



Application of Taguchi Experimental Design Method for Optimization the COD Removal Process in Upflow Anaerobic Filter

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Authors' contributions

This work was carried out in collaboration between both authors. Author AMOK designed, analyzed and interpreted and prepared the manuscript. Author LX revised the manuscript contents. Both authors read and approved the final manuscript.

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ABSTRACT

In this study, two stages of upflow anaerobic filters (UAF) were used to investigate their performance based on the chemical oxygen demand (COD) removal from the rural domestic wastewater. Several factors were considered during the design and operation of an anaerobic process for successful treatment of the wastewater. Furthermore, Taguchi method was applied to investigate and evaluate the effect of selected factors on the performance efficiency of the UAF reactor. The experimental factors were optimized by L_9 (3^4) orthogonal array design, which includes four factors with three levels using statistical analysis. The four factors involve the water acidity (pH), temperature (T), hydraulic retention time (HRT) and organic loading rate (OLR). The results revealed that all factors had a significant influence on the COD removal efficiency. The results demonstrated that the optimum conditions for achieving maximum COD removal efficiency were: initial pH of 7, temperature of 25°C, HRT of 1.5 day and OLR of 0.166 Kg. COD/m³.day. Moreover, the results showed that the HRT had highest percentage contribution in the COD

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removal process with 39.92%, followed by temperature of 33.78%, OLR of 13.75% and the pH of 9.18%. Confirmatory experiments conducted at the optimized conditions and compared with the predicted result show a good agreement.

Keywords: Upflow anaerobic filter (UAF); chemical oxygen demand (COD); taguchi orthogonal array; hydraulic retention time (HRT); analysis of variance (ANOVA).

1. INTRODUCTION

Biological treatment is used extensively for the removal of organic contaminants from domestic and industrial wastewaters. The chemical oxygen demand (COD) is the measure of organic contaminants in wastewater, which related to designing and evaluation of biological treatment processes. Anaerobic reactor is one of the most important biological treatment processes used to convert organic material into a biogas, a source of energy with minimal quantity of sludge [1]. High-rate anaerobic reactors such as an upflow anaerobic filter (UAF) is often applied as pretreatment of domestic wastewater to remove the organic and inorganic matter by the microorganisms in the absence of molecular oxygen. The UAF reactors have been widely used in developing countries for domestic and industrial wastewater treatment [2,3]. Further, there are several advantages such as the small space requirement, no need for aeration, low operation and maintenance costs, reduced of sludge bulking, production of biogas [4,5]. In general, some of the performance parameters have a significant effect on anaerobic decomposition of domestic wastewater such as temperature, pH, hydraulic retention time (HRT), organic loading rate (OLR), suspended solids, and reactor design [6].

In this study, the orthogonal array design $L_9 (3^4)$ was used, and the COD removal efficiency considered as the response function of those experiments. The Taguchi approach was applied in this study to optimize the COD removal efficiency and to evaluate the factors have a significant effect on reactor performance. Taguchi method is a robust statistical experimental technique and has an ability to find the significant and the optimum factors that affecting the process efficiency. The Taguchi method uses orthogonal arrays to study various factors with a reduced number of experiments [7]. In addition, this method offered other advantages includes process variability reduction, a simple and systematic method to optimize the design of performance and

efficiency, and thus the operating cost reduction [8-10]. Numerous researchers used the Taguchi experimental design method for optimization the process of organic matter and other contaminants removal from wastewater [11-14]. In the Taguchi method, S/N ratio is used to determine the deviation of the response functions from the required values [15]. The Taguchi statistical method uses other optimization techniques such as the analysis of variance (ANOVA), which was used for testing the significance and validity of the model [16].

The main objective of this study is to evaluate the influence of some important operating factors in COD removal process using UAF reactor. For this purpose, the Taguchi method was applied to determine the optimum combination factors to achieving maximum COD removal.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Two pilot scale of the upflow anaerobic filters (UAFs) with a total working volume is 23.56 liters (1.5 m height, 0.1 m diameter for each one) were applied. The performance efficiency of UAF reactors for COD removal from domestic wastewater was evaluated at different operating conditions according to Taguchi method. The UAF was filled with non-woven fabric media to improve the microorganism growth on the biofilm. These reactors were fed by activated sludge taken from the domestic sewage treatment plant in Wuxi city- China, and then UAF reactors operated with 2 days of HRT until the reactor reached the steady state after 28 days with the stability of the COD removal ratio. The synthetic wastewater was prepared daily in the laboratory 100 liter plastic tank using glucose as the main organic source, ammonium carbonate as nitrogen source and potassium phosphate as the phosphorus source. The influent COD concentrations varied between 125 to 500 mg/l during the entire operational experiments. The reactors were equipped with wastewater by using the peristaltic pump to control the flow rate and

