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Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

New kinetic models for predicting the removal of oil and grease from food-processing industry wastewater

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ARTICLE INFO

Article history:
Received 28 July 2022
Received in revised form 4 October 2022
Accepted 31 October 2022
Available online 4 November 2022

Keywords:
Biochemical accumulation rate
Kinetic model
Oil-contaminated wastewater
Packed-bed column reactor
Serratia marcescens SA30

ABSTRACT

Biochemical accumulation rate of *Serratia marcescens* SA30 to remove the oil and grease (O&G) contaminant from a wastewater can be described using the kinetic models of packed-bed column reactor (PBCR) treatment system. The aim of this study was to develop the linear and logarithmic equations for predicting the efficiency of O&G removal from food-processing industry wastewater. The results showed that the performance of PBCR treatment process can achieve nearly 100% efficiency when the PBCR experiments were run using the initial O&G concentrations of 26.9 and 33.5 g L^{-1} with a volumetric flow rate of 0.18 L h^{-1}. The applicability of the linear and logarithmic equations represented a quick and reliable method to monitor the trend of O&G removal by the PBCR treatment process contributes to strengthening the future biotechnological methods of treating oil-contaminated wastewater in the tropical environment.

1. Introduction

Oil and grease (O&G) as one of the water quality parameters measures a variety of substances including fuel, animal-derived fat, lubricating oil, hydraulic oil, motor oil and cooking oil originally coming from anthropogenic sources (Eljaiek-Urzola et al., 2019). Understanding the variations of O&G contaminant released from different human activities are critical to determine the point and nonpoint sources of pollution in an aquatic environment. The concentrations of O&G are commonly monitored for lake, river, stormwater runoff and wastewater due to the risk of persistent O&G pollutant derived from various human activities can deleteriously affect the quality of surface water. An excessive amount of O&G released from food-processing industry wastewater (FPIW) into the aquatic environment can lead to a decreased aesthetic value of water body causing the environmental problems (He et al., 2011). The engineering process of O&G removal from FPIW using a best treatment option is required due to the low solubility of O&G in water can cause serious problems passing the main stages of the water and wastewater treatment processes (Fulazzaky and Omar, 2012). Many biological and physicochemical treatment systems have been practiced for the removal of O&G contaminant from wastewater using white rot fungus *Phanerochaete chrysosporium* (Behnood et al., 2014), strain of *Serratia marcescens*

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https://doi.org/10.1016/j.cherd.2022.10.047

SA30 (Fulazzaky et al., 2015a) and natural zeolite-packed column (Shavandi et al., 2012). An excessive amount of O&G interfered an aerobic biological process reducing the rate of oxygen transfer could be harmful to bacterial growth leading to disrupt the entire process of biological wastewater treatment (Olajire, 2020). The conventional method of biological process used to remove the contaminant of O&G under a defined set of the environmental conditions is naturally resistant to some degrees of biodegradation (Malakahmad et al., 2014). Therefore, the application of biosurfactant-producing bacteria (BSPB) in biological treatment process can lower the tension of oil-water interface to be considered as an effective option for eco-friendly biodegradation of O&G from FPIW effluent. Benefit of understanding the ability of locally isolated BSPB to remove the contaminant of O&G from the FPIW effluent is to acquire the new approach to solving environmental problems.

Biosurfactant as amphiphilic molecule that has both hydrophobic and hydrophilic domains plays an important role in the emulsion and stability of the O&G uptake by regulated micelle formation (Nikolova and Gutierrez, 2021) and has the ability of its surfactant properties to reduce the interfacial tension between two media, either oil/water or oil/air systems (Fulazzaky et al., 2015a). Micelle formation enables biosurfactants to increase solubility and bioavailability of the hydrophobic organic compounds and plays a variety of the roles in helping the survival of microorganisms in the most hostile environments of containing the toxic inorganic and organic compounds (Pacwa-Płociniczak et al., 2011). The treatment of O&G conditioned under biological process requires an extensive effort to develop a detailed study protocol and to bring an isolated bacterial strain adapted to the right environment of bacterial host. Kinetic modelling of biological system to determine the kinetic parameters (Sánchez-Ramírez et al., 2022) is becoming a necessity for predicting the efficiency of biological treatment process of FPIW mediated by BSPB. Oil palm frond (OPF) is one of the suitable carriers for immobilizing bacterial cells to increase the survival of bacteria in the field of wastewater treatment plant operation (Gentili et al., 2006). The selection of OPF as a supporting material has been viewed from the fact that approximately 26.2 million tonnes of OPF generated from the palm oil industries of no economic value in Malaysia are difficult to dispose as the wastes (Kaniapan et al., 2021). The surface of OPF as an inert material with its high roughness and hydrophilic property can easily attach the biofilms of BSPB to support bacterial growth during the treatment process of O&G removal from FPIW effluent. Using the OPF material is more advantageous to biological treatment process than other supporting materials of such as grain sorghum, peach stone, citron leaf and rambutan peel since the use of OPF offered by ease to find is not expensive facing the operation cost involved to collect and to prepare for the purpose of FPIW treatment (Zhao et al., 2018).

