticides and toxic or hazardous materials adsorbed on the surface. As a result, many countries usually deem suspended solids content as one of the paramount parameters of water pollution index.

On the other hand, discharge of highly turbid wastewater will certainly affect the aquatic creatures adversely, and disturb other biological processes through interference with light penetration in the receiving water body. Moreover, the freshwater bodies have been burdened by wastewater streams due to perpetual pollution loadings. This has led to intensive research programs focused on the polishing of conventionally treated wastewaters before being discharged into the water ways.

Adsorption processes are usually thought of as a polishing process for wastewater streams having a number of persistent pollutants after biological treatment processes (Amosa, Jami, Alkhatib, Jimat, & Muyibi, 2015). In fact, adsorption systems can be effective in removing, suspended solids, turbidity, dissolve metals, organics and dyes. Recently, there are extensive investigations on the treatment of wastewaters using adsorption process. Adsorption has been successfully employed for the removal of organic contents (AbdulHalim et al., 2011; Aber & Sheydaei, 2012; Adham, Snoeyink, Clark, & Anselme, 1993; Amosa, Jami, & Alkhatib, 2016; Amosa et al., 2015; Muyibi, Tajari, Jami, & Amosa, 2014), heavy metals (Acharya, Sahu, Mohanty, & Meikap, 2009; Ahn, Park, Woo, & Park, 2009; Al Saadi, Al Mamun, Alam, Amosa, & Atieh, 2015; Amosa, 2015; Amosa et al., 2016; Belviso et al., 2014; Doula, 2006; Erdem, Karapinar, & Donat, 2004; Ho, 2003; Taffarel & Rubio, 2009; Wingenfelder, Hansen, Furrer, & Schulin, 2005), and other constituents such as dissolved gases, dissolved solids, suspended solids, turbidity and colour (Alkhatib, Mamun, & Akbar, 2014; Amin, 2008; Amosa, 2015; Amosa et al., 2016; Hameed, Tan, & Ahmad, 2008; Ho, Chiang, & Hsueh, 2005; Malekbala, Khan, Hosseini, Abdullah, & Choong, 2014; Mortula & Shobani, 2012; Muyibi et al., 2014; Rolence, Machunda, & Njau, 2014) from synthetic and real wastewaters. The results of these investigations showed that these pollutants, at varying operating conditions, were substantially removed. Factually, it could be resolved that adsorption process can potentially stand up to scrutiny in the removal of a variety of contaminants from wastewater streams and gaseous mixtures.

There are quite a number of articles on turbidity and suspended solids removal from POME using adsorption processes, but literatures on the attainment of optimum values and effects of the operation variables are not well studied especially with an empty fruit bunch (EFB)-based powdered activated carbon (PAC). Moreover, larger number of previous studies on EFB-based PAC was either focused on synthetic environments, or utilized chemical activation route for the PAC production. Here, we tested the utility of the EFB-based PAC for the treatment of real and high-strength
wastewater with interests in the removal of turbidity and suspended solids from biotreated POME. Besides, we emphasized the physical route of PAC activation (steam pyrolysis), which presents no mechanistic complexity, or any hazardous residual chemicals in the treated wastewater as a result of chemical reagents (employed for activation process) dissolving from the structure and cavities of the PAC. More importantly, the interactive effect of process parameters; PAC dosage, contact time and mixing speed was extensively examined, and the mechanistic adsorption pathway of the constituents of concern were modelled and presented.

2. Materials and methods

2.1. Sampling of EFB
Samples of EFB to be utilized as pre-cursor for the PAC production were collected from Sime Darby Palm Oil Mill in Carey Island, Malaysia. The EFB was preserved in a cold room at 4°C. The EFB was soaked in clean water for 12 h, washed and dried at 105°C for 24 h in an oven for dehydration until constant weight was achieved and crushed to desired particle size before the carbonization and activation treatments were performed.

