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Optimisation of static magnetic field (SMF) on physical properties of biomass using central composite design experiment

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Abstract. One of the principle issues for the biomass is the poor settleability that therefore influences the effluent quality. Batch tests were led to appraise the optimal conditions for improving the settleability of the biomass under static magnetic field (SMF). A four-factor central composite design (CCD) was executed to investigate the main and interaction effects of the factors while response surface methodology (RSM) was used for process optimization. Four independent factors, viz. SMF (15.0 – 88.0 mT), exposure time (0.5 – 48.0 h), biomass concentration (2000 – 4000 mg/L) and agitation speed (200 – 400 rpm) were applied and quadratic model was worked to anticipate the reactions. Analysis of variance (ANOVA) was utilized to assess the significance of the autonomous factors. At the optimum conditions of 88.0 mT SMF, 16.5 h exposure time, 2800 mg/L biomass concentration and 300 rpm agitation speed, the turbidity removal, aggregation and settling velocity achieved its highest predictions of 92%, 99% and 0.011 cm/s, respectively. The analysis demonstrated that the applied SMF could enhance the settling property of the biomass through the enhancement of its aggregation ability. These suggesting that the SMF is dependable in accelerating the biomass settleability, subsequently potential to improve the performance efficiency in treating wastewater.

1. Introduction

Performance of activated sludge system relies on a good solid-liquid separation. Even though the system has been commonly used in treating municipal and industrial wastewaters, its stable operation is still plagued by the separation and settling problems. Such problem can lead to the deterioration of the effluent quality, sludge washout, and further potential to collapse the overall treatment system performances (Martins et al., 2011). Hence, it is a necessity to investigate for a favourable strategy that able to enhance the property of biomass mainly on its separation and settling process.

Static magnetic field (SMF) has been reported in significantly influenced the bacterial activity in heterogeneous sewage, resulted in the enhanced performances of organic compound biodegradations (Ji et al., 2010; Łebkowska et al., 2011; Zaidi et al., 2016). According to Łebkowska et al. (2011), the implementation of 7 mT reduced the formaldehyde (FA) concentration and COD by 30% and 26%, respectively. Liu et al. (2008) applied SMF in an anammox upflow system, thus resulted in significant nutrient removal. The study which varied the SMF between 16.8 and 218.0 mT observed a maximum increase of nitrogen removal by 30% at 60 mT. Apparently, an excessively strong magnetic field could harmed the bacteria while the low field intensity has no or less effect to the bacteria. Such evidences show that there is lack of confirmation findings on the suitable range of SMF that can possibly enhance the separation and settleability of the biomass, hence improving the removal performances of the treatment system.

Despite many studies conducted on the SMF application towards biomass, there are still lack of understandings on the influence of magnetic field, exposure time, biomass concentration and agitation speed in enhancing the separation and settling property of biomass. While the important of these factors has been qualitatively studied, most studies have not yet explored the potential interactions between the factors. The traditional method, known as the one-factor-at-a-time (OFAT) does not fully explore all phenomena that could possibly occur and may cause misinterpretation of the results (Kusic et al., 2010; Dopar et al., 2011). Therefore, the aim of this study is to investigate the influence of magnetic field, exposure time, biomass concentration and agitation speed on the separation and settling property of biomass in terms of turbidity removal, aggregation and settling velocity. The central composite design (CCD) approach was employed to quantitatively analyse the effects of those factors, the interactions between them and to indicate any correlation between the factors and the responses.

2. Materials and methods

2.1 Experimental procedures

A total volume of 500 mL containing measured wet volume biomass (2000 – 4000 mg/L) and raw wastewater was mixed in a glass flask that placed in a shaker. The shaker was fabricated to allow an installation of the permanent magnets of sizes 100 x 50 x 5 mm, arranged at all four surfaces of the flask in alternate order. The mixture of the biomass was exposed to the magnetic field ranging from 15.0 to 88.0 mT within exposure time of 0.50 to 48.00 h. The initial values of the responses (i.e. turbidity removal, aggregation and settling velocity) were initially measured before the batch tests started. Throughout the experiments, the mixture was mixed under a specified agitation speed (200 to 400 rpm). After the magnetic exposure, the mixture was allowed to idle for 10 min before 10 mL of the liquid samples were collected and analyzed for final turbidity. The exposed sludge of 10 mL was also taken to be measured for the final settling velocity.