Many technological approaches of the physical, chemical, biological and membrane treatments have been subjected to the practice of O&G removal from produced water of oil and gas extraction (Olajire, 2020) and from synthetic and real produced water with high O&G content and salinity (Souza et al., 2020). The potential application of biosurfactants in the remediation of environmental pollution caused by O&G have been suggested for the treatment of wastewater (Silva et al., 2014). However, the treatment of FIPW mediated by the accumulation of BSPB biomass on the OPF matrix of rough surface to remove the O&G contaminant is still not fully understood. The limitations of this study are the sampling of oil-contaminated wastewater focused on one particular industry and lack of analysis of the mass transfer phenomena occurred during the bioaccumulation of O&G on the surface of OPF mediated by *Serratia marcescens* SA30 strain. A causal modelling approach to the development of theory-based behaviour change interventions for the removal of O&G contaminant from FIPW effluent could be the subject of this study by several research modifications. It is hypothesized that the new empirical kinetic models developed as the necessity and innovation of this work would be used as a tool for measuring the performance of biological treatment process for the removal of O&G contaminant from FPIW effluent. The objectives of this study are (1) to develop the linear and logarithmic equations based on several assumptions about the values of kinetic data and (2) to test the assumptions for assessing the effects of concentration and volumetric flow rate (VFR) on the efficiency of O&G removal from FPIW effluent mediated by *Serratia marcescens* SA30 applied to a packed-bed column reactor (PBCR). This article is structured by firstly introducing a background knowledge and reasoning capacity to get better understanding on the necessity and innovation of the work. Section of materials and methods discusses the sampling locations of FPIW effluent, the treatment procedure to remove the contaminant of O&G, and the development of the linear and logarithmic models. The section of the experimental results was separated from the section of discussion aimed to demonstrate how the objectives of this study can be met before presenting the take-home messages as the capsule value of this paper in the section of conclusions.

2. Materials and methods

2.1. *Food-processing industry wastewater and sampling locations*

All samples used for this work were collected from food-processing factory (FPF) located at Rengit, 90 km from Johor Bahru, the state capital of Johor, Malaysia. The sampling points were selected at two locations: (1) outlet of the processing and manufacturing processes (OPMP) located inside the FPF yard and (2) factory sewer system (FSS) located outside the FPF yard before discharging into the river. For sampling purpose, 1 L of FPIW sample from each location was filled in 1-L sterilized Schott bottle. The samples of being transported to the testing laboratory were kept at 4 °C in an ice-packed container. The main characteristics (Table 1) of FPIW effluent show that the processing and manufacturing processes of FPF can generate oily wastewater with a high O&G contaminant. Table 1 shows that the effluent of FPIW collected from OPMP has its biodegradability index (BI) of 0.45 and that collected from FSS has its BI of 0.70. Even though the diversity of BSPB isolated from FPIW sample or soil contaminated with O&G could be useful for an adaptable system of the biological treatment process, the sample of FPIW effluent collected from OPMP inside the FPF yard was used for isolating the strain of BSPB. Using the samples of FPIW collected from OPMP and those collected from FSS for running the experiments was aimed to predict the performance of PBCR process estimated by the kinetic models.

Table 1 – Main characteristics of the FPIW effluent.

No	Parameter	unit	EO [(a)]	DS [(b)]	Analytical method
1	Temperature	°C	28.9	28.9	Polarographic sensor (YSI Model 5100)
2	pH	–	5.46	5.73	Polarographic sensor (YSI Model 5100)
3	DO	mg O_2 L^{-1}	3.5	4.5	Polarographic sensor (YSI Model 5100)
4	BOD	mg O_2 L^{-1}	2800	2875	Dilution, incubation at 20 °C for 5 days
5	COD	mg O_2 L^{-1}	5625	4125	Dichromate digestion
6	NH_4^+	mg N L^{-1}	146.1	181.6	Polarographic sensor (YSI Model 5100)
7	SS	mg L^{-1}	7800	9100	Gravimetric
8	TDS	mg L^{-1}	393	390	Polarographic sensor (YSI Model 5100)
9	O&G	mg L^{-1}	42974	19395	Partition Gravimetric

Remarks that: (a)EO is the FPIW collected at outlet of the processing and manufacturing processes inside the FPF yard and (b)DS is the FPIW collected at FSS located outside the FPF before discharging into the river.

2.2. *Experimental equipment and operating procedure*

This study used the PBCR system consisting of the FPIW storage tank with a capacity of 5 L, acrylic column with its dimensions of 50.0-cm height × 4.6-cm inner diameter, Masterflex peristaltic pump (Cole-Palmer) and treated FPIW storage tank with a capacity of 3 L, as shown in Fig. 1. The packed-bed column (PBC) of acrylic column was divided from the bottom to top into four sections, from which 3 cm of the bottom PBC bed was filled with an inert stone in the granular size of 1–2 cm, 35 cm of the middle PBC bed filled with dried OPF of 90 g, 2 cm of the top PBC bed filled with an inert stone of the same granular size filled the bottom FBC bed, and leave of approximately 10 cm upper the top PBC bed as the empty column. The removal of impurities from the inert stones was soaked in pure water for 24 h, rinsed with distilled water and then dried at 30 °C in an incubator of Memmert IN110 for 24 h. The PBC bed was filled by the OPF materials with a length range of 1–2 cm, width range of 1–1.5 com and height range of 0.3–0.5 as the main component of PBCR system to support the immobilization of bacterial cells. The empty space in active zone of filled the OPF matrix of rough surface was around 0.46 L. After rinsing with 2-L deionized water at constant flow rate of 0.18 L h^{-1}, OPF matrix can prevent the potential clogging of PBC to allow the electrostatic charge and hydrophobic interactions necessary for adhesion of bacteria. The adapted strain of *Serratia marcescens* SA30 that has been sequenced in the GenBank nucleotide sequences databases under accession number KF686740 (Fulazzaky et al., 2016) was immobilized onto the OPF surface using the Masterflex peristaltic pump (Cole-Palmer) with continuous circulation at a flow rate of 0.18 L h^{-1}. The rinsing step of 3 d can allow an initial bacterial attachment until reaching steady state condition of the PBCR process (Maganti et al., 2008). Application of *Serratia marcescens* SA30 as the potential BSPB strain has been proposed to describe the kinetics and mass transfer mechanisms of the O&G biosorption applied in hydrodynamic PBCR process (Fulazzaky et al., 2015a). Using the strain of *Serratia marcescens* not well adapted to the experimental processing conditions can cause a reduced metabolic activity of biosurfactants leading to low performance of PBCR process (Mishina and Zeier, 2007). PBC was enriched with 2 L of nutrient broth for 2 d to ensure an initial bacterial attachment under a steady state condition. The presence of 10-cm empty column upper top of the non-aerated PBC bed (see Fig. 1) can help ensuring consistent availability of dissolved oxygen (DO) supplied into PBCR to allow the growth of *Serratia marcescens* SA30 immobilized and securely held on the OPF matrix of rough surface. When the capture of air