2.2. Sampling of BPOME
The biotreated palm oil mill effluent (BPOME) sample (wastewater) was also collected from Sime Darby Palm Oil Mill in Carey Island, Malaysia. The physicochemical characteristics of the BPOME were determined using the Standard Methods for the Examination of Water and Wastewater. The sample was then preserved according to the recognized wastewater preservation standards (USEPA, 1982) such as storing in a cooling room at 4°C to avoid biodegradation of the constituents in the wastewater over time, amongst other preservations adopted.

2.3. PAC production
The physical activation of activated carbon involved a thermal treatment (carbonization) step where the volatile components of the EFB precursors were removed (de-volatilization) with 2.5 L/min N₂ gas flow rate at 900°C at 25°C/min heating rate for 30 min in a tubular horizontal furnace (Carbolite brand—CTF model, UK). Thereafter, the pre-cursor was subjected to activation process with a steam flow rate of 8.0 mL/min and activation time of 15 min and the reactor was allowed to cool down to room temperature as methodically reported elsewhere (Amosa, 2015; Amosa et al., 2015, 2016). The PAC was taken out of the furnace and ground with a grinder. PAC particles should not be bigger than 297 μm according to American Water Works Association (AWWA) standard and should not be smaller than 177 μm according to the American Society for Testing and Materials (ASTM) D5158 standard (Bandosz, 2006; Çeçen & Aktaş, 2012). Therefore, the PAC was sieved into size fractions of 212 micron (so as to attain exactly a 70-mesh size) thereby striking some sort of trade-off between the two standards.

2.4. Apparatus and measurements for physicochemical characterization of PAC
Autosorb-1 (Quantachrome Instruments, USA) was used for determining the pore size, as well as BET and Langmuir surface areas. The methylene blue (MB) surface area was also determined using the standard analytical method. Mastersizer 2000 (Malvern Instruments, UK) was employed for the particle sizing and distribution analysis, while the Spectrum-100 (Perkin Elmer, USA) was used for FTIR/surface chemistry analysis. Scanning electron microscope (SEM) was employed in the morphological characterization of the PAC using JSM-5600 (JEOL Ltd Company, Japan). Bulk density, moisture and ash contents of the PAC were also analysed using appropriate instrumentation and methods.

2.5. Design of experiment (DOE) software
The experimental design for the process optimization and its statistical analyses was carried with the aid of Design Expert® software version 9.0.6.2 (STAT-EASE Inc., Minneapolis, USA).
2.6. Batch adsorption tests

Batch adsorption experiments were carried out on the BPOME sample to study the adsorption efficiency and the effects of operating parameters using a 2-level factorial design as suggested by the Design Expert® software. To be assured of representative samples throughout the tests, the sample was homogenized using large aliquot to minimize random sampling errors in the laboratory, and samples were taken from well-mixed and/or turbulent zones to minimize sampling errors caused by segregation effects.

The tests were conducted by mixing different quantities of PAC with 100 mL of BPOME. The mixture was agitated in 250 mL Erlenmeyer flasks at various mixing speeds and contact time, depending on the levels of factor combination as offered by the software. Throughout this study, the pH and temperature of the wastewater were left unaltered at 8.56 to effectively simulate the condition of the wastewater being discharged in the laboratory. All the experiments in this study were replicated three times and the mean values were recorded. Water analyses before and after the treatment (for suspended solids and turbidity) were carried out following the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, & WPCF, 2005; HACH, 2012).

2.7. Apparatus and measurements for wastewater quality

Turbidity was measured using turbidimeter—Model 2100P (HACH Company, Loveland, USA) and it was expressed in nephelometric turbidity units (NTU). Suspended solids were measured using a HACH DR 5000 spectrophotometer (HACH Company, Loveland, USA). pH was measured using a pH meter (Mettler Toledo, MP220 model, USA). Hardness and alkalinity were measured using the burette titration method. Total dissolved solids, conductivity and salinity were measured with HACH Sension 7 (HACH Company, Loveland, USA). Other water qualities were measured with the HACH DR 5000 spectrophotometer.