2.2 Analytical methods

All tests were conducted based on Standard Methods for the Examination of Water and Wastewater (APHA, 2005) – MLSS with method 2540B and settling velocity with method 2710E. Turbidity parameter (NTU) was measured using Milwaukee Turbiditimeter. As for aggregation, the parameter was measured in terms of turbidity following the method by Zaidi et al. (2016).

2.3 Experimental design

The magnetic field, exposure time, biomass concentration and agitation speed were identified as the set of four independent process variables that been investigated based on the influence towards turbidity removal, aggregation and settling velocity of the biomass. The CCD method was adopted to decide the number of batch test experiments to be performed for optimization of the process variables. For a design of four independent variables (n = 4), each with two different levels, the total number of experiments (N) was calculated as; N = (2n + 2n + nc) = 24 + (2 x 4) + 6 = 30. This includes the standard 2n factorial points with their origin at the centre, 2n axial points fixed at a distance (α) from the centre to generate the quadratic terms and nc replicate points at the centre (Myers and Montgomery, 2001). After the range of each of the process variables have been defined, the limits are coded at ± 1 for factorial points, 0 for centre point and ± α for axial points. In this study, α for axial points was set to 1.0 (also known as face-centred) due to the consideration that region of interest is approximately same as region of operability (Kraber, 2002). Thus, the limit for axial points was eventually same as the factorial points. The selected process variables with their limits are given in Table 1.

Table 1: Process control variables and their limits.

Variables	**Factorial**		**Star points***		**Centre point**
	-1	**+1**	**-1**	**+1**	**0**
A: Magnetic field (mT)	15.0	88.0	15.0	88.0	51.5
B: Exposure time (hours)	0.50	48.00	0.50	48.00	24.25
C: Biomass concentration (mg/L)	2000	4000	2000	4000	3000
D: Agitation speed (rpm)	200	400	200	400	300

[a] Limit for star points is the same as factorial due to the consideration of α = 1.0 (face-centered)

3. Results and discussions

3.1 Response surface analysis or turbidity removal, aggregation and settling velocity

The results were statistically analysed using full quadratic terms, which include linear, square and interactional terms with the aid of Design-Expert® (version 6.0.4). The results of the analysis of variance (ANOVA) for the responses are summarised in Table 2.

Table 2: p-values of the response surface modeling analysis.

Term	**p-values**		
	Turbidity removal	**Aggregation**	**Settling velocity**
A: Magnetic field	0.0023	< 0.0001	0.0368
B: Exposure time	< 0.0001	< 0.0001	0.8716
C: Biomass concentration	0.0027	< 0.0001	0.6287
D: Agitation speed	0.0097	0.7578	0.2654
A^2	0.4374	0.9901	0.2488
B^2	0.0446	0.0003	0.0676
C^2	0.4656	0.9422	-[a]
D^2	0.4319	0.7828	0.0309
A x B	0.0421	0.0007	-[a]
A x C	0.6691	0.0063	-[a]
A x D	0.0521	0.3195	-[a]
B x C	0.0361	0.0016	0.4606
B x D	0.1690	0.7408	0.4606
C x D	0.6244	0.2380	-[a]
R-squared value	92.6%	94.4%	61.8%

[a] Eliminated value resulted from the improved model

With respect to the turbidity removal, the results show that all the linear terms, square term in exposure time, interactional term between magnetic field and exposure time, as well as between exposure time and biomass concentration are significant. The analysed R-squared value of 92.6% indicates the acceptability of the model. The best statistical model that describes the relationship between turbidity removal and the variables (magnetic field, exposure time, biomass concentration and agitation speed) is given in equation (1).