adjusted HRT for the reactors. The influent pH was adjusted, before feeding wastewater using NaOH or H₂SO₄. In addition, the room temperature was adjusted and controlled by the automatic thermostat system lamps. The schematic diagram of the system used in this study is shown in Fig. 1.

2.2 Taguchi Orthogonal Array (TOA)

Taguchi orthogonal array L₉ (3⁴) applied to define the optimum conditions regarding the selected factors to achieve high COD removal efficiency by using UAF anaerobic reactor. The experiments design involved four factors with three-levels for each factor as follows pH, HRT, temperature, OLR. Based on Taguchi orthogonal array, nine experiments were conducted with the different combinations of the levels as shown in Table 1. Each level group of the experiments was performed in triplicate.

2.3 Analytical Methods

The UAF reactor performance efficiency of organic matter removal was evaluated. Influent and effluent COD concentrations were measured according to standard methods [17]. The COD removal in UAF reactor indicates to a difference between the influent and effluent of COD concentrations; hence the COD removal efficiency ratio was calculated and expressed by using equation (1).

$$\text{COD}_{\text{removal}} \% = \frac{\text{COD}_{\text{inlet}} - \text{COD}_{\text{out}}}{\text{COD}_{\text{inlet}}} \times 100 \quad (1)$$

Where the COD_{inlet} and COD_{out} are influent and effluent COD concentrations (mg/l).

Taguchi orthogonal array standard L₉ contains four-factor columns and nine level rows, as shown in Table 2. In addition, the factors and their levels selected were presented in Table 1.

Taguchi method analyzed the results by using signal to noise ratio (S/N) and analysis of variance (ANOVA). The main target of these experiments is to maximize the COD removal efficiency to improve the quality of treated wastewater through the UAF process. Therefore, the definition of S/N as "larger is better" of quality characteristic is selected, and can be expressed according to the equation (2) [18].

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (2)$$

Where n is the number of measurements in a trial/row, and y_i is the measured value in a trial/row.

Design-Expert® software was used for the generation and evaluation of our experiments design model. All experiments results were analyzed using this software to perform statically model and analysis of variance (ANOVA). The data were expressed as mean and level of significance was taken at p-value of 0.01. Furthermore, the confirmation tests were conducted to compare the experimental results with predicted results.

3. RESULTS AND DISCUSSION

The removal efficiency of COD using upflow anaerobic filter (UAF) was optimized and evaluated. Taguchi L₉ (3⁴) was applied for experimental design to optimize the factors affecting the COD removal efficiency. The experimental design consisted of nine experiments conducted with different combination factors, and each experiment was implemented in triplicate. The S/N ratio was determined, and ANOVA analysis was performed to analysis the experimental results. The S/N ratio serves as the objective functions for optimization, and presented further help in data analysis and the prediction of the optimum results. Furthermore, ANOVA is utilized to identify the optimum combination of process factors more accurately by investigating the relative importance of process parameters. The averages S/N ratio for each level groups of the parameters factors were illustrated in Table 2. The level of a factor with highest average S/N ratio corresponds to a better performance and gives the best combination level. The averages S/N ratios in Table 2. refers to the levels that were chosen for the optimum experimental design based on the highest COD removal efficiency for the corresponding factor. Therefore, the optimum combination levels of these factors based on response function are A₂B₃C₃D₁, as shown in Fig. 2. It is evident that according to S/N ratio analysis, the HRT and temperature parameters have significant influence on COD treatment when adjusted on its highest levels.