2.8. 2-level full factorial design (FFD) for factor interaction study

A 2-level (2^3) FFD with three replicates at the centre point was carried out. 2-level FFD is a mathematical tool under the factorial design that helps in the screening of many factors to discover the vital few, and perhaps how they jointly interact (Montgomery, 2004). And because there are usually only two levels for each factor, it is assumed that the response is approximately linear over the chosen range of the factor levels, especially when the study about a process or system is just starting and there is a necessity to conduct factor screening experiments. Factorial designs are important because they are widely used in research works to form the basis of other designs of considerable practical value. The regression model for response (Y) prediction for such designs is given in Equation 1 (Montgomery, 2004):

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \cdots + \epsilon \]  

where \( x_1, x_2 \), and \( x_3 \) represent factor (independent) variables, and \( \epsilon \) is a random error term. Throughout the tests, independent variables for adsorbent dosage, mixing speed and contact time were, respectively, presented as variables A, B and C, respectively. The range and levels of the variables investigated in this study are shown in Table 1 for the experimental design. The range of settings for variable factors was adjusted based on the preliminary results coupled with the previous findings and literature (AbdulHalim et al., 2011; Alam, Ameem, Muyibi, & Kabbashi, 2009; Alkhatib, Muyibi, & Amode, 2011; Amosa, 2015; Amosa, Jami, Alkhatib, Jimat, & Muyibi, 2014b; Amosa et al., 2015; Emad, 2010; Neşe & T. Ennil, 2008; Razali, Yunus, Jemaat, & Alias, 2010; Tumin, Chuah, Zawani, & Rashid, 2008).

2.9. Equilibrium and kinetic studies

The optimized operating conditions were applied to the varying contact time (Koay, Ahamad, Nourouzi, & Chuah, 2014), from 10 min up to 24 h at room temperature (26 ± 1°C). The concentration of the contaminants was monitored and recorded at specific time intervals for the kinetic studies. The sorption kinetic rates were examined using the pseudo-first- and pseudo-second-order kinetic models. For equilibrium isotherm data, varying PAC dosage from 0 to 5 g was added to ten 250 mL
capacity Erlenmeyer flasks containing 100 mL of BPOME solution. The flasks were subjected to 150 rpm mixing speeds for 60 min contact time. The molecular distribution of the pollutants subjected to adsorption between the BPOME and PAC particles as they reach equilibrium state was evaluated using the Langmuir and Freundlich isotherm models. The linear plots and parametric values pertaining to each isotherm were evaluated in search of the best-fitting model that could better describe the adsorption processes.

3. Results and discussion

3.1. Physicochemical characterization

The complete physicochemical characterization of the PAC has been reported elsewhere (Amosa, 2015), and the summary is hereby presented in Table 2 (Amosa, 2015).

The scanning electron microscopy (SEM) analysis was carried out on the PAC and opened micropores were observed in the images as presented in Figure 1. Combinations of large and fine pores were also observed contained in the microphotographs at magnifications ×1,500 and ×2,000.

3.2. Characterization of biotreated POME (BPOME)

Table 3 shows the concentration levels of constituents contained in BPOME. It was imperative to measure as many as possible of the constituents in order to conjecture the potential adsorption competition that usually arise in multi-component streams during the adsorption process. Besides, the sedimentation process aided in lowering the suspended solids (SS) content of the wastewater which will in turn reduce its potential in obstructing the PAC pores, hence, decreasing its interference in the quantification of the PAC’s efficiency.

| Table 1. Independent variables for the full factorial design (FFD) |
|---------------------------------------------------------------|
| Factors | Units | Levels |
|---------|-------|--------|
| A: adsorbent dosage | g/100 mL | Actual (low) | Actual (high) |
| B: mixing speed | rpm | 100 | 200 |
| C: contact time | min | 30 | 60 |

| Table 2. Physicochemical characteristics of PAC produced |
|---------------------------------------------------------|
| Parameter | Unit | Steam-activated PAC |
|------------|------|---------------------|
| BET surface area | m²/g | 886.2 |
| Langmuir surface area | m²/g | 999.1 |
| MB surface area | m²/g | 1,185.3 |
| Total pore volume | cc/g | 0.663 |
| Average pore diameter | Å | 35.4 |
| Surface weighted mean “D[3, 2]” | μm | 11 |
| Volume weighted mean “D[4, 3]” | μm | 42 |
| Moisture content | % | 6.94 |
| Bulk density | g/cc | 1 |
| Ash content | % | 8.13 |
| Carbon yield | % | 25 |
| Surface chemistry | Carbonyl, aldehydes and ketones, mono-alkyl, amines, acid anhydrides, alcohol and phenols, sulphanyl chloride, sulphate and phosphoramides |
3.3. Full factorial optimization of adsorption operating conditions