$$\text{Turbidity removal} = +96.40 + 7.09*A + 18.14*B + 6.92*C - 5.73*D - 4.06*A^2 - 11.16*B^2 - 3.81*C^2 - 4.11*D^2 - 4.56*A*B - 0.89*A*C + 4.32*A*D - 4.72*B*C + 2.96*B*D\ 1.02*C*D \qquad (1)$$

Figure 1 shows the contour and surface plot of the defined model (exposure time and biomass concentration) for the turbidity removal. This interaction has the most significant p-values (0.0361) compared to the other interaction model terms. The figure clearly shows that as the exposure time increased, turbidity removal is also increased. Such observation can be explained in terms of magnetic memory retained by the biomass particles throughout the reaction period. As the exposure time of the particles towards magnetic field increased, their positive and negative charges may become highly in charged. This could increase the possibility of the collision between particles thus, potential to enhance the coagulation and further reducing the turbidity (Johan, 2003; Omar et al., 2018). The increment in turbidity removal is also governed by the effect of biomass concentration. Similar as the exposure time, the plot also shows that as the biomass concentration increased, turbidity removal is also increased. This can be reasoned due to the existance of microorganisms that been supplied with respect to the biomass. Lots of microorganisms during the reaction period could improved the turbidity removalas more 'workers' are available to degrade the particles' contaminants. Positive effects gave by both parameters (exposure time and biomass concentration) allow the interaction to result in significant enhancement on the turbidity removal.

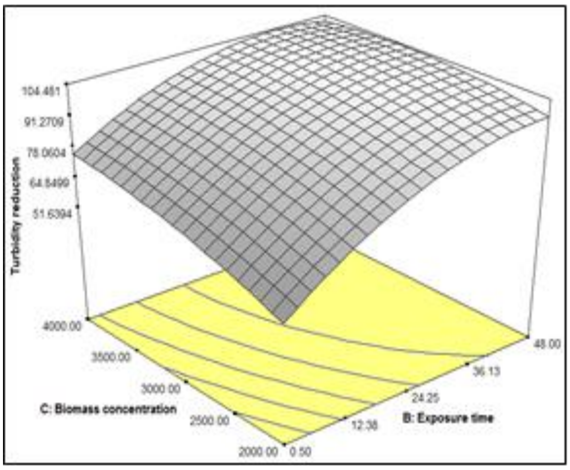

Figure 1. Response surface plot on the relationship between the exposure time, biomass concentration and turbidity removal.

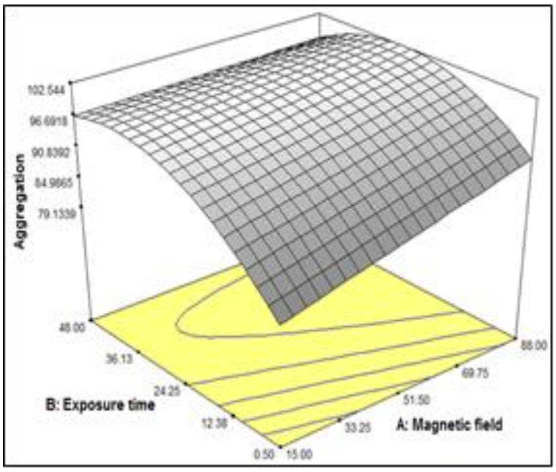

Figure 2. Response surface plot on the relationship between the magnetic field, exposure time and aggregation.