Table 1. Controlled variables and levels

Control variables (factors)	Unit	Level 1	Level 2	Level 3
pH	-	6.5	7	7.5
Temperature	°C	15	20	25
Hydraulic retention time (HRT)	Days	0.75	1	1.5
Organic loading Rate (OLR)	Kg. COD/m ³ .day	0.166	0.25	0.333

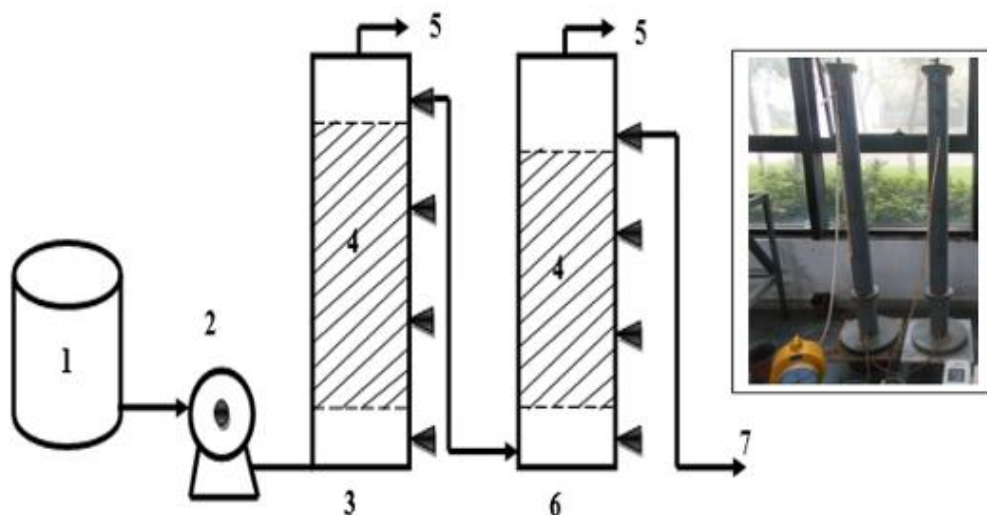


Fig. 1. Schematic diagram of the two phases of up flow anaerobic filter; 1. influent tank; 2. peristaltic pump; 3. first anaerobic filter; 4. non-woven fabric media; 5. biogas; 6. second anaerobic filter; 7. effluent wastewater

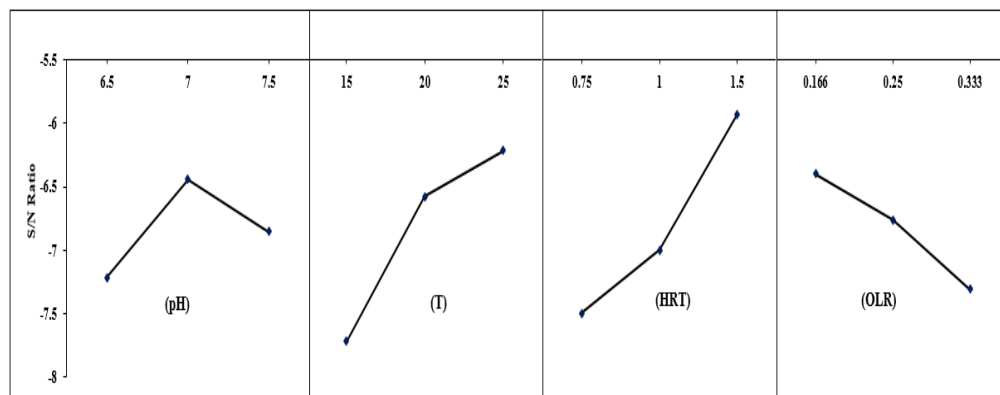


Fig. 2. The effect of experimental parameters on S/N ratio

3.1 General Linear Model

In order to specify the most effective parameters and their confidence levels based on COD removal efficiency, the orthogonal array design model was carried out according to Taguchi method. The analysis of multi factor variance (ANOVA) was conducted, which were

illustrated in Table 3. Furthermore, all the factors in this model were statically significant different at ($P < 0.01$). Based on ANOVA analysis, the HRT and temperature factors had a highly significant effect, according to their mean sum of a square. The last column in Table 3 presented the percentage of contribution (PC %) of all factors on the process performance. The PC % of each

factor was calculated according to the following equation:

$$PC\% = \frac{SS'}{SS_{Total}} \times 100 \quad (3)$$

Where SS' is referred to the pure sum of the square and is calculated by $(SS - SS_{error})$; SS is the individual sum of squares; SS_{error} is the sum of square error; and SS_{Total} is the total sum of squares of all factors.