The $2^3$ FFD revealed a total number of eleven experimental runs with three replicates at the centre points, and was used for monitoring the adsorption trends of the contaminants in order to obtain the relation between the variables affecting the adsorption process. Table 4 shows the experimental

| Contaminants                        | Raw Sample (±SD) | Sample after 24 h sedimentation |
|-------------------------------------|------------------|----------------------------------|
| Turbidity, NTU                      | 1,050 ± 47       | 840                              |
| Total dissolved solids (TDS), mg/L  | 1,207 ± 51       | 970                              |
| Chemical oxygen demand (COD), mg/L | 1,730 ± 110      | 1,387                            |
| Iron as Fe, mg/L                    | Not detected     | Not detected                     |
| Manganese as Mn, mg/L               | 3.08 ± 0.5       | 2.14                              |
| H$_2$S, mg/L                        | 0.88 ± 0.1       | 0.6                              |
| Calcium hardness, mg/L              | 240 ± 23         | 200                              |
| Magnesium hardness, mg/L            | 1,800 ± 71       | 1,480                            |
| Silica, mg/L                        | 73 ± 20          | 58                               |
| Phenolphthalein alkalinity, mg/L    | 180 ± 17         | 160                              |
| Total/methyl alkalinity, mg/L       | 2,000 ± 79       | 1,700                            |
| suspended Solids (SS), mg/L         | 761 ± 67         | 284                              |
| pH                                  | 8.65 ± 0.1       | 8.56                             |
design and responses for the process optimization, employing the low-cost PAC as adsorbent. All the results were further analysed using the analyses of variance (ANOVA).

Analyses of variance (ANOVA) describes a statistical algorithm that subdivides the total variation in a set of data into element items relating to particular sources of variation for the purpose of testing hypotheses on the parameters of the model (Turan & Ozgonenel, 2013). The statistical significance of the mean square ratio variation due to regression and residual errors of the mean square was evaluated using the ANOVA technique. It was experiential that the optimized parameters yielded response that are relatively close to each other in the experimental runs (Table 4). Some factors also exhibited significant effects ($p < 0.05$) while non-significance ($p > 0.05$) was attributed to others.

### 3.3.1. Statistical analysis for suspended solids (SS) sorption

From the initial concentration of 284 mg/L of suspended solids, the highest removal down to 31 mg/L of its concentration was observed at two centre points of 3.5 g/100 mL adsorbent dosage, 150 rpm mixing speed and 45 min of contact time (Table 4). However, the efficiencies observed at higher PAC dosage and contact time reduced significantly. This may be attributed to possible interference from PAC particles that might have escaped through the filter medium during filtration of the adsorbed wastewater.

Besides, the 3D plots in Figures 2a–2c illustrate the responses and interactions of the three factors that are involved in the adsorption process for suspended solids removal. In all the interactions, only the increase in the mixing speed from 100 to 200 rpm contributed positively to SS uptake from BPOME as it lead to lowering of the SS residual concentration. However, increase in the contact time (from 30 to 60 min.) and PAC dosage (from 2 to 5 g/100 mL) have negative effects. The SS concentration increased as those two factors were increased in all the interactive 3D plots. Here, the best removal could only be attained with lower contact times and PAC doses. This is evident from the very slight disparities exhibited in the axes of the 3D plot. The removal of SS with PAC could be attributed to the presence of pores bigger enough in the adsorbent to trap some of the particulates of SS that are of smaller sizes.