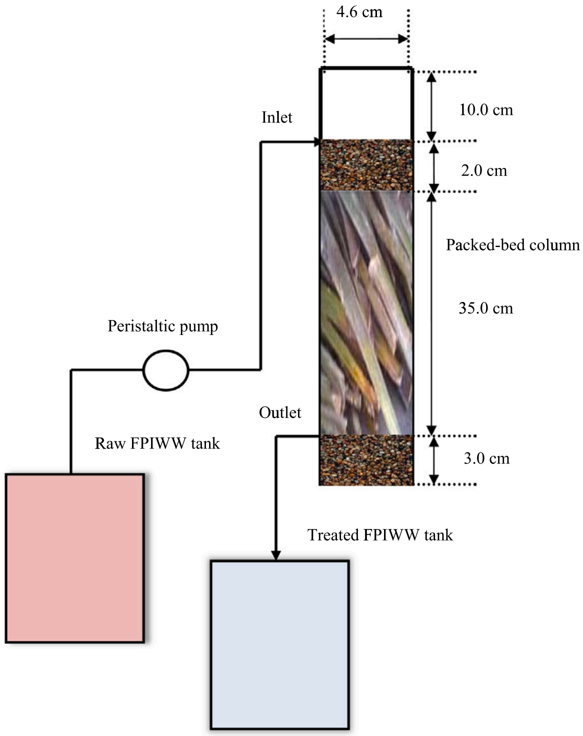

Fig. 1 – Schematic of the PBCR treatment system.

contained high DO level in the empty column meets the flow of water contained low DO level in FPIW effluent, the diffusion of oxygen caused by a tremendous difference in the DO concentration could be due to high driving force of oxygen moved from the air to water (Mölder et al., 2005). It could be understood due to approximately 10 cm of the empty column contained air upper the top PBC bed that stagnant FPIW in the storage tank and then flowing through the PBC bed were not aerated at a given airflow rate for the purpose of running the experiments. The running of PBCR processed using the food-to-microorganism ratio of 0.72 g COD/g SS per day for the treatment of FIPW collected from OPMP and that of 0.45 g COD/g SS per day for the treatment of FIPW collected from FSS was conducted at room temperature. Sludge retention time criterion was not defined based on the fact that the growth of *Serratia marcescens* SA30 continuously immobilized on the surface of OPF during the experiment period. The empty space in middle part of the PBC reactor through which the FPIW effluent passing was connected with an inert stone at the bottom and top of the PBC tank to provide a hydraulic retention time (HRT) of 2.56 h.

The concentrations of O&G were monitored once per day at inlet and outlet of the PBCR system. The analysis of O&G was made using the partition-gravimetric method of 5520-B (American Public Health Association APHA, 2005) at the Laboratory of Centre for Environmental Sustainability and Water Security, Universiti Teknologi Malaysia, on the same day of sampling date. The performance of PBCR process was evaluated based on the concentrations of O&G monitored from OPMP inside the FPF yard during a 6-day trial. One of the key objectives was to evaluate the effect of different O&G concentrations of 16.4 $g L^{-1}$ (50%, v/v), 26.1 $g L^{-1}$ (75%, v/v) and 33.5 $g L^{-1}$ (100%, v/v) for the samples of FPIW collected from OPMP on the performance of PBCR treatment processed running at constant VFR of 0.18 $L h^{-1}$. Another key objective was to evaluate the effect of different VFRs of 0.18, 0.30, 0.42 and 0.54 $L h^{-1}$ on the performance of PBCR treated the FPIW effluent with the O&G concentrations of 26.9, 19.3, 20.5 and 20.4 $g L^{-1}$, respectively, for the samples of FPIW collected from FSS before entering the river. The choice of these O&G concentrations was to reflect in vivo exposure to the real concentrations similar to those detected in the specific effluent of FIPW released from home industries. The experimental data were used to test and validate the applicability of the kinetic models proposed for predicting the efficiency of PBCR process to remove the emerging pollutants of O&G before discharging into the aquatic environment. The concentrations of O&G monitored at inlet and outlet of the PBCR system (see Table 2) were analysed to put the simulation hypothesis to the test and to meet two key objectives of the experiment. The operation of PBCR process was aimed to investigate the biosorption of O&G mediated by the growth of *Serratia marcescens* SA30 to increase the amount of biomass attached on the surface of OPF over time (Fulazzaky et al., 2015a).

Table 2 – Concentrations of O&G monitored at inlet and outlet of the PBCR system.

t (d)	C_0 ($g L^{-1}$)	C_e ($g L^{-1}$)	C_0 ($g L^{-1}$)	C_e ($g L^{-1}$)	C_0 ($g L^{-1}$)	C_e ($g L^{-1}$)	C_0 ($g L^{-1}$)	C_e ($g L^{-1}$)
The PBCR experiments were run using a constant VFR								
24	16.4	12.1	26.1	14.1	33.5	16.0		
48	16.4	10.5	26.1	13.1	33.5	10.3		
72	16.4	8.7	26.1	7.3	33.5	4.3		
96	16.4	7.3	26.1	3.6	33.5	1.5		
120	16.4	5.6	26.1	1.4	33.5	0.9		
144	16.4	3.7	26.1	0.5	33.5	0.1		
The PBCR experiments were run using different VFRs								
24	26.9	20.8	19.3	14.8	20.5	16.2	20.4	15.6
48	26.9	11.2	19.3	12.1	20.5	14.1	20.4	13.5
72	26.9	6.5	19.3	11.5	20.5	12.4	20.4	10.5
96	26.9	3.1	19.3	9.3	20.5	10.5	20.4	9.4
120	26.9	1.8	19.3	6.9	20.5	8.3	20.4	7.2
144	26.9	0.1	19.3	3.1	20.5	6.1	20.4	5.9

Remarks that C0 is the O&G concentration in the raw FPIW effluent and Ce is the O&G concentration in the treated FPIW effluent.