3.1.1 Effect of the pH on the COD removal process

The pH of an anaerobic system has a significant effect on the microbial conversions. It is typically maintained between methanogen limits (around neutral pH conditions) to prevent the predominance of the acid-forming bacteria, which may cause volatile fatty acids accumulation [19]. According to the results, the pH factors showed lower influence on the on the response function (COD removal %) with the percentage contribution of 9.18%. The reduction of the pH contribution in process performance was attributed to the values range of this factor used, which are suitable for the methanogenic bacteria growth to accomplish organic matter removal and production biogas. Many references reported that the best pH range of appears to be around neutrality, while the range between (6.5 ~7.6) is generally believed to be optimal. Fia et al. [20] studied the anaerobic filter to evaluate the influence of flow direction on the treatment performance and stated that the pH values in the influent mentioned in range of 6.8 ~ 7.5. Moreover, Rajakumar et al. applied the up flow anaerobic filter for the slaughterhouse wastewater treatment and reported that during operated system, pH values ranged between 7 ~ 7.6 in the influent wastewater [21]. Therefore, the effect of pH on process performance was limited. Fig. 2 illustrated the influence of the pH factor on the process. It is evident from this figure the optimum pH value is 7 (level 2) that to obtain the maximum COD removal efficiency. Furthermore, the pH factor was in the last order of the whole factors affecting the process performance according to the delta value of 0.769.

3.1.2 Effect of the temperature on the COD removal process

Temperature is one of the most important factors affecting microbial activity within an anaerobic digester, and microorganism able to adaptation and growth within different temperature [22]. The UAF reactors were operated in the psychrophilic conditions in the temperature range between 15 to 25°C. The result demonstrated that the COD removal efficiency, increased with an increase in temperature, and the factor at third level had been achieved high contribution 33.78% on the process performance. Halalsheh et al. studied the upflow anaerobic sludge blanket reactor during more than two years at different conditions to evaluate the high-strength wastewater treatment at ambient temperatures, where the average temperatures were 18, 25°C during winter and summer season, respectively [23]. Further, their results showed that the average COD removal efficiency is 62% during the summer, while it reduced to 51% during winter season [23]. Bodik et al. concluded that the average COD removal efficiencies were ranged between 46–92% for the temperature between 9 to 23°C when the UAF reactor operated for municipal wastewater treatment [24]. Furthermore, results revealed that the temperature in the second order of the entire factors affecting the process performance according to the delta value of 1.497.

3.1.3 Effect of HRT on the COD removal process

The HRT is defined as a measure of the average length of time that a soluble compound remains in a reactor. HRT is one of the most important factors for UAF reactor, which has a significant effect on the process performance. The results demonstrated that the HRT has a significant effect on the COD removal process with the maximum PC% of 39.92%. In addition, the optimum level of this factor is 1.5 day (third level). Hesnawi et al. [25] stated that the HRT has a significant effect of the efficiency and extent on the COD removal and methane production. The influence of HRT factor on response function according to the average S/N ratio was shown in Fig. 1. In addition, the results revealed that the HRT is the most effective factors on the process efficiency, according to the delta value of 1.601, as shown in Table 2.

Table 2. Taguchi L₉ (3⁴) orthogonal array with response and averages S/N ratio

Experiment run	PH (A)	T (B)	HRT (C)	OLR (D)	Average COD removal %	S/N ratio
1	1	1	1	1	38.164	-8.367
2	1	2	2	2	44.211	-7.089
3	1	3	3	3	49.075	-6.183
4	2	1	2	3	39.775	-8.008
5	2	2	3	1	57.167	-4.859
6	2	3	1	2	47.503	-6.466
7	3	1	3	2	45.873	-6.769
8	3	2	1	3	40.829	-7.781
9	3	3	2	1	50.104	-6.003
SN 1	-7.213	-7.715	-7.538	-6.409		
SN 2	-6.444	-6.576	-7.033	-6.775		
SN 3	-6.851	-6.217	-5.937	-7.324		
Delta	0.769	1.497	1.601	0.914		

$$\Delta = |SN_{max} - SN_{min}|$$

Table 3. ANOVA analysis and the factors percentage contribution on process

Factor	Sum of square (SS)	Degree of freedom (DF)	Mean sum of square (MS)	F-value	Pure sum of square(SS')	P	PC%
Model	0.085	8	0.011	237.6		0.00	Significant*
A	0.009	2	0.0045	95.4	0.008	0.00	9.18
B	0.029	2	0.015	328.9	0.029	0.00	33.78
C	0.035	2	0.017	387.5	0.034	0.00	39.92
D	0.012	2	0.006	138.8	0.012	0.00	13.75
Error	7.14×10 ⁻⁴	16	4.46×10 ⁻⁵		0.0029		3.37
Total	0.085	26			0.085		100.00
Pure Total	0.082						