The ANOVA for the removal is presented in Table 5. The Model $F$-values of 55.23 in the ANOVA infer that the model was significant and that there is only a chance of 1.79% that a Model $F$-value this large could occur due to noise. The overall model was also significant by having a $p$-value of 0.001. Values of “Prob. > $F$” less than 0.050 are indications that model terms are significant, while values greater than 0.100 indicate non-significance of the model terms.

| Run | A: dosage (g) | B: mixing (rpm) | C: time (min) | Suspended solids (mg/L) | Turbidity (NTU) |
|-----|---------------|-----------------|---------------|------------------------|----------------|
| 1   | 2             | 200             | 30            | 33                     | 76             |
| 2   | 3.5           | 150             | 45            | 31                     | 72             |
| 3   | 5             | 100             | 60            | 45                     | 83.8           |
| 4   | 5             | 100             | 30            | 43                     | 82.5           |
| 5   | 2             | 200             | 60            | 35                     | 78.5           |
| 6   | 3.5           | 150             | 45            | 31                     | 72.2           |
| 7   | 5             | 200             | 30            | 40                     | 78.8           |
| 8   | 5             | 200             | 60            | 41                     | 79.5           |
| 9   | 2             | 100             | 30            | 35                     | 77.1           |
| 10  | 2             | 100             | 60            | 41                     | 81.1           |
| 11  | 3.5           | 150             | 45            | 32                     | 72.3           |
The “Curvature F-value” of 397.38 also implied that there was a significant curvature (as measured by difference between the average of the centre points and the average of the factorial points) in the design space. Moreover, there is only a 0.25% chance that a “Curvature F-value” this large could occur due to noise. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable, hence, the ratio of 26.170 indicates an adequate signal.
Figure 3 depicts the plot of predicted values against the actual values and the closeness of the points towards attaining linearity proves that the experimental and model values were relatively in agreement with each other. In this case $A$, $B$ and $C$ are the significant model terms with an $R^2$ value of 0.9949 and an adjusted $R^2$ value of 0.9768. $R^2$ values as high as this is an indication that the model was successful in correlating the response to the studied parameters. This model can be used in navigating the design space. The model exhibited a standard deviation of 0.58 and the final regression equation in terms of actual factors is given in Equation 2:

$$
\text{Suspended solids (mg/L)} = +16.33 + 5.33A + 0.047B + 0.49C - 0.013AB - 0.078AC - 2.00E-003BC + 3.33E-004ABC
$$

Table 5. ANOVA for selected factorial model for sorption of suspended solids

| Source       | Sum of squares | df | Mean square | $F$-value | $p$-value | Prob. > F |
|--------------|----------------|----|-------------|-----------|-----------|-----------|
| Model        | 128.88         | 7  | 18.41       | 55.23     | 0.0179    | Significant |
| A-PAC dosage | 78.13          | 1  | 78.13       | 234.38    | 0.0042    |            |
| B-mixing speed | 28.13          | 1  | 28.13       | 84.38     | 0.0116    |            |
| C-contact time | 15.13          | 1  | 15.13       | 45.38     | 0.0213    |            |
| AB           | 0.13           | 1  | 0.13        | 0.38      | 0.6026    |            |
| AC           | 3.13           | 1  | 3.13        | 9.38      | 0.0922    |            |
| BC           | 3.13           | 1  | 3.13        | 9.38      | 0.0922    |            |
| ABC          | 1.13           | 1  | 1.13        | 3.38      | 0.2076    |            |
| Curvature    | 132.46         | 1  | 132.46      | 397.38    | 0.0025    | Significant |
| Pure error   | 0.67           | 2  | 0.33        |           |           |           |
| Cor total    | 262            | 10 |             |           |           |           |
3.3.2. Statistical analysis for turbidity sorption

The turbidity level was lowered from its initial value of 840 NTU to the lowest value of 72 NTU at one of the centre-point operating conditions of 3.5 g/100 mL adsorbent dosage, 150 rpm mixing speed and contact time of 45 min (Table 4). The other remaining two centre point conditions also resulted in close turbidity values of 72.2 and 72.3 NTU expectedly.