2.3. *Models development*

Many physical and mathematical models have been used to describe the level of change in a biological wastewater treatment process (Rezaee et al., 2016). The modelling of mass transfer processes has been proposed to describe the kinetics of O&G bioaccumulation on the adsorbent matrix of rough surface applied in PBCR (Fulazzaky et al., 2015a) and continuous stirred-tank reactor (Pintor et al., 2015). Mathematical modelling of bacterial growth and process performance could be the powerful platform in developing design and operation of the biological treatment process (Weingarten et al., 2012). The need to operate the PBCR process on the day-to-day basis in practice requires a further development of the robust, integrated macro or microfluidic systems. In this work, a conceptual model was proposed to predict the performance of PBCR process to remove the contaminant of O&G from FPIW effluent. The data of daily monitoring the concentrations of O&G at inlet and outlet of the PBCR system were used to verify and validate the dynamic mass balance equations. Factors influencing a biological process such as the amount of DO required to support the growth of bacteria as well as the production of biomass and metabolites as the eligible components of PBCR treatment system were not taken into account for the purpose of models development. The development of the kinetic models was focused on the importance of O&G degradation during the biological treatment process in spite of change in the catabolic pattern with DO can affect the production of biomass and metabolite (López et al., 2012). By assuming the PBC bed as a black box, the mass balance equation for the removal of O&G from FPIW effluent after reaching a steady state condition at the level of PBCR system can be written as:

$$\frac{dq}{dt} = r \tag{1}$$

where q is the amount of O&G accumulated onto the OPF surface migrating from the FPIW solution to support the needs of bacterial growth and metabolism in the PBC tank (in g), t is the accumulation time for the PBCR treatment process (in h) and r is the rate of biochemical accumulation (in $g h^{-1}$).

An argument in the chemical kinetics refers to the case of O&G removal that the biochemical rate of accumulation depends on the concentration of O&G while the value of exponent is equal to one. There is because the development of mass balance equation has the only one basis of O&G assimilation. Assuming that r is the first order hence the rearrangement of Eq. (1) yields a continuous equation in the form of:

$$\frac{dq}{dt} = kq \tag{2}$$

where k is the biochemical accumulation rate coefficient (in h^{-1}).

It is hypothesized that the amount of O&G accumulated on the OPF surface migrating from the FPIW solution to support bacterial activities in the PBC tank can exponentially increase since the renewable sources of carbon and energy properly support an exponential growth of bacteria. By separating the variables, then Eq. (2) can be integrated in the form of:

$$q = q_0 e^{kt} \tag{3}$$

The kinetic model of Eq. (3) used to predict the biosorption of O&G by means of linear regression approach (Rout et al., 2017) can then be arranged to have a constant slope into the linear form of:

$$\ln(q) = kt + \ln(q_0) \tag{4}$$

where q_o is the amount of O&G accumulated onto the OPF surface migrating from the FPIW solution to support the needs of bacterial growth and metabolism in the PBC tank at time zero after reaching a steady state condition (in g).

The performance of PBCR treatment process to remove the contaminant of O&G from FPIW effluent can be expressed in the equation of:

$$E = \frac{C_0 - C_e}{C_0} \times 100\% \tag{5}$$

where E is the O&G removal efficiency (in %), C_0 is the O&G concentration in the raw FPIW effluent monitored at inlet of the PBCR system (in mg L^{-1}); C_e is the O&G concentration in the treated FPIW effluent monitored at outlet of the PBCR system (in mg L^{-1}).

Growth of bacteria in the PBC tank requires carbon source to not only coming from the O&G compounds but other organic carbon sources in the FPIW effluent coming from food debris. Yet, the development of logarithmic equation depends on O&G in spite of the presence of microbial activities during the process of FPIW treatment is not only able to metabolize O&G as the sole carbon source. One need to understand for developing a kinetic model is the role of each component and the biokinetic parameters involved during the treatment of FPIW (Priyadarshini et al., 2021). A systematic approach to develop a conceptual model was based on the assumptions that (1) since the value of C_o is the only organic carbon derived from O&G taken into account for developing the new concept of mass balance equation, the amount of O&G metabolized by microbial activities in the PBC tank should be considered as the accumulation of C_o - C_e to having an optimal function of the PBCR process, (2) the value of E used to predict the efficiency of PBCR depends on a number of factors including HRT, C_o and VFR, (3) the tendency of becoming a more rational experiment needs to be run with more variables, using different initial O&G concentrations and different VFRs for examples, and (4) the need to operate the PBCR process on a day-to-day basis in the practise can totally remove the contaminant of O&G from FPIW after passing an appropriate t of the biological treatment.

Accumulated amount of O&G in biomass attached on the OPF surface migrating from FPIW solution to support the growth of bacteria and their metabolism during time of t has experienced with the multiple-residence times of FPIW flowing passed through the PBC tank. The use of the adsorption kinetic and isotherm models could be useful to investigate the behaviours of phosphate adsorbed onto dolochar (Rout et al., 2015) and antimony adsorbed onto the modified magnetic sepiolite adsorbent (Saleha et al., 2022). A new logarithmic equation can be developed based on the hypotheses that (1) ln(t) can be thought of as the inverse of an exponential, due to the value of q is equal to an accumulated C_o - C_e value after passing the multiple-residence times, and can replace t in Eqs. (4), (2) $\ln(q_o)$ in Eq. (4) is a constant and can be replaced by c, which is defined as the initial accumulation rate constant relying an amount of O&G has been accumulated on the OPF surface for reaching a steady state condition at a weight of microorganisms, and (3) E can replace ln(q) in Eq. (4) due to the percent $\left(\frac{(C_o + C_e)}{C_o}\right)$ in Eq. (5) of O&G accumulated has been balanced by the percent $\left(\frac{(S + S_o)}{S_o}\right)$ of biomass accumulated on the OPF surface and then the unit of q (in g) can be replaced by the unit of E (in %) since the accumulation of O&G on biomass has been divided by the total amount of O&G entered PCB. Linear model of Eq. (4) can be arranged in the logarithmic form of:

$$E = \left(\frac{k\,(S + S_o)}{S_o}\right) \times \ln(t) + c \tag{6}$$

where S is the biomass concentration after time t (in mg L^{-1}), S_o is the concentration of the initial biomass in PBCR after reaching a steady state condition (in mg L^{-1}) and c is the initial accumulation rate constant (dimensionless) relying an amount of O&G accumulated on the OPF surface after reaching a steady state condition at a weight of microorganisms.