Statistical model as shown in equation (2) was also developed to relate the magnetic field, exposure time, biomass concentration and agitation speed to aggregation.

$$\text{Aggregation} = +98.87 + 3.39*A + 5.89*B + 3.36*C - 0.20*D - 0.021*A^2 - 7.62*B^2 - 0.12*C^2 + 0.46*D^2 - 2.82*A*B - 2.09*A*C - 0.68*A*D - 2.53*B*C - 0.22*B*D - 0.81*C*D \quad (2)$$

As shown in Table 2, linear term of magnetic field, exposure time and biomass concentration, square term in exposure time, interactional terms between magnetic field and exposure time, magnetic field and biomass concentration, as well as exposure time and biomass concentration are significant in influencing the aggregation of biomass. Figure 2 illustrate the relationship of the most significant model term (magnetic field and exposure time) on aggregation with p-value of 0.0007. Based on the figure, at low magnetic field of 15.0 mT, an increase in exposure time resulted in drastic increment of aggregation from about 83.0% to 98.6%. However, the increment is in concave shape indicates that further increase in exposure time would lead to the decrease in aggregation. This could be due to the ability of microorganisms in sustaining high magnetic effect as a result of longer exposure time. Some of the microorganisms can only sustain low level of magnetic effect. If this level is exceeded, the microorganisms may act adversely, thus show reverse effect to the biomass property (Zaidi et al., 2014; 2019). Contrary, an increase in magnetic field illustrated increment on aggregation (at low exposure time of 0.50 h) in more saddle shape. This type of surface plot suggested that the increment was in more progressive manner, thus showing that the aggregation enhancement of biomass is more stable under such condition (Chin et al., 2006).

For the response of settling velocity, p-values of the model terms that been listed in **Table 2** are the terms that obtained after the statistical model been improved. The purpose of the improvement is because the initial model was insignificant. As a result, the p-value of the model was improved from 0.1208 (not significant) to 0.0082 (significant). The R-squared value of this model is still slightly lower (61.8%) compared to the R-squared value for turbidity removal (92.6%) and aggregation (94.4%). The only significant model terms are linear term of magnetic field and square term of agitation speed. Whereas, the interactional terms viz. exposure time and biomass concentration as well as exposure time and agitation speed are both insignificant with obtained p-values of 0.4606. Nonetheless, the best statistical model that can be used to represent the settling velocity within the range of the experimental conditions in this study is shown in equation (3) below.

$$\text{Settling velocity} = +0.011 + (1.139 \text{ x } 10^{-4})*A + (8.333 \text{ x } 10^{-6})*B + (2.5 \text{ x } 10^{-5})*C - (5.833 \text{ x } 10^{-5})*D + (1.523 \text{ x } 10^{-4})*A^2 - (2.477 \text{ x } 10^{-4})*B^2 - (2.977 \text{ x } 10^{-4})*D^2 + (4.063 \text{ x } 10^{-5})*B*C - (4.062 \text{ x } 10^{-5})*B*D \tag{3}$$

3.2 Experimental condition optimization

Considering whether the turbidity removal, aggregation and settling velocity were higher than the arbitrarily chosen constraint values identified the optimization of experimental conditions. Based on the model, the predicted optimized conditions occurred at magnetic field of 88.0 mT, 16.5 h exposure time, 2800 mg/L of biomass concentration and at agitation speed of 300 rpm. These conditions resulted in 92.1% of turbidity removal, almost 100% (≈ 99.9%) of aggregation and 0.011 cm/s of biomass settling velocity. In order to verify the optimization result obtained from Design-Expert, batch test experiments were carried out in triplicate using the obtained optimum conditions. Average turbidity removal of 89.1%, aggregation of 97.8% and settling velocity of 0.011 cm/s were recorded against the predicted optimum responses. Although there are differences between the predicted and experimental values of the responses after optimization, the deviation was still in well agreement.

4. Conclusion

This study investigated the advantage of static magnetic field (SMF) and their optimized experimental conditions for improving the physical properties of biomass. Under the optimal condition of 88.0 mT magnetic field, 16.5 h exposure time, 2800 mg/L biomass concentration and 300 rpm agitation speed, the maximum turbidity removal, aggregation and settling velocity of 92.1%, 99.9% and 0.011 cm/s, respectively, were obtained. Overall, the element analysis evidenced that the applied SMF could enhance the settling property of the biomass through the improvement on its aggregation capability. These suggest that the SMF is reliable in accelerating the biomass settleability, thus potential to enhance the removal performance efficiency of the wastewater treatment systems.

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