Study of the operating conditions’ interactive effects on the sorption was also carried out and the effects are depicted in the 3D plots (Figures 4a–4c). While mixing speed favoured turbidity removal as it increased from 100 to 200 rpm, decreasing PAC doses and contact time favoured its removal. All 3D plots depict the lowering of turbidity levels only at lower ranges of adsorbent doses and contact time, while plots in Figures 4a and 4c depict the lowering of turbidity levels at higher ranges of mixing levels. It could be well observed that the adsorption trend resulting from the operating conditions are similar for both suspended solids (SS) and turbidity. This is a good indication that the two pollutants are interrelated and can technically represent each other.

From the ANOVA presented in Table 6 above, the Model $F$-value of 302.07 for the turbidity removal indicated an adequately significant model, and there is only a chance of 0.33% that “Model $F$-value” this large could occur due to noise. The $p$-value of the overall model was $<0.001$, implying that the model was very significant.

Furthermore, the “Curvature $F$-value” of 5,253.90 implied a significant curvature in the design space, and that there was only a 0.02% chance that a “Curvature $F$-value” this large could occur due to noise.

All factors were highly significant both singly and interactively in the adsorption process as highlighted in the ANOVA. In this case $A$, $B$, $C$, $AB$, $AC$, $BC$ were significant model terms. Figure 5 depicting the predicted vs. actual plot suggests that the model values were in good agreement with the
Experimental values as the linearity of the plot is obvious with the $R^2$ and adjusted $R^2$ values of 0.9991 and 0.9957, respectively. Adequate precision of 84.196 indicates an adequate signal from the model, and the model can be used to navigate the design space. The model exhibited a standard deviation of 0.15, and the final regression equation in terms of actual factors is given in Equation. 3:

$$
\text{Turbidity (NTU)} = 64.97 + 3.87A + 0.03B + 0.26C - 0.01AB - 0.04AC - 7.00E - 004BC + 1.00E - 004ABC
$$

(3)
Generally, it is crystal clear that all the predicted values obtained were pretty close to the actual values indicating that the models developed for suspended solids and turbidity sorption were efficacious in spanning the correlation between the factors and respective uptakes. Quality of the developed models was evaluated based on the coefficient of determination ($R^2$) values and all $R^2$ values obtained were evidently high. Besides, it was also observed that $R^2$ values were in reasonable agreement with their respective adjusted $R^2$ values for sorption of the two pollutants studied. Beside this, the model equations exhibited very low standard deviations. The closer the $R^2$ value to unity and the lower the standard deviation, the better the model and this gives a buoyancy of established closeness between the actual and predicted values of the responses.

Furthermore, within the operating condition ranges tested in this study based on previous reports from related findings as earlier reported in this paper, it was observed that suspended solids and turbidity experienced lowest possible residual concentrations at operating conditions of 3.5 g/100 mL adsorbent dosage, 150 rpm mixing speed and 45 min of contact time.

3.4. Equilibrium isotherm of adsorption

Adsorption isotherms describe how the molecules subjected to adsorption are distributed between the liquid and solid phases when the adsorption process reaches an equilibrium state. The analysis of the isotherm data being fitted to different isotherm models is an important step in finding the suitable model that can be used for design purposes (Demiral & Gündüzoğlu, 2010). The Langmuir and Freundlich isotherm models were applied for fitting the adsorption data in this study to describe the sorption mechanistic pathway.

The basic assumption in the Langmuir theory is based on the assumption of monolayer sorption, and that adsorption takes place at specific homogenous sites within the adsorbent following the linearized mathematical relation thus in Equation. 4 (AbdulHalim et al., 2011; Amosa, 2015; Amosa et al., 2016; Foo & Hameed, 2010):
where \( q_e \) is the amount of suspended solids adsorbed in mg/g, \( C_e \) is the equilibrium concentration (mg/L), \( b \) is the adsorption equilibrium constant (L/mg) which is related to the energy of adsorption (Lee, 2003), and \( q_m \) (mg/g) is the maximum adsorption capacity. A plot of \( 1/q_e \) vs. \( 1/C_e \) gives the adsorption coefficients. For this model, a further analysis can be made based on a dimensionless equilibrium parameter \( R_L \) (Dada, Olalekan, Olatunya, & Dada, 2012; Demiral & Gündüzoğlu, 2010; El-Naas, Al-Zuhair, & Alhaija, 2010; Ho, Porter, & McKay, 2002; Toth, 2002). If the average of the \( R_L \)
values for each of the different initial concentrations used is between 0 and 1, the favourable adsorption is provided.