3. Results

3.1. *Linear kinetic models to assess the loading rate and O&G utilization*

This study analysed the functional relationship between ln(q) and t in Eq. (4) using the value of k to describe the rate of biochemical accumulation. By plotting ln(q) versus t accorded to Eq. (4) yields the linear function of ln(q) increased with increasing of t (see Fig. 2). Table 3 shows the value of $\ln(q_o)$ increased with increasing of the organic loading rate (OLR). The same k value of around 0.02 h^{-1} obtained from the PBCR experiments was verified using different O&G concentrations and different VFRs. An increase in the value of $\ln(q_o)$ from 2.72 to 3.72 and to 4.18 g with increasing of the OLR from 3.0 to 4.7 and to 6.0 g h^{-1} could be related to the concentration of O&G entering the PBCR system increases from 16.4 to 26.1 and to 33.5 g L^{-1}, respectively (see Table 3).

Fig. 3 shows the graphs of plotting the O&G accumulation on the OPF surface versus the accumulation of O&G loaded the PBCR system to yielding the linear equation: $Y = a \times X - b$, where the slope of a (dimensionless) determines the ratio of O&G needed for bacterial growth to O&G loaded the PBCR treatment system under a steady state condition and the value of b (in g) obtained from the interception of curve Y versus X defines the initial O&G needs for bacterial growth and metabolism after reaching a steady state condition, Y is the accumulation of O&G attached on the OPF surface (in g) and X is the accumulation of O&G loaded the PBCR treatment system (in g). Fig. 4 shows the SEM image of the surface roughness and morphology of the OPF material partly covered by O&G before fully immobilized by the strain of *Serratia marcescens* SA30 (see Fig. 4a) and that fully covered by the immobilization of *Serratia marcescens* SA30 strain (see Fig. 4b). The value of a increased from 0.563 to 0.814 and to 0.909 with increasing of the O&G concentration from 16.4 to 26.1 and to 33.5 g L^{-1}, respectively, was verified from the running of the PBCR experiments at a constant VFR of 0.18 L h^{-1} (Fig. 3a; see Table 4). The a values of 0.840, 0.547, 0.496 and 0.549 were verified from the running of the PBCR experiments using the different VFRs of 0.18, 0.30, 0.42 and 0.54 L h^{-1}, respectively (Fig. 3b; see Table 4).

3.2. *Logarithmic kinetic model to predict the PBCR performance*

Several models for predicting the performance of biological process have been reported in the literatures. The mathematical model of bioreactor has been proposed taking into account the liquid phase and biofilm of the biological process, axial dispersion of the liquid and gas phase, external

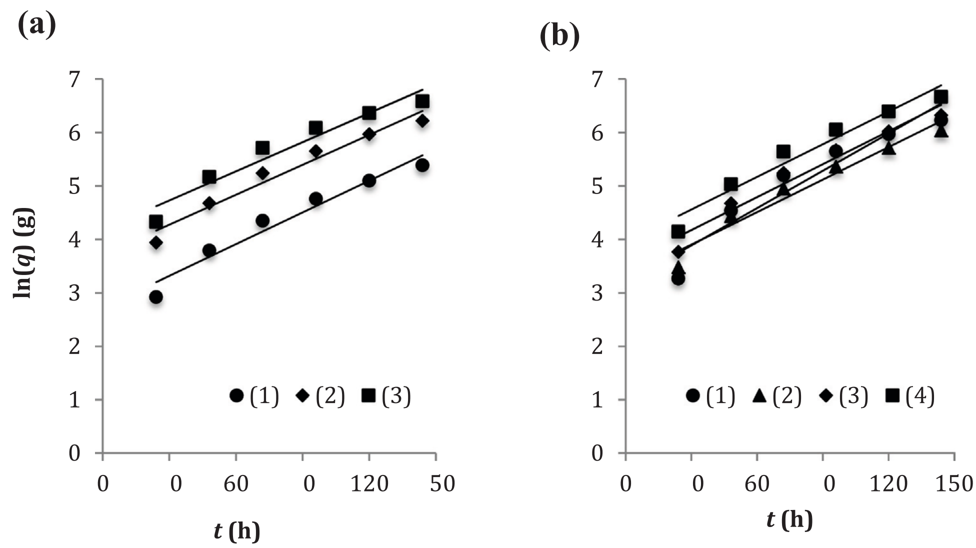

Fig. 2 – Linear graphs of plotting ln(*q*) versus *t* to show the trend of experimental data. Notes that: *(a)* the PBCR experiments were run at a constant VFR of 0.18 L h^{-1} with different O&G concentrations of (1) 16.4 g L^{-1}, (2) 26.1 g L^{-1} and (3) 33.5 g L^{-1} and *(b)* the PBCR experiments were run at different VFRs of (1) 0.18 L h^{-1} with O&G concentration of 26.9 g L^{-1}, (2) 0.30 L h^{-1} with O&G concentration of 19.3 g L^{-1}, (3) 0.42 L h^{-1} with O&G concentration of 20.4 g L^{-1} and (4) 0.54 L h^{-1} with O&G concentration of 20.5 g L^{-1}.

Table 3 – Values of *k* and ln(q_o) obtained from plotting ln (*q*) versus *t*.