*means that this model and all factors were statically significant and the model showed R-squared of 0.9917 and the Adj R-squared is 0.9875

3.1.4 Effect of OLR on the COD removal process

The OLR is considered as one of the important operating factors and denotes the biological conversion capacity of an anaerobic treatment reactor. Chen et al. [26] studied the effect of OLRs on the performance of UAF, and concluded that at higher OLRs and shorter HRTs the process became unstable. In general, when the organic loading rate is high, the acid accumulation occurs and pH value decreases in the reactor. This situation as well affects the activity of the bacteria in a negative way, which that effecting on the COD removal efficiency [27]. In the anaerobic filters, the bacteria used in the systems are sensitive against organic loading rate. The result demonstrated that the COD removal efficiency, increased with decrease in

OLR, and it has 13.37% of percentage contribution on the process performance. Fig. 1 showed the effect of the OLR on COD removal according to S/N ratio. The results showed that the best level of OLR to get maximum COD removal efficiency is 0.166 kg.COD/m³.day (first level). Table 2 revealed that the temperature in the third order of the factors affecting the process performance, which according to the Delta value of 0.914.

According to experimental results, it is observed that the optimum settings of pH, temperature, HRT and OLR are 7, 25°C, 1.5 day and 0.166 kg COD/m³.day, respectively. Therefore, we can conclude that the combination setting A₂B₃C₃D₁ can give the highest S/N ratio and consequently, the maximum COD removal efficiency.

3.2 Prediction of the Optimum Results

In order to investigating of the optimum combination, use a predictive equation to predict a response value given the contributions of each factor at its level in the optimum combination. Moreover, Design-Expert software also can be used to predict the response value at optimum conditions. The predicted value of COD removal efficiency at the optimum factors ($y_{\text{predicted}}$) can be calculated by the following equation by adding the average performance to the contribution of each factor at the optimum level using the following equations,

$$y_{\text{predicted}} = \bar{y}_{\text{exp}} + (\bar{y}_A - \bar{y}_{\text{exp}}) + (\bar{y}_B - \bar{y}_{\text{exp}}) + (\bar{y}_C - \bar{y}_{\text{exp}}) + (\bar{y}_D - \bar{y}_{\text{exp}}) \quad (4)$$

Where $\bar{y}_{\text{predicted}}$ is the predicted response value (COD removal efficiency); \bar{y}_{exp} is the overall mean response of all the experimental runs; $\bar{y}_A, \bar{y}_B, \bar{y}_C, \bar{y}_D$ are the response effects for factors A, B, C and D at the optimum levels.

The optimum combination factors and their levels were identified as the $A_2B_3C_3D_1$ according to S/N ratio and ANOVA analysis. Since, these optimum combination conditions were not previously tested for the process performance, so a confirmatory experiment was required. The confirmatory experiment was conducted in triplicate with optimized factors level and the predicted value from the optimization model were set as a control. According to Taguchi method and prediction equation above the COD removal efficiency at the optimum conditions was 58.65%. In contrast, when the UAF reactor was operated at the optimum combination factors, the average COD removal efficiency was 59.8%. The experimental result of COD removal compared with the predicted result showed a good agreement.

4. CONCLUSION

This study presented the results of several factors influenced on the performance of UAF reactor based on COD removal efficiency. The Taguchi orthogonal array design was applied to optimize the optimum conditions of UAF reactor performance for COD removal from domestic wastewater. Based on the S/N ratio and ANOVA analyses, it was found that the optimum combination for achieving a maximum COD removal was $A_2B_3C_3D_1$, which corresponding the pH 7, temperature 25°C, HRT 1.5 day and OLR 0.166 kg.COD/m³.day. In addition, ANOVA analysis was shown highly significant for the HRT and temperature factors with percentages

contribution were 39.92% and 33.78%, respectively. The experimental results were confirmed with predicted results and a good agreement had obtained. Therefore, this study revealed that the Taguchi orthogonal array design method could be applied successfully to determine the optimum conditions for COD treatment in the UAF reactor with a limited number of experiments and reduced the time, which are necessary for any wastewater treatment system.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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