On the other hand, the Freundlich isotherm model was derived by assuming the application to non-ideal sorption on a heterogeneous surface with a non-uniform distribution of heat of adsorption over the surface (Ho et al., 2002). This model is not bound by a maximum uptake, and it does not approach Henry’s law at low concentrations (El-Naas et al., 2010). Freundlich isotherm model is mathematically expressed in non-linear and linearized forms as shown in Equations. 5 and 6, respectively (Amosa et al., 2014a; Freundlich, 1906; Hameed & Daud, 2008):

\[ q_e = K_F C_e^{1/n} \]  
(5)

\[ \log q_e = \log K_F + \frac{1}{n} \log C_e \]  
(6)

where \( K_F \) and \( n \) are Freundlich constants which represent adsorption capacity and adsorption intensity, respectively. The Freundlich constants were determined from the slope and intercept of a plot of \( \log q_e \) vs. \( \log C_e \).

The equilibrium isotherm study was conducted in terms of suspended solids only, since the sorption trends were similar. Figures SM-1 and SM-2 (Supplementary Materials), and Table 7 depict the Langmuir and Freundlich model plots and their parametric model values.

The two model plots exhibited good linearity with a relatively high \( R^2 \) values. However, the values of isotherm parameters for the Langmuir model (\( q_m, b \) and \( R_L \)) in Table 7 being negative due to a negative intercept from the plot, are indications that the model did not follow the assumptions upon which it was established, thus the adsorption processes cannot be explained by the model. Similar results have been reported in previous investigations (Amosa et al., 2014a, 2016; Ho, 2003; Ho et al., 2005; Kamari & Ngah, 2009; Muyibi et al., 2014; Štrkalj, Glažaš, & Brnadić, 2013). The reason may as well be as a result of the complex nature of the multi-component system, and consideration must be given to the competition between the sorbates which, in many cases, result in lack of equilibration for some models. Previous investigative reports have arrived at similar conclusions with respect to the negative slopes and intercepts exhibited by isotherm models (Hamdaoui & Naffrechoux, 2007; Kiurski, Adamovic, Krsic, Oros, & Miloradov, 2011; Maarof, Hameed, & Ahmad, 2006; Shah, Shah, & Shah, 2011; Vandenbruwane, De Neve, Qualis, Sleutel, & Hofman, 2007).

Furthermore, the regression values \( R^2 \) clearly show that sorption process fitted better with the Freundlich isotherm model with \( R^2 \) value of 0.9057 as compared to the Langmuir isotherm model with \( R^2 \) value of 0.8424. Moreover, the Freundlich model constant, \( 1/n = 2.6459 \) indicates a cooperative adsorption since \( 1/n > 1 \) (Foo & Hameed, 2010).

### 3.5. Kinetics of adsorption

Molecular diffusion of BPOME constituents into the channels and cavities of PAC particles, and rate prediction of the sorption processes were carried out using the Lagergren’s pseudo-first- and pseudo-second-order kinetic models. All model plots were evaluated for the selection of best-fitting

| Table 7. Isotherm model parameters and values |
|----------------------------------------------|
| **Parameters for Langmuir model** | \( q_m \) (mg/g) | \( b \) | \( R_L \) | \( R^2 \) |
|----------------------------------------------|
| -5.577 | -1.83E-02 | -0.238 | 0.8424 |
| **Parameters for Freundlich model** | \( n \) | \( 1/n \) | \( K_F \) | \( R^2 \) |
|----------------------------------------------|
| 0.3779 | 2.6459 | 8.56E-04 | 0.9057 |
kinetic model that accurately describe the sorption mechanism. The models for the pseudo-first- and pseudo-second-order kinetics are presented in Equations 7 and 8, respectively, in their linear forms thus:

\[
\log(q_e - q_t) = \log q_e - \frac{k_1 t}{2.303}
\]  

(7)

\[
\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}
\]  

(8)

where \(q_e\) and \(q_t\) are amount of adsorbate adsorbed (mg/g) at equilibrium and at time \(t\) (min), respectively, \(k_1\) (l/min) is the rate constant of first-order adsorption, and \(k_2\) is the pseudo-second-order rate constant (g/mg/min) (Lee, 2003). The models plots pseudo-first- and pseudo-second-order models are presented in Figures SM-3 and SM-4 (supplementary Materials), respectively.