Loading rate (g h^{-1})	*k* (h^{-1})	ln (q_o) (g)	R^2
The PBCR experiments were run with using different O&G concentrations			
3.0	0.02	2.72	0.9557
4.7	0.02	3.72	0.9611
6.0	0.02	4.18	0.9387
The PBCR experiments were run with using different VFRs			
4.8	0.02	3.19	0.9088
5.8	0.02	3.29	0.9529
8.6	0.02	3.56	0.9556
11.1	0.02	3.95	0.9502

mass transfer from gas to liquid and then from liquid to biofilm, resistance of internal mass transfer in biofilm and during detachment of biofilm (Skoneczny and Cioch-Skoneczny, 2021). Shashidhar et al. (2007) proposed the bench scale transport and biotransformation experiments using the mathematical model simulations coupled with adsorption and Monod's inhibition kinetics for immobile bacteria to study the transports of Cr(VI) and molasses using the laboratory-scale column experiments. Pan et al. (2019) developed a model to describe the electron competition during three-step denitrification to understand the effects of H_2S among nitrogen oxide reduction and N_2O accumulation. In this study, by plotting the correlation between *E* and *t* accorded to Eq. (6) is able to model the removal of O&G from FPIW effluent processed in the PBCR system (see Fig. 5). Fig. 5a shows the logarithmic graphs of plotting *E* versus *t* obtained from the running of the PBCR experiments using the O&G concentrations of 16.4, 26.1 and 33.5 g L^{-1}. Fig. 5b shows the logarithmic graphs of plotting *E* versus *t* obtained from the running of the experiments using the VFRs of 0.18, 0.30, 0.42 and 0.54 L h^{-1}. All curves of plotting *E* versus *t* comply with the logarithmic function in Eq. (6) making the graphs showing a decreased *c* constant with increasing of the OLR value. Correlation for the parameters of *k*, $(S+S_o)/S_o$ and *c* obtained from the analysis of logarithmic regression is very good ($R^2 > 0.919$, except for the running of the PBCR experiment at a VFR of 0.30 L h^{-1} in which $R^2 = 0.8493$; see Table 5). It is believed that the use of logarithmic equation in Eq. (6) could be useful to predict the PBCR performance.

4. Discussion

The level of active O&G bioaccumulation on the OPF surface after reaching a steady state condition depends on the quantity of O&G in FPIW solution. The value of ln(q_o) increased from 3.19 to 3.29–3.56 and to 3.95 g with increasing of both OLR from 4.8 to 5.8–8.6 and to 11.1 g h^{-1} and VFR from 0.18 to 0.30–0.42 and to 0.54 L h^{-1} (see Table 3; see also Fig. 2) could be due to the velocity of FPIW solution movement determines the initial rate of O&G bioaccumulation before reaching a steady state condition. A constant *k* value of 0.02 h^{-1} as the reproductive health indicator of *Serratia marcescens* SA30 strain, which is expected to grow at a constant rate in the foreseeable future, provides a perspective for the further development of biological wastewater treatment related to a dynamic optimisation strategy. Number of bacteria associated with O&G contaminant depend on the nonspecific physicochemical and biospecific interactions (Pan et al., 2019). The biodegradation of waste motor oil by the *Nostoc hatei* TISTR 8405 strain could be dependent on the various experimental conditions (Luo et al., 2015). By considering the physicochemical interactions are similar to all experimental conditions since to the effluent of FPIW flowed through the PBCR tank with its HRT of 2.56 h was in the same direction. The fastest growth of *Serratia marcescens* SA30 strain required more carbon and energy to produce more biosurfactants can lead to an increased biomass with increasing of the O&G availability (see Fig. 3a,b; see also Table 4). The presence of biosurfactant as microbial bioactive compounds can enrich the PBCR treatment system leading to an increased bioavailability of O&G by demulsification (Pimda and Bunnag, 2015). Velocity and O&G concentration of FPIW effluent can simultaneously influence the rate of bacterial production

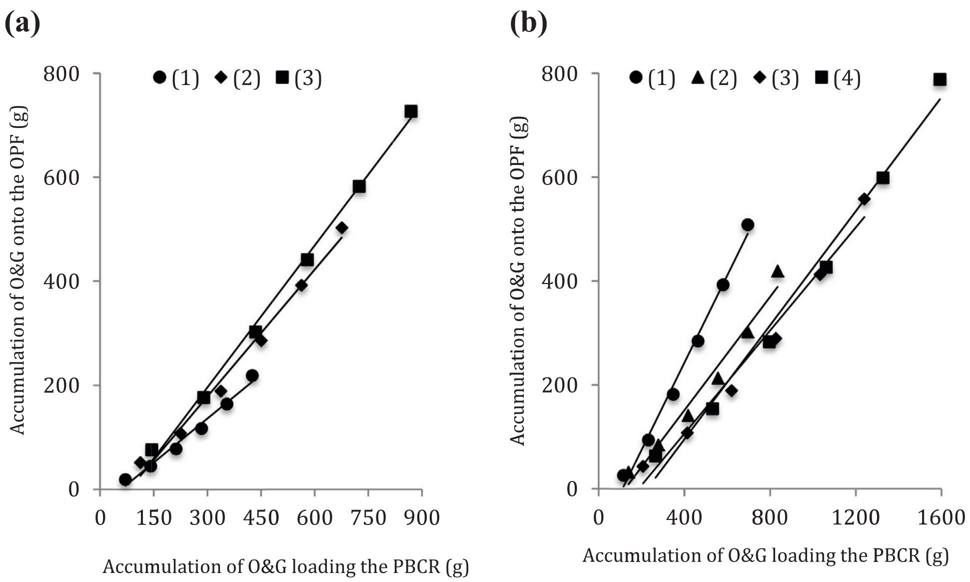

Fig. 3 – Linear graphs of plotting the accumulation of O&G onto OPF against the accumulation of O&G loaded the PBCR to represent the experimental data. Notes that: *(a)* the experiments run at a constant VFR of 0.18 L h^{-1} with different O&G concentrations of (1) 16.4 g L^{-1}, (2) 26.1 g L^{-1} and (3) 33.5 g L^{-1} and *(b)* the experiments run at different VFRs of (1) 0.18 L h^{-1} with O&G concentration of 26.9 g L^{-1}, (2) 0.30 L h^{-1} with O&G concentration of 19.3 g L^{-1}, (3) 0.42 L h^{-1} with O&G concentration of 20.4 g L^{-1} and (4) 0.54 L h^{-1} with O&G concentration of 20.5 g L^{-1}.

(Chafale and Kapley, 2022). The *b* values of 93.0, 67.1, 92.4 and 124.5 g obtained from the PBCR experiments using the OLRs of 4.8, 5.8, 8.6 and 11.1 g h^{-1} (see Table 4), respectively, could be due to the sources of carbon and energy required for the needs of bacterial growth and metabolism after reaching a steady state condition depend on both the availability of O&G in the FIPW solution and VFR. More diverse microbial communities are related to the availability of various and complex types of the substrates in the FIPW effluent (Prévoteau et al., 2015).

In spite of dynamic O&G accumulation can reveal the percentage of O&G removal increased with increasing of the PBCR operation time, the performance of nearly 100% efficiency was verified for the running of the PBCR experiments setup at a VFR of 0.18 L h^{-1} with the O&G concentrations of 26.9 and 33.5 g L^{-1} in the raw FPIW effluent (see Fig. 5a, b). The source of carbon originated from O&G and other organics contained in the FPIW effluent could simply be one of the most influential factors to enhance the performance of O&G removal accelerated by adding the adapted strain of *Serratia marcescens* SA30. The logarithmic model of Eq. (6) can be used to predict the performance of PBCR process achieved nearly 100% removal of O&G under the optimum operating conditions. The application of chitinolytic bacterium of *Serratia marcescens* has been proposed as model organism to increase the efficiency of freeze-dried alginate beads used as the immobilized biocontrol agent (Lemaire et al., 2008) and to increase the removal of phosphorus from palm oil mill effluent (Zohar-Perez et al., 2005). Conditioning the alternating aerobic anoxic process has been practiced to enhance the removal of inorganic nitrogen pollution from domestic wastewater (Fulazzaky et al., 2019). The performance of PBCR process cannot reach 100% efficiency when the setup of VFR was not appropriate (see Fig. 5b) even though the rate of biochemical reaction was relatively high as shown by the $(S+S_o)/S_o$ ratio of 1495 for the running of the PBCR experiment with setting the VFR of 0.30 L h^{-1} and OLR of 5.8 g h^{-1} (see Table 5). The $(S+S_o)/S_o$ ratio is proportional to the biochemical reaction rate and can be used to determine the behaviour of O&G accumulation metabolized by the *Serratia marcescens* SA30 strain (Fulazzaky et al., 2015b). The results (Fig. 5b; see Table 5) show that the performance of PBCR process can reach nearly 100% efficiency with the $(S+S_o)/S_o$ ratio of 2155 and can never attain 100% efficiency with the $(S+S_o)/S_o$ ratios of 1495, 1325 and 1335.

Table 5 showing the value of c decreased from 66.1 to 64.9 and to 36.7 is related to an increased concentration of O&G from 16.4 to 26.1 and to 33.5 g L^{-1} (see Fig. 5a) and that decreased from 111.1 to 77.7–68.1 and to 64.7 is related to an increased value of VFR from 0.18, to 0.30, to 0.42 and to 0.54 L h^{-1} (see Fig. 5b). It is suggested that accumulation of O&G onto the biomass attached on the surface of OPF mediated by *Serratia marcescens* SA30 strain (see Fig. 4b) after reaching a steady state condition depends on both the O&G concentration and VFR. The results of this modeling study can help provide a better understanding of the PBCR operating conditions designed to achieve the performance of nearly 100% efficiency. Biochemical accumulation rate with its $(S+S_o)/S_o$ ratio of 2155 determines the optimal operating condition of PBCR treated the FPIW effluent. This opens the new innovation opportunities and challenges for engineering the *Serratia marcescens* SA30 strain to remove the contaminant of O&G from industrial wastewater. The removal of O&G mediated by *Serratia marcescens* SA30 during the biological FPIW treatment by PBCR process can accelerate the bioaccumulation of biomass compared to the conventional methods of skimming tank (He and Yan, 2016) and O&G trapped in a treatment plant in the tropical environment (Giovanella et al., 2015). The production of biosurfactant requires the presence of miscible hydrophilic and oil to degrade different high molecular weight hydrocarbons of O&G in the form of smaller molecules (Wallace et al., 2017). An artificial neural network model has been proposed to predict the production of biosurfactant mediated by *Klebseilla sp.* FKOD36 bacteria (De Almeida et al., 2016). The role of biosurfactant produced by *Serratia marcescens* SA30 can aid oil

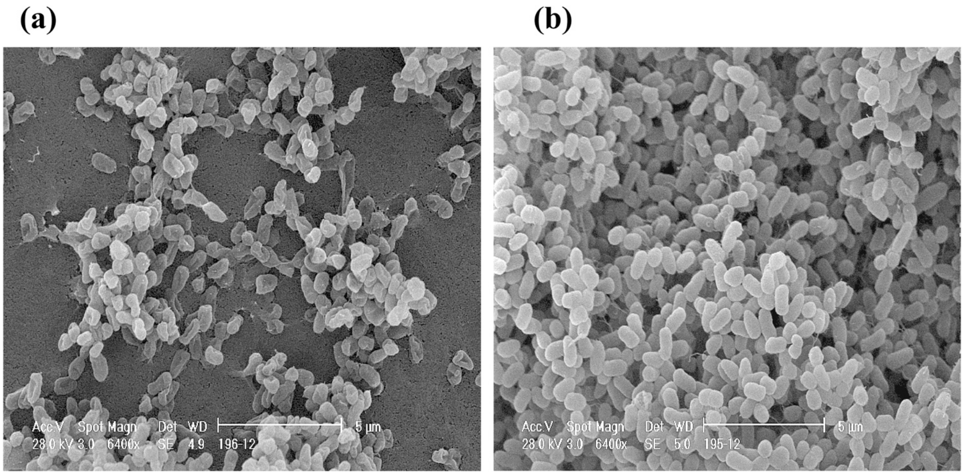

Fig. 4 – The SEM images of OPF surface, with *(a)* before fully immobilized by the adapted strain of *Serratia marcescens* SA30 and *(b)* after fully immobilized the adapted strain of *Serratia marcescens* SA30.