It was observed that the sorption rates were very rapid in the first 10 min. The Lagergren’s pseudo-first-order kinetic model was not suitable in describing the adsorption rate as the plots clearly deviated from linearity (Figure SM-3). This implies that pore diffusion was not the sole rate controlling step. However, as depicted in Figure SM-4, pseudo-second-order model gave clear linear plots with \(R^2\) value of 0.9998 as compared with pseudo-first order that gave \(R^2\) value of 0.8865. This indicates that chemisorption had the highest influence on the adsorption mechanistic pathway of the two contaminants. The values of the kinetic parameters are given in Table 8.

| Parameters | Pseudo-first order | Pseudo-second order |
|------------|--------------------|---------------------|
| \(q_e\) (mg/g) | \(k\) (min\(^{-1}\)) | \(R^2\) |
| 1.306 | 0.054 | 0.8865 |
| \(q_e\) (mg/g) | \(k\) (g/mg min) | \(R^2\) |
| 7.003 | 0.102 | 0.9998 |

The pseudo-second-order model is related to chemisorption due to the presence of functional groups promoting irreversible type of adsorption (Amosa et al., 2016; Itodo & Itodo, 2010). Similar observations have been reported in previous works (Alam, Muyibi, Mansor, & Wahid, 2006; Amosa et al., 2014a, 2016; Cao et al., 2014; Crosson & Sandmann, 2013; Hassani, Vafaei, Karaca, & Khataee, 2014; Ho, 2003; Husin, Wahab, Isa, & Boudville, 2011; Kushwaha & Sudhakar, 2013; Robati, 2013; Vázquez, Fernández-Bea, Freire, González-Álvarez, & Antorrena, 2007). Furthermore, the calculated \(q_e\) value of 7.003 mg/g (Table 8) was also in good agreement with the experimental value of 6.91 mg/g for sorption of suspended solids.

4. Summary and concluding remarks

The results obtained in this study suggest a potential application of EFB-based PAC in the efficient removal of turbidity and suspended solids from BPOME which is a high-strength wastewater.

The result of the full factorial design showed that suspended solids and turbidity could be significantly removed with the operating conditions of 3.5 g/100 mL PAC dosage, 150 rpm mixing speed and 45 min of contact time. Moreover, the Freundlich isotherm and pseudo-second-order kinetic models were the suitable models that could better describe the adsorption mechanism, with \(R^2\) values of 0.9057 and 0.9998. This suggests the heterogeneity of the adsorption mechanistic pathway while the chemisorption could also be said to have contributed to the sorption trend due to its accurate fitting with the pseudo-second-order model.
The levels of turbidity and suspended solids were significantly reduced from 840 to 72 NTU and 284 to 31 mg/L, respectively. This huge reduction in the concentration loading of the end-of-pipe effluent will reduce the pollution loading of the waterways and rivers. Additionally, while the suspended solids may not meet the Class I (<25 mg/L suspended solids) Water Quality Index of Department of Environment (DOE) Malaysia, it was certainly below the benchmark of the Class II to V of the quality index (DOE, 2008, 2010). This suggests possible reuse of the treated water for recreational purpose, irrigation and livestock drinking provided that all other pollutants of concern are also within the recommended standard allowed. This methodology has a strategic potential for reducing turbidity and suspended solids in wastewater samples and it could be said that the two pollutants are interrelated since they exhibited similar trends in their removals. However, presence of other contaminant species in the multi-component effluent can affect the final function obtained, especially if the affinity of these species is greater than those of interest. Overall, EFB-based PAC could be utilized as a standard adsorbent which could sustainably replace the expensive adsorbents usually procured for environmental abatement processes.

Supplementary material
Supplementary material for this article can be accessed here http://dx.doi.org/10.1080/23311916.2016.1162384.

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