Table 4 – Values of *a* and *b* obtained from plotting the accumulation of O&G onto the OPF surface against the accumulation of O&G loaded the PBCR treatment system.

Loading rate (g h^{-1})	*a*	*b* (g)	R^2
The PBCR experiments were run with using different O&G concentrations			
3.0	0.563	33.1	0.9832
4.7	0.814	65.9	0.9883
6.0	0.909	77.0	0.9965
The PBCR experiments were run with using different VFRs			
4.8	0.840	93.0	0.9924
5.8	0.547	67.1	0.9755
8.6	0.496	92.4	0.9794
11.1	0.549	124.5	0.9860

Table 5 – Values of *k*, $(S+S_o)/S_o$ and *c* obtained from plotting *E* versus *t*.

Organic loading rate (g h^{-1})	*k* (h^{-1})	$(S+S_o)/S_o$	*c*	R^2
The PBCR experiments were run with using different O&G concentrations				
3.0	0.02	1375	66.1	0.9296
4.7	0.02	1630	64.9	0.9195
6.0	0.02	1410	36.7	0.9731
The PBCR experiments were run with using different VFRs				
4.8	0.02	2155	111.1	0.9886
5.8	0.02	1495	77.7	0.8493
8.6	0.02	1325	68.1	0.9219
11.1	0.02	1335	64.7	0.9649

emulsification leading to detach a coverture of oily biofilm from the OPF surface (see Fig. 4a) and has a great potential for the treatment of high O&G concentration even in the presence of toxic organics and/or metals in an industrial wastewater (Ahmad et al., 2016). The hydrophobic property of OPF surface inhibited a biofilm formation can be eliminated in the presence of *Serratia marcescens* SA30 as a mediator to increase the rate of O&G bioaccumulation (Zhang,

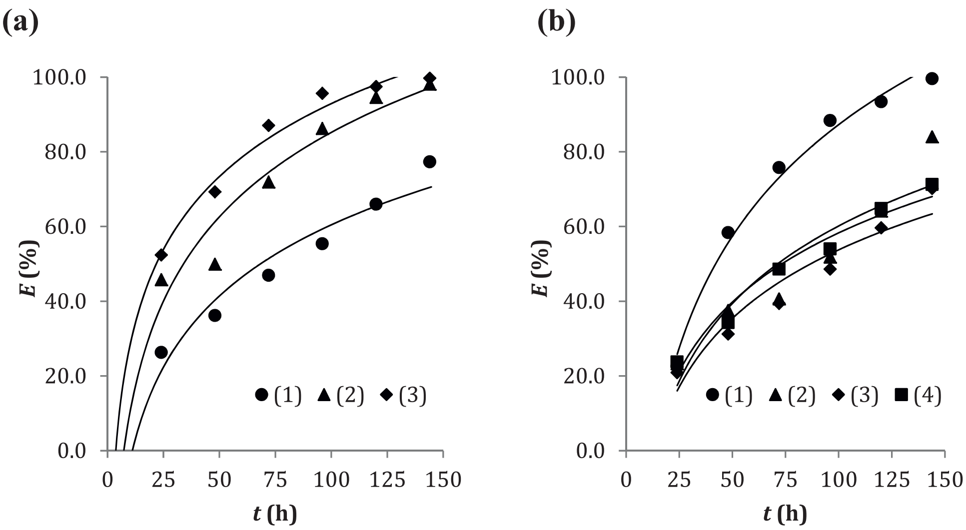

Fig. 5 – Logarithmic graphs of plotting E versus t to show the trend of experimental data. Notes that: *(a)* the PBCR experiments were run at a constant VFR of 0.18 L h^{-1} with different O&G concentrations of (1) 16.4 g L^{-1}, (2) 26.1 g L^{-1} and (3) 33.5 g L^{-1} and *(b)* the PBCR experiments were run at different VFRs of (1) 0.18 L h^{-1} with O&G concentration of 26.9 g L^{-1}, (2) 0.30 L h^{-1} with O&G concentration of 19.3 g L^{-1}, (3) 0.42 L h^{-1} with O&G concentration of 20.4 g L^{-1} and (4) 0.54 L h^{-1} with O&G concentration of 20.5 g L^{-1}.

2017). The best performance of PBCR process predicted using the linear and logarithmic models depends on the operating conditions during the treatment O&G contained in FPIW effluent.

5. Conclusions

An effort made of developing the mathematical equations provides an insight on the various aspects of conducting a modelling study to obtain an optimal operating condition of the PBCR treatment process. Application of the linear and logarithmic equations has been validated from the experiments using the concentration of O&G in a range of 16.4–33.5 $g\,L^{-1}$ and the VFR value in a range of 0.18–0.54 $L\,h^{-1}$ to predict the performance of PBCR process. The best performance of PBCR process can achieve nearly 100% efficiency for the running of the PBCR experiments with setting the VFR of 0.18 $L\,h^{-1}$ for the treatment of FPIW effluent with the O&G concentrations of 26.9 and 33.5 $g\,L^{-1}$. The biodegradation of O&G compounds mediated by the *Serratia marcescens* SA30 strain can enhance accumulation of biomass on the OPF surface providing a contribution to advanced biotechnology methods of solving environmental problems in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors gratefully acknowledge financial support from the Universiti Teknologi Malaysia, Malaysia, for Research University Grant No. Q.J130000.2509.07H01.

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